THE APPLICATION OF OVERALL EQUIPMENT EFFECTIVENESS (OEE) AS A MEASURE FOR IMPROVING PRODUCTIVITY AND EFFICIENCY IN A TYPICAL FACTORY ENVIRONMENT

by

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(ABSTRACT)

Many systems in use today do not fulfill their expectations when operating, and are in a non-operating state much of the time due to maintenance. The accomplishment of maintenance often turns out to be costly and may significantly influence performance and the competitive position of a factory. In response to maintenance problems in the industrial environment, "Total Productive Maintenance (TPM)" is rapidly becoming the reliable, efficient, and cost-effective approach to maintaining the system to be operated at the full capacity with high productivity and low production cost.

"Overall Equipment Effectiveness (OEE)" has been developed to measure the effectiveness of a given maintenance approach. It involves all of the operation and maintenance parameters required to measure the overall operating condition of the factory and its equipment. Measuring in terms of the OEE assists in identifying the production losses experienced in a factory, and aids in planning possible countermeasures to eliminate those losses.

The concept of TPM and the steps involved in TPM implementation is introduced. A specific measure of TPM effectiveness, OEE, is defined, employed, and the results are analyzed. A computerized OEE model is developed to facilitate the measurement and evaluation process. The countermeasures necessary to eliminate the losses defined in TPM are also discussed. Application of OEE measurement and evaluation is illustrated through a case study assuming a hypothetical factory environment. A cost-effectiveness analysis in terms of the total product cost and the resultant OEE value is also illustrated through the case study. The application of these methods for continuous factory improvement is the objective.

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CHAPTER 1

INTRODUCTION

In today's competitive environment, manufacturing systems, in particular, are becoming increasingly sophisticated, and their performance and effectiveness are often inadequate to meet customer needs. Many of the systems in use are in a non-operating state much of the time due to maintenance. Additionally, the accomplishment of maintenance often turns out to be quite costly [Blanchard, 1994]. In order to survive in the competitive environment and maintain the systems at full capacity, system maintenance must receive the same attention as system performance when companies require smooth functioning, reliable, efficient and cost-effective maintenance programs.

1.1 Problem Statement

Many systems in use today are neither performing as intended, nor cost-effective in terms of their operation and support. Manufacturing systems often operate at less than full capacity with low productivity and high production cost. To remain competitive in today's global markets, a manufacturing company needs a cost-effective system designed for peak operation of its production machinery. Maintenance includes all actions necessary for retaining a system in, or returning it to, its desired operating condition and serves as a major contributor to the performance and profitability of the system [Blanchard and Verma, 1995]. From the cost standpoint, one study has revealed that from 15% to 40% of the total cost of a product can be attributed to maintenance-related activities in the factory [Mobley, 1990]. With regard to the issue of cost due to maintenance-related activities, experience has indicated that a large portion of product cost is caused by these high maintenance costs which refer to the direct maintenance labor and material costs in the factories that produce the product. This, in turn, significantly impacts sales in a highly competitive marketplace. In other words, high maintenance costs in the factory are causing a reduction in sales and a loss of revenue. In addition, recent surveys have shown that one third of all maintenance expenditures is wasted because of unnecessary or improper maintenance program implementation [Mobley, 1990]. The traditional approach to plant maintenance does not support timely, innovative, profitable solutions to the waste, inefficiency, and cost problems associated with previous deficiencies. As systems become more complex, it is essential that an effective and profitable maintenance approach be implemented throughout the entire life of the system. Consequently, a nontraditional approach to plant maintenance, which integrates design, engineering, production, and maintenance, reduces maintenance downtime and life-cycle cost, and applies maintenance technologies to improve equipment effectiveness, must be implemented.

Generally, a measure of effectiveness is used to describe how well the outputs achieve the desired goals. In practice, effectiveness is concerned with the definition, control, and measurement of system performance [Blanchard, 1969]. In order to understand the outcomes of a specific implementation approach and to integrate this approach more effectively throughout the company or plant, the current problems, the potential for their solution, and the benefits to be gained must be clarified through the analysis and measurement of effectiveness. This approach can isolate the problems and enhance the system's potential for improvement. Lack of a concept of analysis and the measurement of effectiveness may lead to redundant effort and misguided solutions. Such analysis and the measurement of effectiveness helps to pinpoint areas which are experiencing problems, and helps to identify where those problems are in the system. Finally, such an effort can help plan countermeasure prevention and improve in the implementation of maintenance approach.

An "overall equipment effectiveness (OEE)" model, defined in the effectiveness measurement of "Total Productive Maintenance (TPM)" which is a new integrated life-cycle maintenance approach, has been developed to measure the effectiveness of a given maintenance approach [Nakajima, 1988]. OEE is the best way to measure the effectiveness of maintenance because it considers all of the operational and maintenance parameters pertaining to the overall operating conditions of a manufacturing system. OEE represents the product of availability, performance efficiency, and quality rate. The causes of equipment losses can be identified from these three parameters and the possible countermeasures for prevention can be planned by analyzing each. In practice, experience indicates that OEE averages 45% at companies where TPM doesn't exist [Kotze, 1993]. Many factories are generally found to have OEE ratings only between 40% and 60% before TPM implementation [Nakajima, 1989]. It is also sad to say that the OEE in most US companies barely break 50% [Wireman, 1994]. These poor OEE values reveal that manufacturing systems are being operated at only one-half of their potential effectiveness, and that traditional equipment maintenance approaches are ineffective. Referring to Nakajima [Nakajima, 1988], an OEE of 85% is considered as being the "benchmark" for world class operations. Thus, there is so much room for improvement in the typical equipment maintenance management program.

As a result, there is a need for current manufacturing systems to implement an aggressive nontraditional approach to plant maintenance to increase the OEE values and reduce manufacturing costs. It is the objective of this project to introduce the concept of TPM and the steps involved in TPM implementation, and to present how to measure OEE values in order to identify production losses and how to analyze an OEE value in order to plan countermeasures to eliminate all production losses.

1.2 Maintenance Overview

With continuous industrial change and increasing competitiveness in the global market, the concepts and practices of traditional maintenance must be updated. The overall objective of every maintenance program should be to make the greatest possible contribution to the long-term profitability of the company. Therefore, an effective maintenance management program capable of maximizing the availability of plant facilities in operating condition, permitting maximum performance, and extending the service life of plant and equipment must be implemented.

TPM is rapidly becoming the approach of choice in this area. It constitutes the design and development of equipment for reliability and maintainability with the objectives of: (1) minimizing maintenance downtime; (2) reducing the requirement for support resources; (3) improving productivity; and (4) reducing life-cycle cost [Nakajima, 1988]. According to the observations of Dyer [Koelsch, 1993], compared to companies that still practice traditional maintenance approach, companies that implement TPM are seeing 50% reductions in breakdown labor rates, 70% reductions in lost production, 50% ~ 90% reductions in setup, 25% ~ 40% increases in capacity, 50% increases in labor productivity, and 60% reductions in cost per maintenance unit. Therefore, TPM is an improved maintenance approach over the more traditional maintenance approaches, which refer to corrective, preventive, and predictive maintenance and maintenance prevention. TPM enhances the state of maintenance, improves product quality, and increase productivity. It also results in reduced waste and reduced manufacturing costs.

1.2.1 Corrective Maintenance

Corrective (or emergency) maintenance is merely reactive repair work that waits for machine or equipment failure before any maintenance action is taken. Corrective maintenance includes all unscheduled maintenance actions performed, as a result of system failure, to recover the system to a specified operational status. Figure 1.1 illustrates a corrective maintenance cycle which performs a series of steps to repair and restore the system to full operating condition. This series of steps includes failure identification and verification, localization and fault isolation, disassembly to gain access to the faulty item, item removal and replacement with a spare or repair in place, reassembly, checkout, and condition verification [Blanchard, 1992].

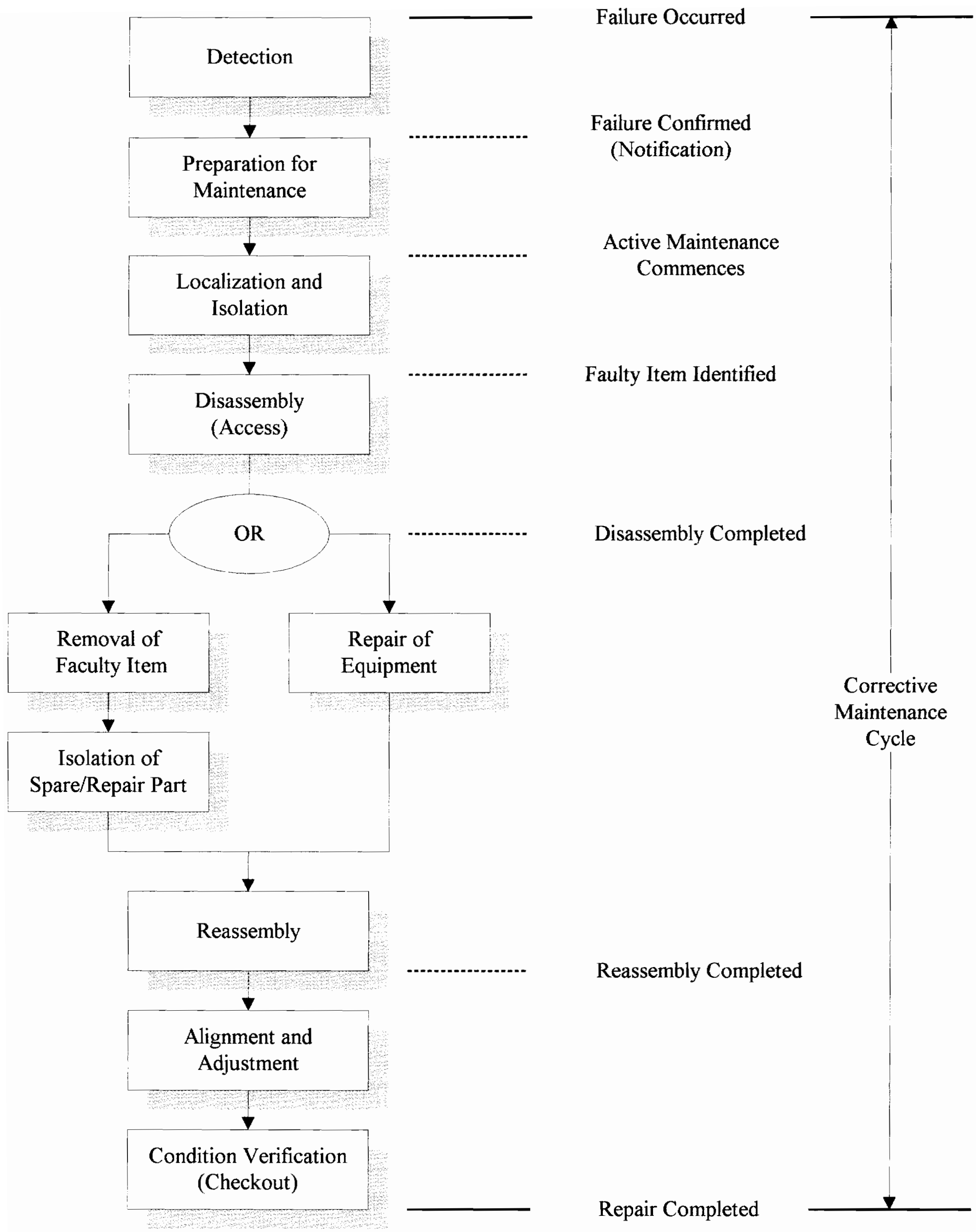

Figure 1.1 Corrective Maintenance Cycle [Blanchard, 1992]

1.2.2 Preventive and Predictive Maintenance

Preventive maintenance includes all scheduled maintenance actions performed to retain a system in a specific operational status. It includes: (1) those periodic inspections to detect conditions that might cause breakdowns, production stoppages, or detrimental loss of function; (2) maintenance to eliminate, control, or reverse such condition in their early stages; and (3) regular maintenance activities such as lubrication, cleaning of the line, and changing of filters, planned to prevent sudden failure of equipment and to help ensure equipment is operating in a satisfactory manner. In other words, preventive maintenance is a periodic maintenance to inspect equipment condition and treat equipment abnormalities before abnormalities cause defects or losses [Nakajima, 1989].

According to Niebel [Niebel, 1994], the principle objectives of preventive maintenance include:

1. Minimizing the number of breakdowns on critical equipment
2. Reducing the loss of production that occurs when equipment failure takes place
3. Increasing the productive life of all capital equipment
4. Acquiring meaningful data relative to the history of all capital equipment so that sound repair, overhaul, or replacement decision can maximize the return on capital investment
5. Permitting better planning and scheduling of required maintenance work
6. Promoting improved work force health and safety.

From the cost perspective, maintenance costs are a major part of the total operating cost of all manufacturing and production plants. The overall objective of maintenance is to maximize the production performance at a minimum cost. A typical cost-versus-delay curve is illustrated in Figure 1.2 [Wireman, 1992]. In order to reduce the preventive maintenance costs, preventive maintenance is only performed when actually necessary to avoid the cost of

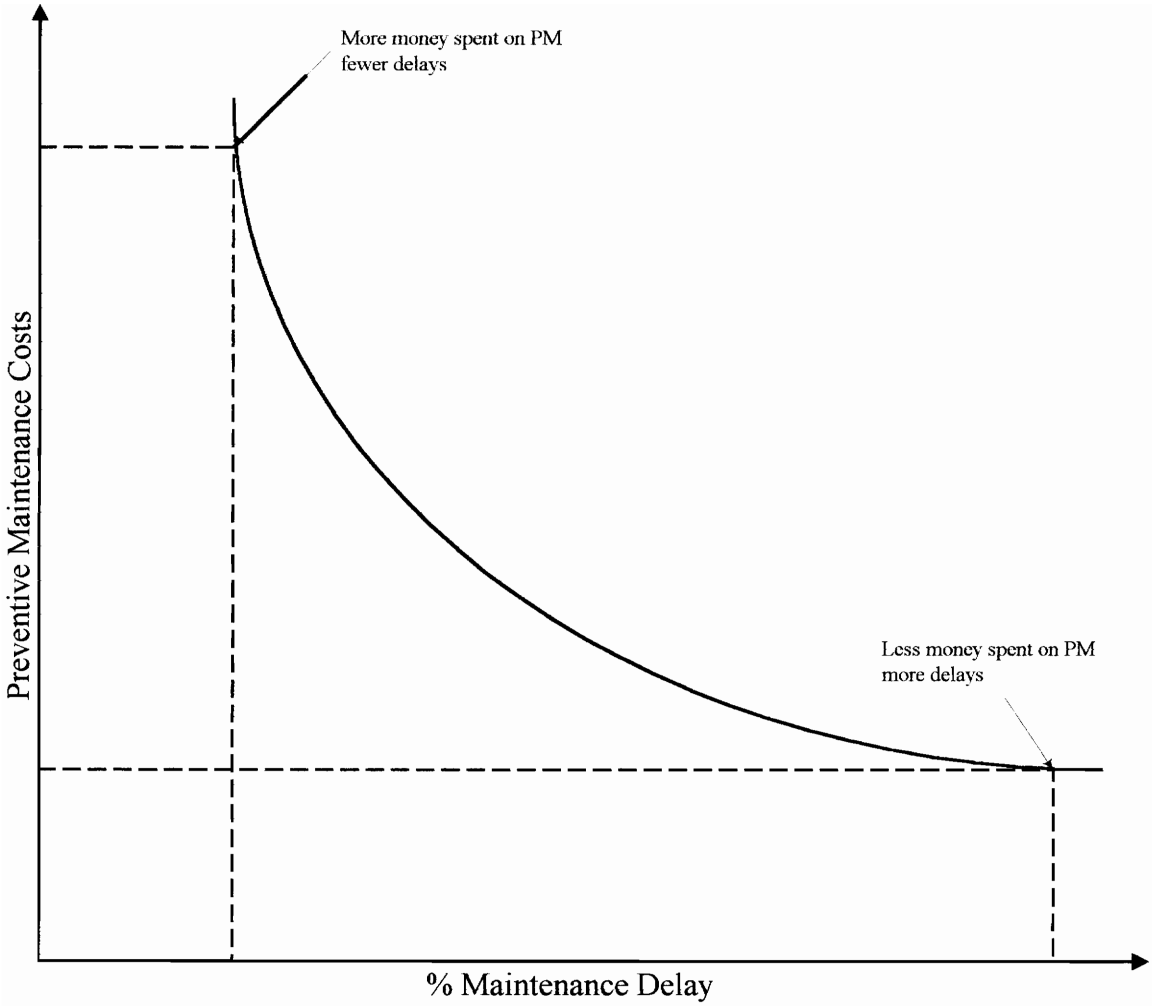

Figure 1.2 Cost-versus-Delay Curve [Wireman, 1992]

the lost of production time and the wasted man hours and materials. Too much preventive maintenance can cause much downtime, the possibility of inducing damage to the related components, and can be very costly. The point of more delay in Figure 1.2 is suggested to reduce the money spent on preventive maintenance.

There will always be a trade-off between corrective and preventive maintenance. The relationship between the cost of preventive and corrective maintenance is presented in Figure 1.3. The costs of preventive maintenance must be weighed against the costs of breakdown [Wireman, 1986]. For some equipment, it is more economical to only perform maintenance when the equipment breaks down, rather than investing the manpower and materials to perform preventive maintenance. If the cost of preventive maintenance is greater or equal to the cost incurred by a breakdown, then preventive maintenance would be a waste of money and should not be executed.

The maintenance approach known as predictive maintenance, or condition-based maintenance, is attracting attention as a highly reliable replacement for conventional periodic preventive maintenance. Predictive maintenance refers to a condition-monitoring preventive maintenance program where direct monitoring methods are used to determine the exact equipment condition, for predicting possible degradation, and for pinpointing the areas where maintenance is needed before capacity reductions or losses occur [Blanchard and Verma, 1995]. Predictive monitoring techniques include: vibration analysis; ultrasonic analysis; thermography; tribology; process monitoring; visual inspection; and other nondestructive analysis techniques [Mobley, 1990]. Most comprehensive predictive maintenance will use vibration analysis as the primary tool. However, a total plant predictive maintenance program must include several techniques depending on the equipment types, their impact on production and plant operation, and the company's goals. The objective is to predict when failures will occur and to take preventive measures accordingly.

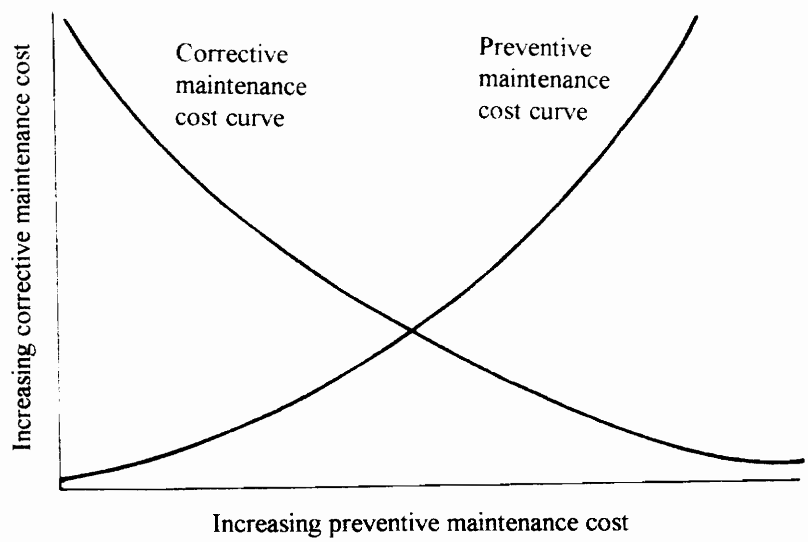

Figure 1.3 The relationship between the cost of preventive and corrective maintenance [Wireman, 1986]

1.2.3 Maintenance Prevention

Maintenance prevention (MP) is primarily used in the context of the concept of "Total Productive Maintenance (TPM)". Maintenance prevention is the design and acquisition of equipment that will not break down or produce defective products and will be easy to maintain and operate. In other words, the goal of maintenance prevention design is to take whatever necessary steps at the design stage to create maintenance-free design.

Maintenance prevention activities are conducted during equipment design, fabrication, installation and test, and commissioning. The goals of these activities are intended to reduce maintenance costs and deterioration losses in new equipment when designing for higher reliability, maintainability, supportability, and other requirements. In other words, it means designing and installing equipment that will be reliable, easy to take care of, and user friendly so operators can easily retool, adjust, and operate it [Nakajima, 1989; Shirose, 1992]. In addition, the concept of maintainability improvement (MI) must also be emphasized. It is an approach to improve equipment effectiveness through the introduction of maintainability characteristics in equipment design. Both of the concepts of maintenance prevention and maintainability improvement, applied in improving equipment design through reliability and maintainability considerations, will offer the greatest potential for meeting the overall objective of TPM in the future [Blanchard, 1994].

Finally, corrective maintenance, preventive maintenance, predictive maintenance, and maintenance prevention have been consolidated under a new type of maintenance approach called "productive maintenance". As defined by Nakajima, "Total Productive Maintenance" is "productive maintenance implemented by all employees," and "is based on the principle that equipment improvement must involve everyone in the organization, from line operators to top management. The key innovation in TPM is that operators perform basic maintenance on their own equipment. They maintain their machines in good running order and develop the ability to detect potential problems before they generate breakdowns [Nakajima, 1988]."

Maintenance prevention is pursued during the equipment design stage to facilitate equipment to be easier and more economical to maintain and more reliable. Once equipment is assembled, corrective maintenance is executed when breakdowns occur and preventive maintenance is performed to prevent equipment failures. The success of TPM depends on the ability to be continuously aware of the equipment condition in order to predict and prevent failures. At this point, predictive maintenance is significant in TPM implementation because it uses modern monitoring and analysis techniques to diagnose the equipment condition during its operation by identifying signs of deterioration or imminent failure. Thus, TPM is an integrated life-cycle approach to plant maintenance and has become a new direction in the future of factory operations.

1.3 Effectiveness Factors

Effectiveness is a desired result, outcome, consequence, or operation. The term *effectiveness* is used in measuring and evaluating how successful a given outcome achieves an intended purpose and how much improvement can be obtained as a result of modifying the system [Mundel, 1983; Habayeb, 1987]. In order to measure and assess the overall effectiveness of a system, effectiveness factors which express the technical characteristics of the system and system life-cycle costs should be defined prior to the identification of outcomes. The various effectiveness factors depend on a particular system or mission requirement. Individual manufacturing situations call for the use of different effectiveness factors. As an illustration, consider the effectiveness factors of a maintenance approach at a production factory. Frequency of maintenance, elapsed time, labor hours per operating hour, and so on, are usually used to express the technical effectiveness factors of the maintenance approach, especially for corrective maintenance and preventive maintenance. Maintainability and reliability characteristics act as the important effectiveness parameters in maintenance-free design (i.e., maintenance prevention). Maintenance costs, which are generated as a result of maintenance actions and are based on the consumption of resources utilized in the performance of these maintenance actions, are used to express the cost effectiveness factors of the maintenance approach. Furthermore, some of the terms underlying the need for the measurement and analysis of effectiveness are briefly defined and discussed herein.

1. System effectiveness

System effectiveness can be expressed and defined as one or more figures of metric representing the extent to which system can successfully meet an operational demand within a given time when operated under specified conditions. The figures of metric used may vary considerably depending on the type of system and its mission requirement [Blanchard, 1992]. In the evaluation of a manufacturing system relative to the TPM, the appropriate "metric" for measurement purpose can be defined in terms of "Overall Equipment Effectiveness (OEE)" which, in turn, is a function of availability, performance rate, and quality rate:

(1) Availability is equal to the ratio of operating time to loading time. Loading time refers to the time available during a given period for manufacturing operations, and operating time is the difference between loading time and downtime. Downtime is the time that system is not operating because of equipment failures, overhaul, calibration and adjustment, setup procedure, and so on.

(2) Performance rate is the product of the operating speed rate and the net operating rate. The operating speed rate is the ratio of the ideal cycle time to the actual cycle time to produce the product. The net operating rate is the actual cycle time to produce the product, multiplied by the processed amount, divided by the operating time. Ideal cycle time represents the designed time that it should take to process an item, as compared to the actual time. Processed amount refers to the number of items processed for a given period.

(3) Quality rate is the processed amount of product into the process or equipment, minus the number of quality defects, divided by the processed amount of product [Nakajima, 1988].

These three factors, which are discussed in detail in chapter three, have significant influence on the desired outcome and should be simultaneously considered in system effectiveness to measure the overall effectiveness of a system. Availability, performance rate, and quality rate should be considered in the measure of an accountable OEE. Then, an OEE analysis will be used in the evaluation of alternatives and the evaluation of various maintenance approaches to indicate the production losses experienced in the factory, and moreover be applied to plan for eliminating all production losses.

Consider the effectiveness factors related to the corrective, preventive, predictive maintenance, and maintenance prevention. Maintenance elapsed-time factors, maintenance labor-hour factors, and maintenance frequency factors are used to represent the effectiveness factors for the traditional maintenance approach. The maintenance elapsed-time causes the downtime in the production process. If maintenance is accomplished more frequently, more downtime is required. The maintenance elapsed-time of corrective maintenance influences the operating time, and that of preventive and predictive maintenance influences the loading time in the production process. Too many corrective maintenance actions result in the low operating time and, in turn, cause the low availability and performance rate. Too many preventive and predictive maintenance actions lead to the low loading time and, in turn, induce the low availability. However, performing the preventive and predictive maintenance when they are really necessary may reduce the downtime and increase the quality of the products. Maintenance prevention is intended to increase reliability, maintainability, and other requirements at the system design stage. This leads to the improvements in availability, performance rate, and quality rate. In short, availability, performance rate, and quality rate are all dependent on maintenance in one form or another.

2. Cost effectiveness

Cost effectiveness is a term which describes the relative value of a system. It measures the life-cycle cost and the capability of the system to fulfill its intended mission (system effectiveness). The primary considerations and elements in a cost-effectiveness analysis are shown in Figure 1.4. This illustration presents not only the various factors that affect system cost effectiveness but also their relationships. The goal is to develop a balanced system that not only satisfies all the necessary technical and performance-related requirements and constraints, but is also cost-effective.

The objective in developing a good maintenance program is to optimize plant effectiveness and profit at a minimum life-cycle cost. An effective maintenance program must result in an increase in the OEE value to achieve the world class benchmark and be cost-effective. To further illustrate the concept, a hypothetical production factory, whose production process flow is illustrated in Figure 1.5, is assumed as the basis for performing an OEE analysis, total cost analysis, and cost-effectiveness analysis.

1.4 Project Objectives

The overall purpose herein is to demonstrate a knowledge and understanding of the problems associated with some of the more traditional approaches used in accomplishing factory maintenance, and to investigate the feasibility of the TPM approach for better performance and lower cost. More specifically, objectives of this project are as follows:

1. To study the concept of Total Productive Maintenance (TPM), its metrics, and the steps of TPM development in a typical factory environment.
2. To analyze possible factors affecting overall equipment effectiveness (OEE) negatively, and to research countermeasures for reducing these effects.

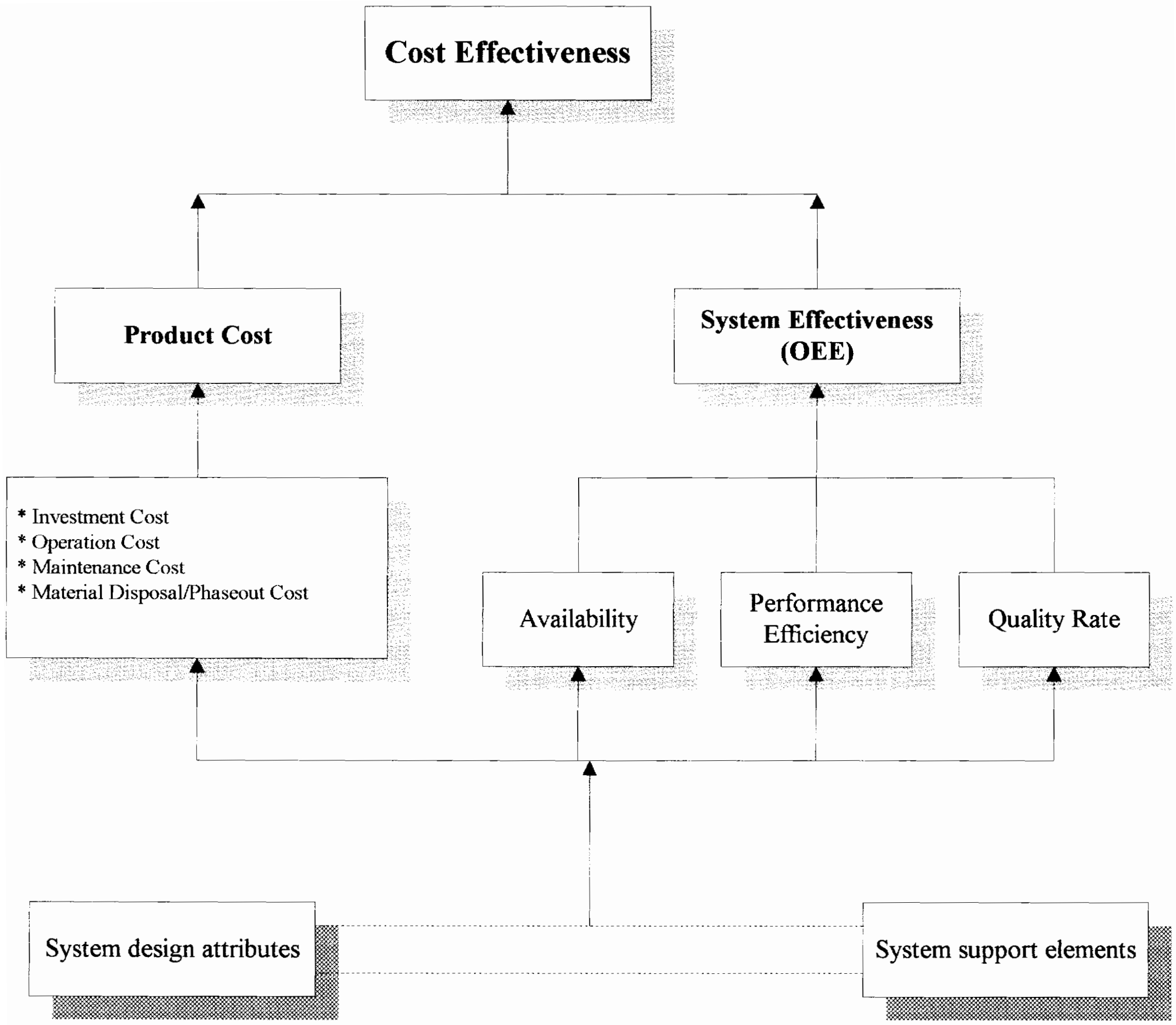

Figure 1.4 Elements of system cost effectiveness [Blanchard, 1995]

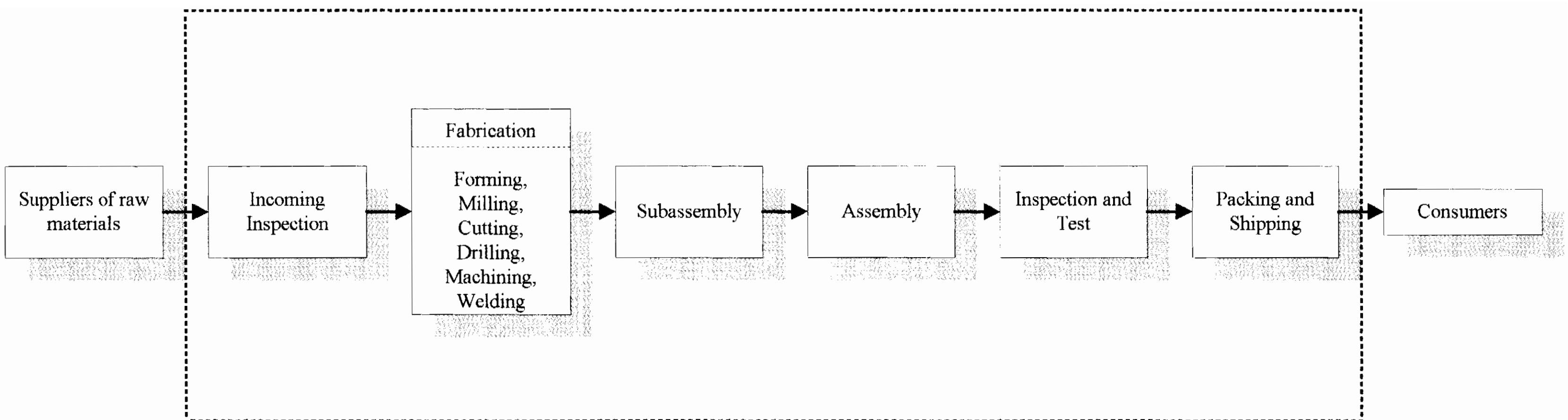

Figure 1.5 Production Process Flow Diagram

3. To develop a computerized model for OEE calculation and to measure the overall equipment effectiveness of equipment.
4. To measure and analyze overall equipment effectiveness (OEE) in a hypothetical factory environment in order to show that OEE values assist TPM implementers to indicate the losses in the productions, the impacts on system effectiveness, and the possible countermeasures to improve the OEE values and factory productivity.

CHAPTER 2

TPM IMPLEMENTATION

More and more plants have successfully implemented TPM in Japan during the past decade. The application of TPM methods and techniques have increased significantly in other countries in recent years. The implementation of TPM has become a major maintenance trend throughout the industrial world. To successfully implement TPM, the concept and essence of TPM must be introduced. An introduction to TPM is made here. Chapter two also identifies characteristics and goals of TPM and describes the steps in developing TPM.

2.1 Introduction to TPM

Total Productive Maintenance (TPM) has gained widespread attention and has become an important topic in the current industrial environment. Initially developed and introduced by the Japanese in 1971, TPM grew out of the philosophy of preventive maintenance. This concept was first introduced to Japan from the United States in 1951, with productive maintenance becoming well-established during the 1960's. Productive maintenance aims to maximize productivity by finding ways to: (1) prevent breakdowns and defects through preventive maintenance; (2) increase reliability and maintenance prevention at the design stage; and (3) use maintainability improvement to enhance equipment design effectiveness. TPM uses the ideas from preventive and productive maintenance, but its distinctive feature is autonomous maintenance by operators. In TPM, the plant operators fill a new role. They not only operate the machinery, but also inspect, clean, perform simple maintenance tasks and assist maintenance personnel as required.

According to S. Nakajima [Nakajima, 1988], a full definition of TPM must contain the following five elements:

1. Maximization of equipment effectiveness (improve overall effectiveness)
2. Establishment of a thorough system of preventive maintenance for the entire life of the equipment.
3. Involvement of various departments in implementing TPM (engineering, operations, maintenance).
4. Active involvement of all employees, from top management to shop floor workers.
5. Reinforcement TPM through autonomous small group activities.

The word " Total" in TPM has three meanings which represent its important features of TPM. Related to these three meanings, the relationship between TPM, productive maintenance, and preventive maintenance is shown in Figure 2.1.

1. Total effectiveness (item 1 above) indicates TPM's pursuit of economic efficiency or profitability.
2. Total maintenance system (item 2 above) includes maintenance prevention (MP), corrective maintenance (CM), and preventive maintenance (PM).
3. Total participation of all employees (item 3, 4, and 5 above) includes autonomous maintenance by operators through small group activities in every department at every level.

The dual goals of TPM are zero breakdowns and zero defects. It means to maximize overall equipment effectiveness (OEE) by eliminating the six major losses. When breakdowns and defects are eliminated, equipment operation rates improve, costs go down, product qualities increase, and as a consequence, labor productivity increases. The six major losses which limit equipment effectiveness are [Nakajima, 1988]:

	TPM features	Productive Maintenance features	Preventive Maintenance features
Economic efficiency (profitable PM)	○	○	○
Total system (MP-PM-MI)*	○	○	
Autonomous maintenance by operators (small group activities)	○	○	

TPM = Productive Maintenance + small group activities

* MP = Maintenance Prevention
PM = Preventive Maintenance
MI = Maintainability Improvement
○ = Yes, it has this concept

Figure 2.1 Relationship between TPM, Productive Maintenance, and Preventive Maintenance [Nakajima, 1989]

Downtime losses

1. Breakdown losses

Breakdown losses are caused by equipment failures which require any kind of repair. For instance, these losses consist of downtime along with the labor and spare parts required to maintain the equipment operation.

2. Setup and adjustment losses

Setup and Adjustment losses are caused by changes in operating condition, such as the commencement of production runs or startup at each shift, changes in products, and operating condition.

Speed Losses

3. Idling and Minor stoppages losses

Idling and Minor Stoppages occurs when production is interrupted by a temporary malfunction or when a machine is idling. These types of temporary stoppage clearly differ from a breakdown, and they are easily overlooked because they are often difficult to quantify.

4. Reduced speed losses

Reduced Speed occurs when there is a difference between the speed at which a machine is designed to operate and its actual speed. For example, reduced speed losses occur when operators intentionally slow a machine down because its designed speed results in quality defects or mechanical problems.

Defect losses

5. Quality defects and rework losses

Quality defects and rework losses are caused by off-specification or defective products manufactured during normal operation. The losses consist of the labor required to rework the products and the cost of the material to be scrapped.

6. Startup/yield losses

Startup/yield losses are those incurred because of the reduced yield between the time the machine is started up and when stable production is finally achieved.

Downtime losses affect the availability of equipment. Speed losses influence the performance rate. Defect losses determine the quality rate of production. By knowing the six major losses, overall equipment effectiveness can be determined to evaluate TPM implementation.

By definition, TPM must be implemented on a company-wide basis in order for it to be effective. For the purpose of successfully and effectively implementing TPM, an overview of TPM is presented in Figure 2.2. This illustration presents the goals of TPM, program participants, and the specific activities of implementing TPM.

2.2 Characteristics of TPM

Traditionally, a maintenance approach separates production and maintenance. The general thinking among equipment operators has been "I run it, you fix it." Operators are accustomed to considering themselves responsible only for setting up unprocessed workpieces and checking the quality of processed ones. They regard all maintenance as the responsibility of the maintenance staff. This way of thinking is a mistake. This kind of maintenance approach reduces the productivity of production and reduces the effectiveness of maintenance. TPM has the potential for providing an almost seamless integration of production and maintenance through autonomous small group activity. Contrasted to the traditional approach to plant maintenance, autonomous maintenance by operators and small group activity are the outstanding and distinctive feature of TPM.

2.2.1 Autonomous Maintenance

One of the most distinctive features of TPM is "autonomous maintenance". The objective of autonomous maintenance is to educate or train equipment operators in how to maintain their equipment by performing daily inspections, lubrications, repairs, precision checks, and other maintenance tasks including the early detection of abnormalities. From a

Overall workshop improvement, developing optimum human-machine conditions

	Individual improvements to raise equipment efficiency: eliminating the six big losses	Establishment of autonomous maintenance system	Establishment of planned maintenance system	Establishment of skills development system for operators and maintenance workers	Establishment of MP design and early equipment management system
Goals	* To achieve the "zero" target (zero breakdowns, defects, etc.) * To get equipment operating at optimum availability (operating rate)	* To train operators in equipment-related skills * To enable operators to take care of their own equipment	* To raise the efficiency of the maintenance department to prevent the six big losses	* To raise operator skill levels	* To design equipment that is less likely to have berakdowns or defects, and to carry out early equipment management that quickly gets the equipment running reliably to reduce and stablize startup times
Participants	* Staff * Line leaders	* Operators * Line leaders	* Maintenance staff, leaders, and workers	* Operators * Maintenance workers	* Production engineers * Maintenance Staff
Specific activities	* Identifying the six big losses * Calculation of overall efficiency and target-setting * Analysis of phenomena and review of related causes * Implementation of PM analysis	* Implementation of the 7 steps for autonomous maintenance * Initial cleaning * Eliminating sources of contamination and inaccessible areas * Cleaning and lubrication standards * General inspection * Autonomous inspection * Workplace organization and housekeeping * Thoroughly implemented autonomous maintenance program	* Daily maintenance and checking measures * Periodic maintenance * Predictive maintenance * Improvements to increase equipment life * Spare parts control * Breakdown analysis and prevention * Lubrication control	* Maintenance fundamentals * Nuts and bults * Keys * Bearings * Power transmissions * Sealing (leak prevention)	* Establish design goals * Autonomous maintainability (MP) * Maintainability (MP) * Operability (MP) * Reliability (MP) * Life cycle costing * Identifying problems at each stage (design, drawing, fabrication, installation, etc.) * Debugging

Figure 2.2 TPM Overview [Shirose, 1992]

human standpoint, autonomous maintenance nurtures the development of knowledgeable operators in newly defined roles. From an equipment standpoint of view, it establishes an orderly shop floor where any abnormalities may be detected at an early stage of occurrence. In practice, operators are trained or educated to accomplish the following major purposes in an autonomous maintenance program [Tajiri, 1992]: (1) to establish basic equipment condition; (2) to observe usage condition of equipment; (3) to restore deteriorated parts through overall inspection; (4) to develop into a knowledgeable operator; and (5) to conduct autonomous supervised operator's routine maintenance.

Operators traditionally are used to devoting themselves full-time to manufacturing, and maintenance personnel expect to assume full responsibility for equipment maintenance. Operator are ultimately more productive when encouraged to be responsible for their own equipment. Customary behaviors and expectations may result in less competitiveness in the global marketplace but can not be changed overnight. Typically, it takes two to three years to accomplish TPM implementation [Nakajima. 1988]. Both equipment operators and maintenance personnel should share the responsibility for equipment and work together in the spirit of cooperation. Ideally, operation and maintenance should be inseparable. However, the maintenance and production function have been customarily separated and the relationship between operators and maintenance personnel has become often somewhat adversarial as equipment has become more complicated and as businesses have grown larger. If, on the other hand, operators can participate in basic maintenance work by becoming responsible for deterioration prevention, maintenance targets are more likely to be achieved.

Efficient productivity depends on both production and maintenance activities. For the purpose of efficient productivity and maintenance, two departments (production and maintenance) must do more than share the responsibility for equipment — they must cooperate with each other. They also must understand each other's situation and avoid being at odds with one another. It is necessary to classify maintenance activities and allocate tasks in the autonomous maintenance program. The maintenance activities and tasks performed by the production department include the following three deterioration-prevention activities:

1. *Deterioration prevention:*

- Operate equipment correctly.
- Maintain basic equipment operating conditions.
- Record data on breakdowns and other malfunctions.
- Collaborate with maintenance department to study and implement improvement.

2. *Deterioration measurement:*

- Conduct daily and specific periodic inspections.

3. *Equipment restoration:*

- Make minor repairs.
- Report on breakdowns and other malfunctions.
- Assist in repairing sporadic breakdowns.

The maintenance department, in contrast, performs periodic maintenance, predictive maintenance, maintainability improvement, assistance and guidance for operators, and other activities including research and development of maintenance technology, setting maintenance standards, keeping maintenance records, evaluating results of maintenance work, and cooperating with engineering and equipment design departments [Nakajima, 1989].

In Japan, the basic principles of operations management are known as the five S's [Nakajima, 1988]: seiri, seiton, seiso, seiketsu, and shitsuke (organization, tidiness, purity, cleanliness, and discipline). At present, most factories implement some of these principles, but many often do so only on a superficial level. To avoid this superficiality in implementing TPM's autonomous maintenance, a step-by-step approach must be taken. Autonomous maintenance development has been organized into seven steps summarized in Table 2.1[Nakajima, 1988]. The tasks involved in each step must be thoroughly learned before going to the next. In steps 1, 2 and 3, these activities focus on creating the foundation of TPM by establishing proper cleaning, lubrication, and tightening of equipment. The major objectives are to establish basic equipment conditions and to understand the meaning of autonomous supervision. Steps 4 and 5 stress a dramatic reduction in breakdowns and minor stoppages, along with training knowledgeable operators through the repetition of education and subsequent practice of inspection. Steps 6 and 7 stress improvement activities informed by operators' increasing knowledge and experience and extending beyond the equipment to its surrounding environment.

The twelve keypoints in implementing autonomous maintenance are summarized in Table 2.2 [Tajiri, 1992]. If any one of these keypoints is not properly addressed, the devoted efforts of shop floor personnel can be expected to fail.

2.2.2 Small Group Activities

The promotional structure of overlapping small groups is a unique feature of TPM. In TPM, organizational and small group improvement activities are integrated by overlapping small groups. The use of "small group activities" facilitates the top-down and bottom-up promotion of TPM activities and ideas. The objective of TPM small group activities is to establish a true participative management to encourage confidence among employees and promote consistently high productivity.

The basis for TPM small group activities is the combination of quality control (QC) circles and zero defects (ZD). QC circles, introduced in 1962, are one kind of Japanese-style small group activity, which began as study groups to teach shop floor supervisors quality control techniques and evolved into problem-solving small groups involving larger segments of the worker population. On the other hand, ZD groups, first used in the United States, are the means of involving all employees in solving problems. QC circles are formed around

Table 2.1 Seven Steps for Developing Autonomous Maintenance [Nakajima, 1989]

Step	Activities
1. Initial cleaning	Clean to eliminate dust and dirt mainly on the body of the equipment; lubricate and tighten; discover problems and correct them
2. Countermeasures at the source of problem	Prevent cause of dust, dirt and scattering; improve parts that are hard to clean and lubricate; reduce time required for cleaning and lubricating
3. Cleaning and lubrication standards	Establish standards that reduce time spent cleaning; lubricating, and tightening (specify daily and periodic tasks)
4. General inspection	Instruction follows the inspection manual; circle members discover and correct minor equipment defects
5. Autonomous inspection	Develop and use autonomous inspection check sheet
6. Orderliness and tidiness	Standardize individual workplace control categories; thoroughly systemize maintenance control • Inspection standards for cleaning and lubricating • Cleaning and lubricating standards in the workplace • Standards for recording data • Standards for parts and tools maintenance
7. Full autonomous maintenance	Develop company policy and goals further; increase regularity of improvement activities Record MTBF analysis results and design countermeasure accordingly

Table 2.2 Twelve Keypoints of Autonomous Maintenance [Tajiri, 1992]

Keypoints	Description
1. Introductory education	Conduct thorough education which includes orientation and lecture on TPM concepts prior to commencement of autonomous maintenance activities
2. Cooperation among departments	Promote maximum cooperation among production-related departments as well as administrative departments. Managers must establish a support system for operators' efforts.
3. Autonomous maintenance is the job!	All employees must recognize autonomous maintenance activity as a mandatory part of operators' routine jobs.
4. Small group	All activities must be developed based on small group.
5. Managers must take the lead!	Front-line managers must take the lead and set an example to demonstrate how to develop forthcoming steps of autonomous maintenance program.
6. Education and practice	Conduct thorough education and practice for operators without missing any minor opportunity.
7. Practice first	Take breakthrough approach by way of thorough practice in order to attain Zero Accidents, Zero Defects and Zero Breakdowns.
8. Actual effects	Provide concrete subjects and targets for operators in terms of each TPM activity, and encourage them to attain actual and effective results.
9. Rules set by operators	The rules must be set by those who must follow them.
10. Autonomous maintenance audit	The autonomous maintenance audit makes the largest contribution toward encouraging and training PM groups.
11. Quick response	The maintenance department must quickly and promptly treat work orders from autonomous maintenance. If not, PM group activity will certainly fail.
12. Be thorough	Be thorough in developing each step of autonomous maintenance program. If an audit is unsuccessful, do not proceed to the next step in a hurry because of the schedule. When this happens, TPM is not firmly implemented due to poor progress in technical knowledge and skills.

specific subjects and goals are set within each subject. ZD groups, on the other hand, must decide goals consistent with the company goals because the objective of ZD is to eliminate defects and promote the achievement of all related goals. Although QC cycles and ZD small groups differ organizationally, they often merge and interact with each other.

TPM small group activities are based on the ZD model and built into the organizational framework. Specifically, TPM promotes autonomous maintenance by operators through small group activities. In TPM, the typically management-directed activities of equipment cleaning, inspection, etc., are performed as small group activities. The reason why TPM small group activities should be integrated into an organizational structure is to facilitate the top-down and bottom-up promotion of all information and requirements. Then, small group goals can coincide with and be the same as company goals — to improve productivity and the work environment [Nakajima, 1988].

Experts' experiences have indicated that success in small group activities depends on three conditions: motivation; ability; and a favorable work environment [Nakajima, 1988]. Motivation and ability are the workers' responsibilities. However, top management must take the responsibility for actively promoting these three key factors. Its first responsibility is to provide the necessary training and education to prepare a knowledgeable operator to perform autonomous maintenance. Management's second responsibility is to provide a favorable work environment by eliminating environmental problems. TPM can not be successfully implemented without the support of top management. Therefore, the function of top management must thoroughly support small group activities.

2.3 Steps of TPM Development

The practical details and procedures necessary to develop a TPM program must be tailored for each company individually. The program must be developed and adjusted to fit individual requirements since needs and problems vary, depending on the company, type of industry, techniques, production methods, and equipment conditions, from company to company. Because of the variation in TPM development for each individual company, a system development process, illustrated in Figure 2.3 [Blanchard, 1990], from the "system" perspective, can be applied to enhance the development of TPM. An effective TPM program begins with the definition of company goal/need and the analysis of system function. Then this gives way to preliminary synthesis and allocation of requirement. The final stage is a trade-off and optimization process. The application of system development process is useful for TPM enhancement.

There are some basis conditions for the development of TPM that apply in most situations. Generally, the minimum requirements for a successful TPM developed program are summarized below [Nakajima, 1988]. These are also the fundamental TPM activities.

- Improving equipment effectiveness
- Autonomous maintenance by operators
- A planned maintenance program for the maintenance department
- Increased skills of operation and maintenance personnel
- An initial equipment management program

TPM is not a quick fix solution to a plant's production equipment and maintenance management problems. It takes two to three years for a full TPM implementation. The span of TPM development can be divided into three stages. Table 2.3 lists the twelve basic steps of a TPM development program [Nakajima, 1988]. In the preparation stage, an appropriate environment has to be created by establishing a plan for the introduction of TPM. The duration of preparation stage depends on the size of the company, level of technology, management standards, and so on. Next, the implementation stage, the second stage, will take two to three years to complete all implementation processes. During the final stabilization stage, a plant must measure actual results accomplished against its TPM goals. Table 2.3 also explains the methods of how to execute each step.

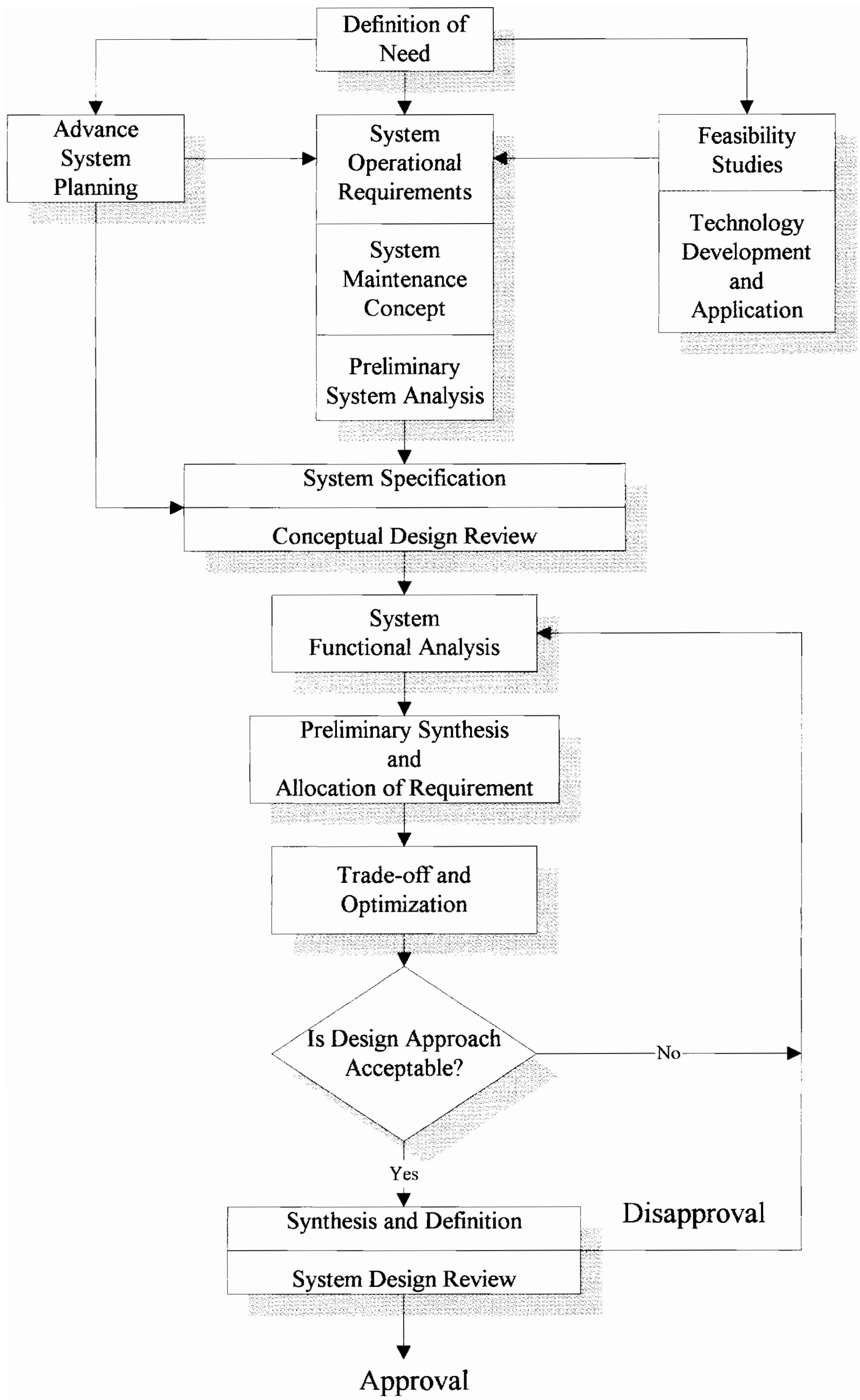

Figure 2.3 System Development Process [Blanchard,1990]

Table 2.3 The Twelve Steps of TPM Development [Nakajima, 1988]

Stage	Step	Details
Preparation	1. Announce top management decision to introduce TPM	Statement at TPM lecture in company; articles in company newspaper
	2. Launch education and campaign to introduce TPM	Managers: seminars/retreats according to level General: slide presentations
	3. Create organizations to promote TPM	Form special committees at every level to promote TPM; establish central headquarters and assign staff
	4. Establish basic and policies and goals	Analyze existing conditions; set goals; predict results
	5. Formulate master plan for TPM development	Prepare detailed implementation plans for the five foundational activities
Preliminary implementation	6. Hold TPM kick-off	Invite clients, affiliated and subcontracting companies
TPM implementation	7. Improve effectiveness of each piece of equipment	Select model equipment; form project teams
	8. Develop an autonomous maintenance program	Promote the Seven Steps; build diagnosis skills and establish worker certification procedure
	9. Develop a scheduled maintenance program for the maintenance department	Include periodic and predictive maintenance and management of spare parts, tools, blueprints, and schedules
	10. Conduct training to improve operation and maintenance skill	Train leaders together; leaders share information with group members
	11. Develop initial equipment management program	MP design (maintenance prevention); startup equipment maintenance; LCC analysis
Stabilization	12. Perfect TPM implementation and raise TPM levels	Evaluate for PM prize; set higher goals

Chapter 3

Measuring TPM Effectiveness

This chapter sketches the reasons for measuring TPM effectiveness and defines and discusses the most basic and appropriate effectiveness measure in use — overall equipment effectiveness (OEE). It also provides the process of a computerized model for OEE calculation. The last section concludes with the countermeasures to eliminate equipment losses.

3.1 TPM Effectiveness Measures

TPM is a continuous maintenance improvement program to eliminate equipment losses and enhance equipment effectiveness. Effectiveness measurement is an important requisite of the continuous improvement process. Problems impeding system output can be isolated and the potential for improvement can be developed after effectiveness has been measured. The measurement of TPM effectiveness makes it possible to find what causes losses and to look for potential improvement. A measuring technique, which isolates the current problems and predicts the potential for improvement, is necessary for each function and in each department on a continuing basis over time in order to implement TPM program more effectively throughout the company. In other words, the reasons for measuring TPM effectiveness are: to help establish priorities for improvement projects, and to accurately and fairly reflect their results [Nakajima, 1989].

A variety of indices showing effectiveness facilitate prompt identification of problem and negative responses to change and facilitate more accurate judgment of the appropriate countermeasures. Also, they help prompt more efficient implementation of TPM activities. These measuring indices provide a close monitoring at all levels to help maintain and upgrade implementation improvements, and to prompt the development of more effective countermeasures to prevent sudden drops in effectiveness. Each company must decide which indices are appropriate in its unique situation.

With increasing robotization and automation in current industrial environment, productivity, cost, inventory, safety and health, and production output, as well as quality, all depend on equipment. A measurement of effectiveness of equipment can accurately reveal which areas are experiencing problems and the nature of those problems. Thus, the measure of equipment effectiveness provides appropriate indicator for understanding and evaluating TPM effectiveness. Equipment effectiveness is a measure of the value added to production through equipment. The goal of TPM is to increase equipment effectiveness so each piece of equipment can be operated to its full potential and maintained at that level.

The most basic and appropriate effectiveness measure related to equipment is overall equipment effectiveness (OEE) [Nakajima, 1989]. It is extremely useful as an overall indicator of factory or equipment performance. The detailed explanation and definition of OEE is presented in section 3.2. Additionally, some effectiveness measures are used to measure the preventive maintenance achievement rate, maintenance improvement rate, indices related to PQCDSM (productivity, quality, cost, delivery, industrial hygiene and safety, moral), and so on. Each rate or index used to measure TPM effectiveness has advantages and disadvantages. Each company must decide the appropriate measure for its own environment and carefully define the terms used. Moreover, the measurements selected must be meaningful to the people who control them. All available data for calculating effectiveness should be correctly and completely collected. Then the meaningful effectiveness measures can be used as a realistic diagnostic measurement to evaluate TPM implementation. Overall equipment effectiveness is selected as the effectiveness measure for this project.

3.2 Overall Equipment Effectiveness

Overall equipment effectiveness (OEE) is very much on the mind of TPM practitioners these days. It is central to TPM scorekeeping and has become the plant standard for improving to production processes. In TPM, overall equipment effectiveness encompasses all of the operational and maintenance parameters to include availability, performance, and quality. This shows that OEE incorporates the overall operating condition of the equipment and thus leads to a more comprehensive, realistic measure of effectiveness. Developing a customized version of OEE will help to maximize metric usefulness as an improvement index and pinpoint equipment losses.

OEE represents the mathematical product of availability, performance rate, and quality rate. The goal of TPM is to increase OEE. A high level of OEE can only be achieved when all three effectiveness measures are high. The calculation and definition of the operating rate, the performance rate, and quality rate are described as follows [Nakajima, 1988]:

1. Availability:

   The operating rate (availability) is based on a ratio of operating time (excluding downtime) to loading time. The mathematical equation is expressed as:

$$\text{Availability (operating rate)} = \frac{\text{Loading Time} - \text{Downtime}}{\text{Loading Time}} \times 100\%$$

   In this case, loading time is the daily (or monthly) operating time minus all forms of non-operating time — breaks in the production schedule, stoppages for routine maintenance, morning meetings, and other routine stoppages. Downtime means the total time taken for stoppages such as breakdowns, retooling, adjustments, blade and drill bit replacement, and so on.

2. Performance rate:

Performance rate is based on the operating speed and the net operating time. The operating speed rate is the ratio of the initial speed of the equipment to its actual speed. In other words, it shows the speed at which the equipment is actually operating relative to its ideal speed. The equation used to define operating speed rate is:

$$\text{Operating speed rate} = \frac{\text{Ideal cycle time}}{\text{Actual cycle time}} \times 100\%$$

Net operating rate measures the maintenance of a given speed over a given period. The formula for net operating time is as follows:

$$\text{Net operating rate} = \frac{\text{Pr ocessed amount} \times \text{Actual cycle time}}{\text{Loading Time} - \text{Downtime}} \times 100\%$$

Then the performance rate is calculated as follow:

$$\text{Performance Rate} = \text{Operating speed rate} \times \text{Net operating rate} \times 100\%$$

3. Quality rate:

The equation for quality rate is defined as:

$$\text{Quality rate} = \frac{\text{Pr ocessed Amount} - \text{Defect Amount}}{\text{Processed Amount}} \times 100\%$$

Figure 3.1 gives an example of a calculation of overall equipment effectiveness for further clarification. The resulting OEE in this example is only 42.6% due to poor operating speed rate and net operating time. This represents the average condition of most companies before TPM implementation. Based on experts' experiences, the ideal conditions are:

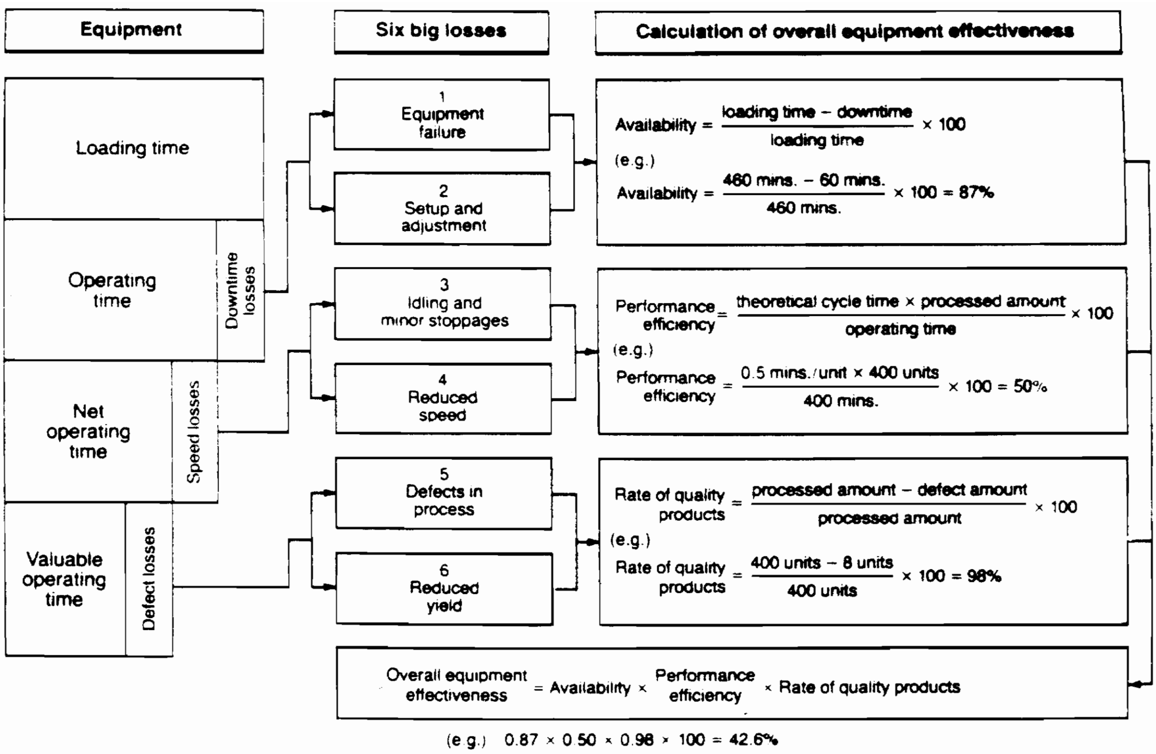

Figure 3.1 Example of OEE Calculation [Nakajima, 1988]

- Availability … greater than 90%
- Performance rate … greater than 95%
- Quality rate … greater than 99%.

Therefore, the ideal for overall equipment effectiveness should be 85% $(0.90 \times 0.95 \times 0.99 \times 100\%)$, which is considered as world class and a benchmark to be established for a typical manufacturing capability [Nakajima, 1988].

In practice, developing a universal calculation for OEE to match all applications of TPM implementation has become more and more important issue [Kotze, 1993; Naguib, 1994]. Because manufacturing processes vary from industry to industry, plant to plant, and even assembly line to assembly line, a generic OEE calculation, which clearly defines the terms used in the OEE formula and completely relates to the operating logistic, current maintenance practices, and the causes of losses, will be useful as an evaluating improvement tool throughout manufacturing process. OEE applications vary depending on how the terms are defined in the formula and how the data for inclusion and exclusion are selected. It is often necessary to interpret all definitions to the people who use them, especially front-line production and maintenance associates. Expert's experience indicated that a consensus on five key definition — planned downtime, unplanned downtime, machine cycle time, defect or yield loss, and number of units produced during available time must be obtained in order to develop a custom version OEE [Kotze, 1993]. The five key definitions are defined as follows:

1. *Planned Downtime:*

   Planned downtime refers to "specially identified time during which available machinery is not scheduled to produce product." It includes scheduled breaks and lunches; scheduled department or team meetings; and scheduled preventive maintenance, but does not include changeovers; setups and adjustments; and startup time.
2. *Unplanned Downtime:*

Unplanned downtime refers to "any time during scheduled production that the machine is not producing product." It includes lost time due to breakdowns and failures; changeovers; startup losses; recorded minor stoppages; setup and adjustments; and idling and waiting time.

3. *Machine Cycle Time:*

Machine cycle time refers to "the engineering specified ideal or theoretical cycle time for a specific machine, usually measured in minutes or fractions thereof."

4. *Defect/Yield Loss:*

Equipment-related yield losses consist of product made during the measured period that is scrapped or fails a quality check and must be reworked.

5. *Number of Units Produced during Available Time:*

It includes all units produced during the measured period which even includes startup and ramp-down period, whether good, bad, or scrapped.

Ultimately, an agreement and consistency regarding which data are included or excluded, the accuracy of the data, and the clear definition of each element used in the OEE calculation are essential for a realistic, useful measure of overall equipment effectiveness. Then, a real OEE value can actually evaluate the production losses being experiencing in the factory. Unable to do these will mislead analysts to find out the real losses occurred in the factory and to plan redundant countermeasures for the wrong causes of losses. Therefore, using OEE as a diagnostic measure to improve equipment and process makes each TPM implementer plan a profitable maintenance program and plan countermeasures against all equipment losses.

3.3 Computerized OEE Model

Based on the definition and discussion of OEE parameters in section 3.2, a computerized OEE model has been developed to measure the effectiveness of any equipment.

The definitions of terms used in the computerized OEE model are also taken from the definitions in the previous section. Figure 3.2 illustrates the logic flow chart of this computer model. The program codes and example of output are presented in Appendix A. The computerized OEE model can be repeatedly used to measure the OEE value for each equipment in the system.

3.4 Countermeasures to Eliminate Equipment Losses

One of the goals of TPM is to enhance equipment effectiveness. However, the six big losses: breakdown losses; setup and adjustment losses; idling and minor stoppage losses; reduced speed losses; quality defects and reworks; and startup/yield losses, limit the achievement of this goal. In order to maximize equipment effectiveness, companies must: (1) understand what is really meant by the six big losses for their specific factory environments; (2) establish improvement targets; and (3) develop countermeasures to eliminate the six big losses.

On the basis of a thorough examination of the factors which reduce equipment effectiveness, major losses are categorized into the six types and has been defined in chapter two. The next step is to establish improvement targets for eliminating the six big losses. Table 3.1 lists improvement targets for the six big losses to achieve a world class OEE value. When improving overall equipment effectiveness, the following principles must be applied [Nakajima, 1989]:

- Make detail, accurate measurements,
- Set firm priorities, and
- Establish clear direction or goal.

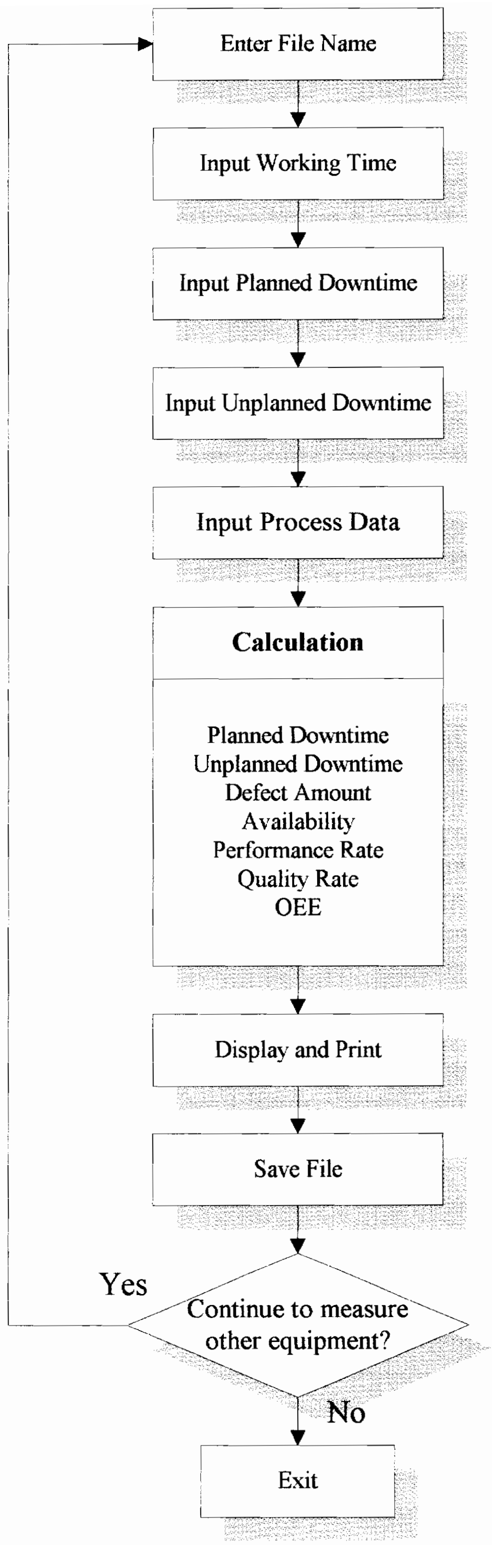

Figure 3.2 Computerized OEE Calculation Model Flow Chart

Table 3.1 Improvement Target for the Six Big Losses [Shirose, 1992]

LOSS	TARGET	DESCRIPTION
Breakdown loss	Zero	Breakdown loss must be reduced to zero for all equipment
Setup and Adjustment loss	Minimize	Minimize set and adjustment loss by doing single setup lasting less than 10 minutes, and with zero adjustment
Reduced Speed loss	Zero	Eliminate all differences between the actual and designed conditions of the equipment
Idling and Minor Stoppage loss	Zero	Idling and minor stoppage loss must be completely eliminated in all equipment
Quality defects and rework loss	Zero	Keep such loss within a minimum range in terms of ppm (such as 30 to 100 ppm)
Startup/Yield loss	Minimize	

Once OEE has been measured, a factory can determine its priorities for improving availability, performance rate, or quality rate, and find the root causes of losses from the results of OEE calculation. Then the factory can establish the specific improvement targets and develop the countermeasures for eliminating all equipment losses for its own situation to increase equipment effectiveness.

To reach the target of zero breakdowns, five countermeasures must be conscientiously pursued. Neglect of any one or more than one of them can directly trigger a breakdown or cause malfunction in equipment. The five countermeasures are[Tajiri, 1994]:

1. Establish the basic equipment condition
2. Adhere to the usage condition of operation
3. Restore deterioration
4. Correct design weakness
5. Enhance operating and maintenance skills

Setup and adjustment downtime is the time required for stopping current production and setting up for production of the next product. Setup and adjustment ought to be performed quickly and accurately. Figure 3.3 presents a systematic improvement program to minimize the setup and adjustment losses.

Idling and minor stoppages are caused by temporary problem in the equipment. Since they can usually be restored quite simply, operators tend to overlook them and not regard them as losses. However, this is a mistake and will cause a reduction in performance rate. The zero idling and minor stoppage goal is essential. Figure 3.4 illustrates an overview of the improvement program for reducing idling and minor stoppages.

A speed loss is the lost production caused by the difference between the designed speed of a machine and its actual operating speed. Keeping the machine operating at the speed set by the operating standard prevents this loss. Table 3.2 outlines a systematic improvement program to eliminate the reduced speed losses. Losses incurred by rework and defect has a

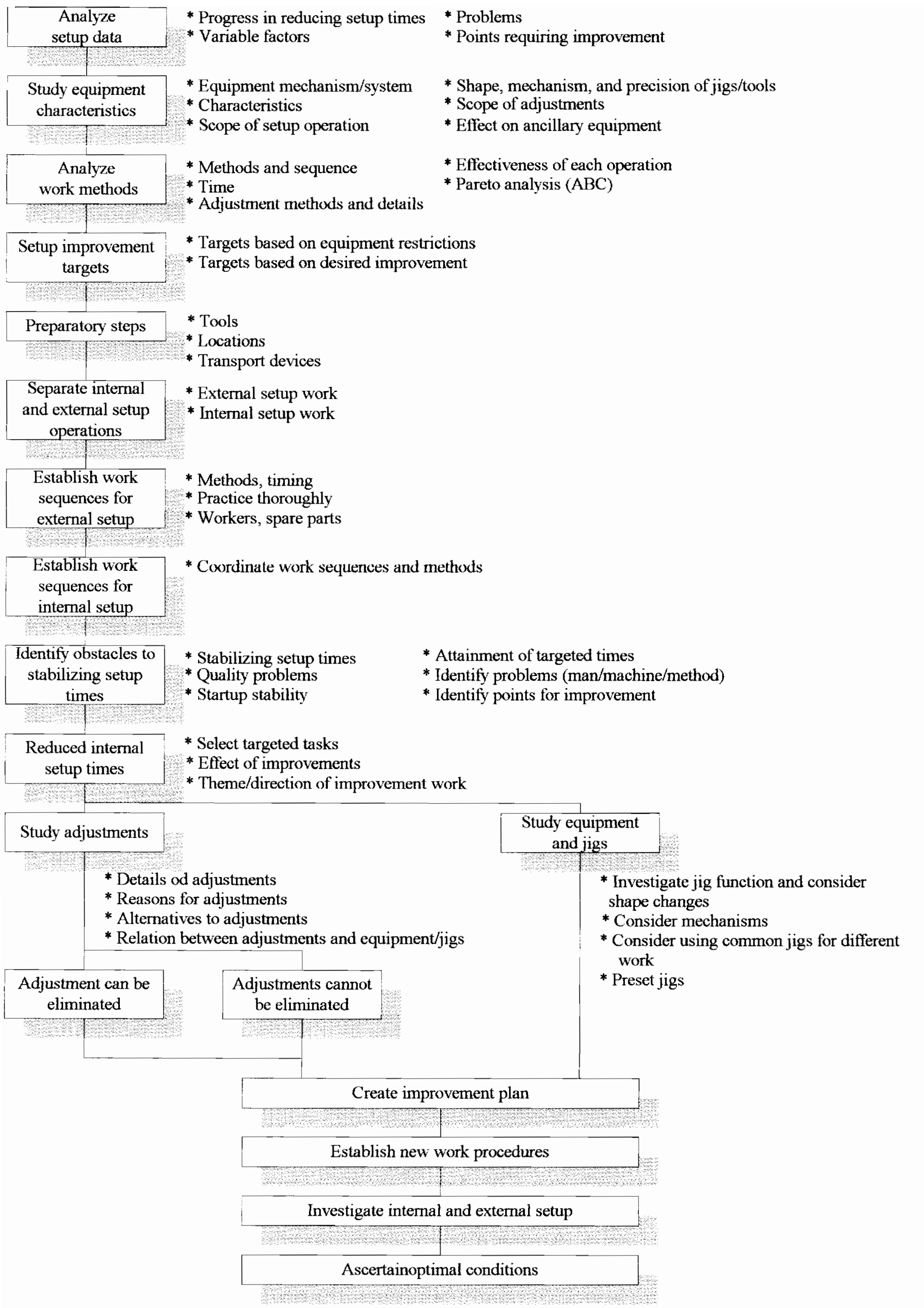

Figure 3.3 Improving Setup and Adjustment [Nakajima, 1989]

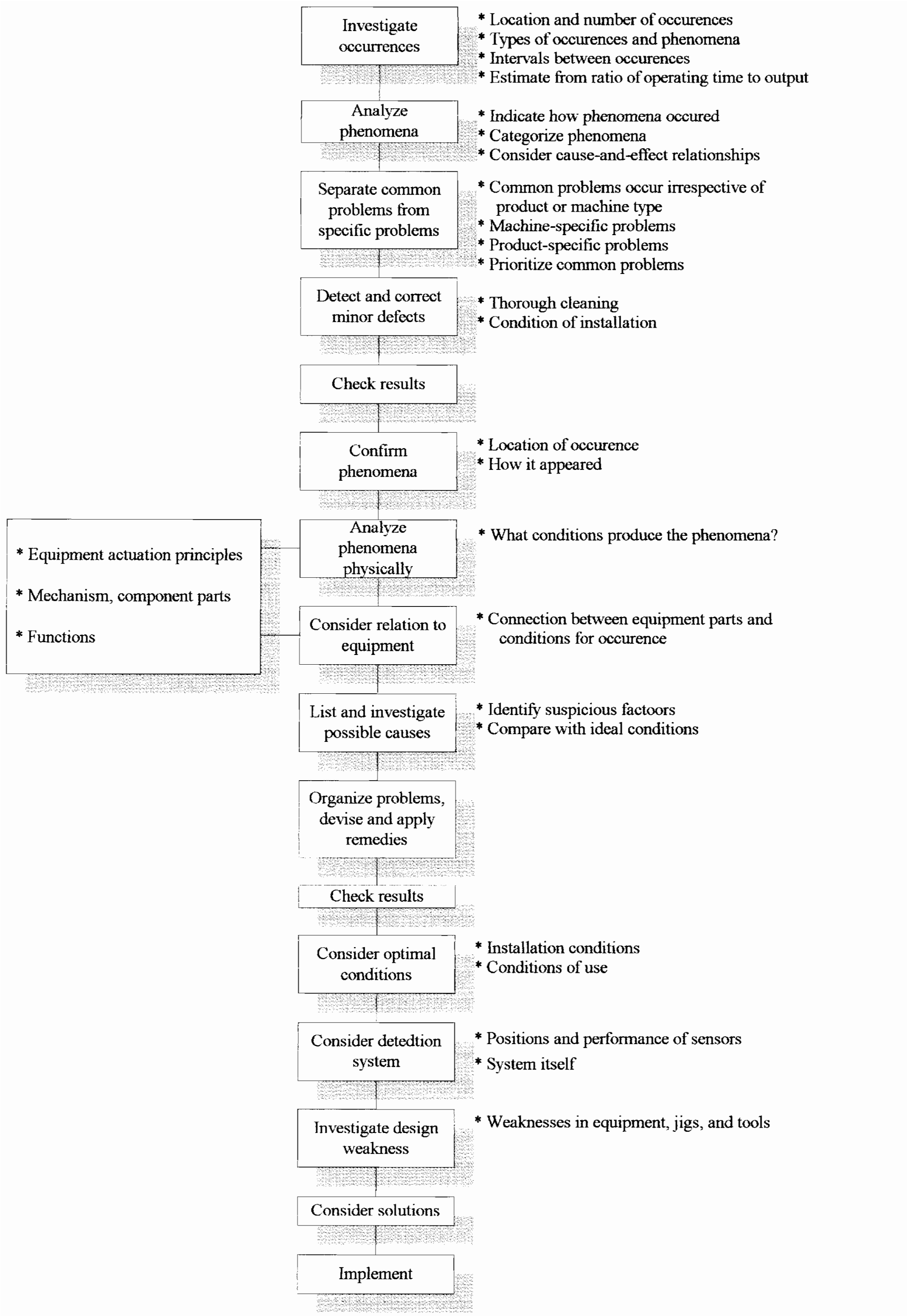

Figure 3.4 Improving Idling and Minor Stoppages [Nakajima, 1989]

Table 3.2 Strategies for increasing Speed [Nakajima, 1989]

Determine present levels	• Speed • Bottleneck processes • Downtime/frequency of stoppages • Conditions producing defects
Check difference between specification and present situation	• What are the specifications? • Difference between standard speed and present speed • Difference in speeds for different products
Investigate past problems	• Has the speed ever been increased? • Types of problems • Measures taken to deal with past problems • Trends in defect ratio • Trends in speeds over time • Difference in similar equipment
Investigate processing theories and principles	• Problems related to processing theories and principles • Machining conditions • Processing conditions • Theoretical values
Investigate mechanisms	• Mechanisms • Related output and load ratio • Investigate stress • Revolving parts • Investigate specification of each part
Investigate present situation	• Processing time per operation (cycle diagram) • Loss times (idling times) • Cp value of quality characteristics • Check precision of each part • Check using five senses
List problems	• List problems and identify conditions that should exist • Compare with optimal conditions • Problems with precision • Problems with processing theories and principles
List predictable problems	• Mechanical • Quality
Take remedial action against predictable problems	• Compare predictable problems with present conditions • Take action against predictable problems
Correct problems	
Perform test runs	
Confirm phenomena	• Mechanical • Quality • Change in Cp values
Review analysis of phenomena and cause-and-effect relationships and carry out remedial actions	• Physical analysis of phenomena • Conditions producing phenomena • Related causes
Perform test runs	

huge impact on equipment effectiveness. Therefore countermeasures against it are among the most important activities in an effort to eliminate the six big losses. Figure 3.5 provides a continual improvement approach to achieve the zero defect target. Ultimately, startup/yield losses refer to the losses that occur during the early stages of production — from machine startup to stabilization. Such losses are latent, and the possibility of eliminating them is often obscured by uncritical acceptance of their inevitability.

In addition, a variety of tools can be effectively applied throughout the life cycle in accomplishing analysis, evaluation, and assessment tasks for a typical manufacturing system. This, in turn, can provide the necessary additional support in maximizing OEE value.

For instance, reliability and maintainability assessments provide a quick measure of equipment availability and the downtimes being experienced. P-M analysis promotes the thorough and systematic elimination of defects. Through P-M analysis, all pertinent factors in losses are efficiently identified [Nakajima, 1989]. Ishikawa's *cause and effect diagram*, also called the "fishbone diagram", is a highly effective technique in delineating potential causes responsible for a failure [Ishikawa, 1982]. The *cause and effect diagram* is used in the FMECA to determine the causes responsible for the occurrence of any particular failure. The failure mode, effects, and criticality analysis (FMECA) is an excellent tool which systematically identify system failures, failure modes and frequencies, the effect of failures on other elements of the system, criticality, and the need for possible preventive maintenance [Blanchard, 1992]. It is a useful technique utilized during the conceptual and preliminary design phase, and evolves through the detail design and development phase. The FMECA is not only best used to enhance the equipment design and the corresponding support infrastructure, but also used to evaluate and continuously improve existing equipment. The objective of both cases is to increase overall equipment effectiveness, reduce maintenance and support costs, increase productivity, and increase overall international competitiveness. The reliability centered maintenance (RCM) is a systematic approach to develop a focused, effective, and cost-efficient preventive maintenance program and control plan for a product or process [Blanchard and Verma, 1995].

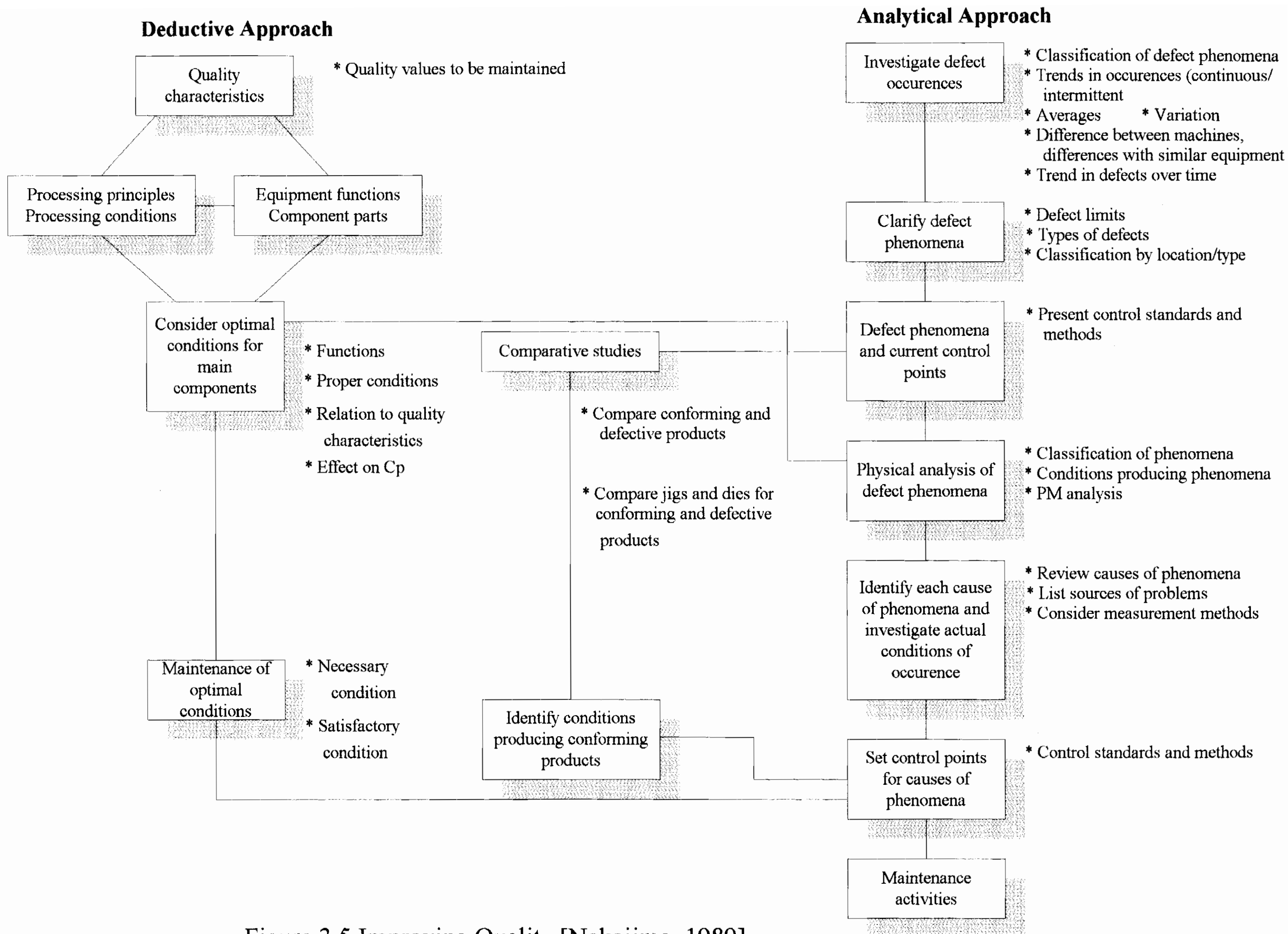

Figure 3.5 Improving Quality [Nakajima, 1989]

Through use of the proper tools, TPM implementers will not only consider the enhancements of equipment effectiveness in the design phase, but also identify the limitations of improving equipment effectiveness in practice. Further, company can plan countermeasures to improve equipment effectiveness by using these tools throughout the equipment life cycle covering the phase of system design and development, system production/construction, operation, utilization, sustaining support of the system, and system retirement/disposal.

CHAPTER 4

CASE STUDY

The objective of this chapter is to analyze and measure overall equipment effectiveness for a hypothetical factory. First, the factory's production process and its operational and maintenance log are established and assumed. Then, the effectiveness and the total cost of this production system is calculated as the baseline condition. Possible potential enhancements to increase the OEE value and reduce the total cost are also discussed.

4.1 Hypothetical Factory Environment

The hypothetical factory environment is assumed here for application of the OEE model. The major product in company XYZ is called product "A". The production process flow of product "A" has been illustrated in Figure 1.5. After assembling the raw materials of product "A", the product process continues with the incoming inspection, fabrication, subassembly, and assembly activities. At the end of process, the inspection and testing is executed to check and examine the quality of product "A". Finally, through the packing and shipping activity, product "A" is packaged and transported to customers.

Company XYZ operates two shifts. The first shift works from 8 a.m. to 5 p.m., the second shift works from 5 p.m. to 12 a.m.. During each shift period, one hour of break time is provided to let employees have their lunch, dinner, and a rest. A group meeting lasting thirty minutes for each shift, is held on each Monday to improve communications and encourage suggestions to increase the productivity and effectiveness of the company. Company XYZ implements a scheduled, time-based preventive maintenance program to reduce and detect failures in advance. It is assumed that company XYZ already has implemented some of the TPM activities such as small group activity.

The owners of company XYZ feel that the production system is not maximally effective and productive. Performing a review and evaluation of the current production system has become necessary. After company XYZ evaluated the entire production process based on the past records, the results show that the overall equipment effectiveness (OEE) of the production system is only around 50% and the cost of maintenance activities is almost 60% of the total product cost, an unfavorable portion of the total product cost. This evaluation indicates that the company experiences a very low production rate with high levels of required maintenance.

4.2 Operational and Maintenance Records

Assessment of the performance and effectiveness of a system requires the availability of operational and maintenance histories of the various elements. A formalized data information feedback subsystem with the proper output defined early in the life cycle with the development of operational requirements and maintenance concepts must be designed, developed, and implemented to achieve this objective. The data information feedback subsystem can provide the necessary data to evaluate and assess the performance, effectiveness, operation, maintenance, and so on, for the system in the field. It also provides historical data which can be applied in the design and development of new system having a similar function and nature.

With realistic overall system requirements defined early in the design phase, the next step is to identify the specific data factors which must be acquired and the method for acquisition. Then, a format for data collection is developed to identify and collect the specific factors and includes both success data and maintenance data. Success data, illustrated in Table 4.1, constitute information including system operation and utilization on a day-to-day basis. Maintenance data, listed in Table 4.2, include each scheduled and unscheduled maintenance event [Blanchard, 1992]. The format for data collection must be compatible with the systems in the factory. However, the data collection form should be easy to understand

Table 4.1 System Success Data [Blanchard, 1992]

System Operational Information Report
1. Report number, report date, and individual preparing report.
2. System nomenclature, part number, manufacturer, serial number.
3. Description of system operation by date (mission type, profiles and duration)
4. Equipment utilization by date (operating time, cycles of operation, etc.).
5. Description of personnel, transportation and handling equipment, and facilities required for system operation.
6. Recording of maintenance events by date and time (reference maintenance event reports).

Table 4.2 System Maintenance Data [Blanchard, 1992]

Maintenance Event Report
1. Administrative data
(a) Event report number, report date, and individual preparing report.
(b) Work order number.
(c) Work area and time of work (month, day, hour).
(d) Activity (organization) identification.
2. System factors
(a) Equipment part number and manufacturer.
(b) Equipment serial number.
(c) System operating time when event occurred (when discovered).
(d) Segment of mission when event occurred.
(e) Description of event (describe symptom of failure for unscheduled actions).
3. Maintenance factors
(a) Maintenance requirement (repair, calibration, servicing, etc.).
(b) Description of maintenance tasks.
(c) Maintenance downtime (MDT).
(d) Active maintenance times (Mct_i and Mpt_i).
(e) Maintenance delays (time awaiting spare part, delay for test equipment, work stoppage, awaiting personnel assistance, delay for weather, etc.).
4. Logistics factors
(a) Start and stop times for each maintenance technician by skill level.
(b) Technical manual or maintenance procedure used (procedure number, paragraph, date, comments on procedure adequacy)
(c) Test and support equipment used (item nomenclature, part number, manufacturer, serial number, time of item usage, operating time on test equipment when used).
(d) Description of facilities used.
(e) Description of replacement parts (type and quantity).
i. Nomenclature, part number, manufacturer, serial number, and operating time on replaced item. Describe disposition.
ii. Nomenclature, part number, manufacturer, serial number, and operating time on installed item.
5. Other information
Include any additional data considered appropriate and related to the maintenance event.

and complete. The factors specified on each form must be clear and concise in terms of application, and not require a lot of explanation and manipulation to obtain. The needed measurement can be completed properly, and the right type of data can be collected.

Operational and maintenance records are the primary available sources to assess the performance and effectiveness of a factory. Keeping them helps evaluate TPM effectiveness and points out the enhancements necessary to eliminate the six big losses in TPM implementation. Furthermore, it encourages a factory to plan countermeasures to decrease losses and increase productivity and effectiveness. Thus, documenting operation and maintenance is one of the most important activities in TPM implementation. The factors to be considered and recorded in OEE evaluation have been identified and defined in Chapter Three. When operational and maintenance records are properly collected and filled out, the factory managers can figure out the OEE level and plan improvements to increase TPM effectiveness.

The formats for data collection and the types of records are not fixed, but are arranged by management to dovetail with a particular plant's requirements. The following types of records, whose uses are summarized in Table 4.3, are minimally required in the practice of TPM [Nakajima, 1989]:

1. Routine inspection records.
2. Lubricant replenishment and replacement records.
3. Periodic inspection records.
4. Maintenance reports.
5. Maintainability improvement records.
6. MTBF analysis records.
7. Equipment logs.
8. Maintenance cost records.

Table 4.3 Maintenance Records and their Uses [Nakajima, 1989]

	Function	Type of Record	Contents	Use	Personnel	Remarks
1	Prevent equipment deterioration	Daily inspection checksheet	Daily record of presence or absence of abnormalities (visual inspection of equipment during operation)	Deal with abnormalities and report to superiors and maintenance department	Line operator	Can also be used for lubrication records
2		Lubrication record	Record replenishment of lubricants and replacement of contaminated lubricants	Improve lubricating methods and check lubricant consumption	Line operator	
3	Measure equipment deterioration	Periodic inspection record	Record of measured degree of deterioration and wear Analyze as necessary	Carry out repairs and maintenance if measurement show that control limits have been reached	Designated maintenance personnel	Control limits are specified in inspection standards
4	Restore equipment	Maintenance report	Details of repair of sporadic breakdowns, planned maintenance, and maintainability improvement	Obtain breakdown statistics and decide priorities for maintenance work Infer causes of breakdowns and take measures to prevent their recurrence	Maintenance personnel responsible	
5		Maintainability improvement record	Record of maintainability improvement plans, execution, and results	Promote standardization of improved procedures and revise original drawings Use as improvement case study material	Maintenance or engineering personnel or staff	Deal with similar items of equipment together
6		MTBF analysis chart	Record of all types of maintenance work, e.g., repair of sporadic breakdowns, replenishment and replacement of lubricants, periodic maintenance, etc.	Extending maintenance intervals and improving efficiency of repair work	Line operators, maintenance department, resident subcontractors, etc.	
7	Document equipment lifetimes	Equipment log	Details and cost records for major breakdown repairs, periodic maintenance, and maintainability improvement	Provide cost data on which to make decisions about equipment replacement and investment based on life cycle costs	Maintenance department personnel or staff	
8	Control maintenance budge	Maintenance cost record	Breakdown of maintenance labor costs, material costs and subcontracting costs Cost breakdown for each piece of equipment	Control maintenance budget, identifying priorities for reducing costs, and planning countermeasures	Maintenance, materials and purchasing department personnel and staff	Data forwarded to accounting department

Each factory should design and arrange the particular formats of the above records to properly monitor the maintenance of any equipment and provide the right types of information for an ongoing assessment of operations. Based on the previous discussion of the principles and importance of keeping records, a real world company must ask all employees to collect and fill out the operational and maintenance records accurately in its standardized formats. Currently, many companies have developed and implemented a computerized maintenance management system (CMMS) to keep records and monitor labor and material costs, process maintenance work orders, control spare parts and inventory, and track the maintenance downtime [Wireman, 1986].

To apply the OEE model, the operational and maintenance records in the hypothetical factory have to be assumed. In order to get the necessary hypothetical data, we assume that a given period was spent on monitoring the production process and logging its hypothetical output and minor disruptions that occurred. We also assume that the operational and maintenance personnel kept and recorded all logbooks for the entire production process. The assumed necessary data, including preventive maintenance downtime, setup downtime, adjustment downtime, breakdown and failure downtime, etc., for applying the OEE model are summarized in Table 4.4 ~ Table 4.8.

The break times in the production schedule and the time for group meetings have been excluded from the operation time frame. In Table 4.4, working time means the total operating time. In Table 4.5, assume the ideal and actual cycle time is obtained from the historical operation data. In Table 4.6, 4.7, and 4.8, the data are summarized from the various operation and maintenance records in the field. According to these assumptions and data, the baseline OEE values of each function in the hypothetical factory can be evaluated by the computerized OEE model developed.

Table 4.4 Summary of working time (minutes)

Process	Incoming Inspection	Fabrication	Subassembly	Assembly	Inspection and Test	Packing and Shipping
Working time	3840	5760	7680	11520	4800	3840

Table 4.5 Cycle time Records (minute per product unit)

Process	Incoming Inspection	Fabrication	Subassembly	Assembly	Inspection and Test	Packing and Shipping
Ideal cycle time	5	7	9	12	6.5	5
Actual cycle time	6.5	9.4	12	17	8.5	6.6

Table 4.6 Quantity of Defect Records

Process	Incoming Inspection	Fabrication	Subassembly	Assembly	Inspection and Test	Packing and Shipping
Processed amount	420	417	415	408	396	392
Defect amount	3	2	7	12	4	2

Table 4.7 Summary of Downtime Records (minutes)

Process	Incoming Inspection	Fabrication	Subassembly	Assembly	Inspection and Test	Packing and Shipping
Preventive Maintenance	140	340	480	900	240	200
Setup	125	210	305	640	200	170
Adjustment	60	85	140	235	90	80
Changover	60	150	200	375	100	90
Breakdown & Failure	260	580	955	1580	385	365
Startup	120	165	180	285	145	160
Minor stoppage	30	120	200	215	100	65
Idling	130	70	80	50	60	70

Table 4.8 Maintenance Action Records

Process	Incoming Inspection	Fabrication	Subassembly	Assembly	Inspection and Test	Packing and Shipping
PM for facility	2	2	2	2	2	2
PM for equipment	2	2	2	2	2	2
CM for facility	2	6	8	12	4	3
CM for equipment	12	25	32	50	24	22

4.3 Effectiveness Evaluation and Analysis

An evaluation and analysis of effectiveness is performed to assess system performance. The effectiveness of the hypothetical factory is evaluated and analyzed in this section. At first, the initial assumed data are used to calculate the OEE values for each function block as the baseline OEE values. The system OEE value is enumerated, based on the assumption of linear relationship between each function block and the entire production process, by using the system OEE model. Then, an analysis on the OEE parameters of function block is carried out to seek possible improvements for increasing OEE value. In addition, since all factories aim to make profits from production, a cost analysis must be performed to pinpoint the high cost drivers in the factory and find reductions in the product costs. Thus, a cost analysis of the hypothetical factory is also included in this section.

4.3.1 OEE Calculation

Overall equipment effectiveness presents a measure of the value added to production through equipment. If there are problems and disruptions in production, the OEE measures will be low. By using the OEE model described in Chapter Three and the hypothetical operational and maintenance records, the OEE values are calculated for each function of the production process. The results of calculating OEE for each function block in this case study are summarized in Table 4.9. The detailed procedures of calculating OEE are given by the example of OEE calculation in incoming inspection as follows:

$$\text{Loading time} = \text{Working time} - \text{Preventive maintenance downtime}$$
$$= 3840 - 140 = 3700 \text{ (minutes)}$$
$$\text{Operating time} = \text{Loading time} - \text{Unplanned downtime}$$
$$= 3700 - 785 = 2915 \text{ (minutes)}$$

Table 4.9 Results of OEE calculation

	Loading time (minutes)	Operating time (minutes)	Availability (%)	Operating speed rate (%)
Incoming Inspection	3700	2915	78.78	76.92
Fabrication	5420	4040	74.54	74.47
Subassembly	7200	5140	71.39	75.00
Assembly	10620	7240	68.17	70.59
Inspection and Test	4560	3480	76.32	76.47
Packing and Shipping	3640	2640	72.53	75.76

Table 4.9 Results of OEE calculation (continued)

	Net operating rate (%)	Performance rate(%)	Quality rate (%)	OEE (%)
Incoming Inspection	93.65	72.04	99.29	56.35
Fabrication	97.02	72.25	99.52	53.60
Subassembly	96.89	72.67	98.31	51.00
Assembly	95.80	67.62	97.06	44.74
Inspection and Test	96.72	73.97	98.99	55.88
Packing and Shipping	98.00	74.24	99.49	53.57

$$\text{Availability} = \frac{\text{Operating time}}{\text{Loading time}} \times 100\%$$

$$= \frac{2915}{3700} \times 100\% = 78.78\%$$

$$\text{Operating speed rate} = \frac{\text{Ideal cycle time per product unit}}{\text{Actual cycle time per product unit}} \times 100\%$$

$$= \frac{5}{6.5} \times 100\% = 76.92\%$$

$$\text{Net operating rate} = \frac{\text{Processes amount} \times \text{Actual cycle time}}{\text{Operating time}} \times 100\%$$

$$= \frac{420 \times 6.5}{2915} \times 100\% = 93.65\%$$

$$\text{Performance rate} = \text{Operating speed rate} \times \text{net operating rate} \times 100\%$$

$$= 0.7692 \times 0.9365 = 72.04\%$$

$$\text{Quality rate} = \frac{\text{Processed amount - Defect amount}}{\text{Pr ocessed amount}} \times 100\%$$

$$= \frac{417}{420} \times 100\% = 99.29\%$$

$$\text{OEE} = \text{Availability} \times \text{Performance rate} \times \text{Quality rate} \times 100\%$$

$$= 0.7878 \times 0.7204 \times 0.9929 = 56.35\%$$

In the field, project teams constituted of production line supervisor and engineering and maintenance staffs select equipment experiencing from the most serious equipment losses and having the lowest OEE value for improvement. When positive results are achieved, the project can be expanded to other similar equipment [Nakajima, 1989]. Then, the system OEE value can be increased by the increasing the OEE value of each piece of equipment in the system. Therefore, the individual OEE of each piece of equipment is more important and useful in performing improvement activities of increasing equipment effectiveness rather than the system OEE value. However, to evaluate whole system or company effectiveness, a system OEE index has to be established to combine the lower level OEE measures.

In the interest of simplicity, it is assumed that the relationship between each function block and the entire production process is linear in this case study. Then, the system OEE value is enumerated as follows:

$$OEE_S = A_S \times P_S \times Q_S$$

where

$$A_S = \frac{\sum_{i=1}^{n} OT(i)}{\sum_{i=1}^{n} LT(i)};$$

$$P_S = \frac{\sum_{i=1}^{n} [PA(i) \times ACT(i)]}{\sum_{i=1}^{n} OT(i)} \times \frac{\sum_{i=1}^{n} ICT(i)}{\sum_{i=1}^{n} ACT(i)};$$

$$Q_S = \prod_{i=1}^{n} Q(i);$$

OEE_S: system OEE value

A_S: system availability

P_S: system performance rate

Q_S: system quality rate

LT(i): loading time of subsystem i

OT(i): operating time of subsystem i

PA(i): processed amount of subsystem i

ACT(i): actual cycle time of subsystem i

ICT(i): ideal cycle time of subsystem i

Q(i): quality rate of subsystem i

i, n: number of subsystem

Since the system loading time is broken down into the loading time of each subsystem in the whole system, the system loading time and the system operating time should be the sum of those in each subsystem. Then, the formula of A_S can be defined as the ratio of the system operating time to the system loading time. The actual cycle time for a product through the whole system equals the sum of actual cycle time in each subsystem. Similarly, the ideal cycle time for the system equals the sum of ideal cycle times of individual subsystems. Therefore, the operating speed rate of the whole system is determined by the ratio of the summation of subsystems' ideal cycle time to the summation of subsystems' actual cycle time. The net operating rate of a system is defined as the system's actual operating time divided by the system's operating time. It is obvious that the system operating time is the sum of the operating time of each subsystem. The system's actual operating time equals the summation of actual operating times of each subsystem. Thus, the formula of P_S can be determined. The quality rate is the probability of good products produced. It is assumed that the quality rates of subsystems are independent of each other, i.e., the quality rate of one subsystem is not dependent on the quality rate of another subsystem. Consequently, for a series production process, the system quality rate is the product of the individual quality rate of the subsystem in the system. Consider a system OEE value in the production assembly process. When one or more bottlenecks occur in the process, the idling downtime for the downstream processes after the bottleneck is increased. Then, the system operating time is decreased because of the more unplanned downtime. Therefore, the system availability and performance rate are decreased, and, in turn, the system OEE value is also decreased.

At company XYZ, the OEE_S of the hypothetical production process is calculated as follows:

$$\sum_{i=1}^{6} LT(i) = 35180 \text{ (minutes)}$$

$$\sum_{i=1}^{6} OT(i) = 25455 \text{ (minutes)}$$

$$\sum_{i=1}^{6} ICT(i) = 44.5 \text{ (minutes per product unit)}$$

$$\sum_{i=1}^{6} ACT(i) = 60 \text{ (minutes per product unit)}$$

$$\sum_{i=1}^{6} [PA(i) \times ACT(i)] = 24519 \text{ (minutes)}$$

$$A_S = \frac{25455}{35180} = 72.36\%$$

$$P_S = \frac{24519}{25455} \times \frac{44.5}{60} = 71.44\%$$

$$Q_S = \prod_{i=1}^{6} Q(i) = 92.86\%$$

$$OEE_S = A_S \times P_S \times Q_S = 48.00\%$$

It shows the OEE_S of the hypothetical factory is only 48.00% and there is a lot of room for improvement to achieve the world class OEE value. The hypothetical factory can analyze the OEE values to plan countermeasures for eliminating the factory's losses.

4.3.2 OEE Analysis and Countermeasures

Performing analysis on parameters of OEE assists in the identification of which areas in the factory are experiencing problems and what those losses are. Then, the countermeasures to eliminate those problems and losses can be planned to increase the OEE values.

The previous OEE calculations for each function show that the low OEE value is caused by the low availability and performance rate of each function, especially in assembly function. Compared with the ideal conditions for a world class OEE value, the availability which ranged from 68.17% to 78.78% and the performance rate which ranged from 67.62% to 74.24 % are far away from the ideal conditions of greater than 90% and 95%, respectively.

To increase the OEE value of factory, the availability and the performance rate of each function must be improved.

Availability is determined by the ratio of operating time to loading time. Assume the loading time is fixed for the current factory environment, then the only way to increase the availability is to reduce the unplanned downtime. According to the assumed operational and maintenance data, breakdown and failure downtime is the highest contributor to the unplanned downtime. To maximize availability, all breakdown and failure downtime must be reduced to zero and the rest of unplanned downtime must also be eliminated. The impacts of respectively increasing the availability of each function block on system OEE are presented in Figure 4.1. These result from the assumptions of the performance rate and the quality rate of each function block keep the same as the baseline conditions and the availability of one function block is increased to 90%. For instance, in the assembly function, the improved OEE_S results from: (1) the loading times of each function block is fixed; (2) the operating times of other function blocks are unchanged; (3) the performance rate and the quality rate of each function block are the same as the baseline conditions; and (4) the availability of assembly is increased to 90% by reducing the unplanned downtime. Then, the OEE_S is computed by using the system OEE formula and is presented as follows:

Loading time (assembly) = 10620 (minutes)

$$\sum_{i=1}^{n} LT(i) = 35180 \text{ (minutes)}$$

Operating time (assembly) = $10620 \times 90\% = 9558$ (minutes)

$$\sum_{i=1}^{n} OT(i) = 25455 - 7240 + 9558 = 27773 \text{ (minutes)}$$

$$A_S = \frac{27773}{35180} = 78.95\%$$

$P_S = 71.44\%$

$Q_S = 92.86\%$

$OEE_S = 0.7895 \times 0.7144 \times 0.9286 = 52.38\%$

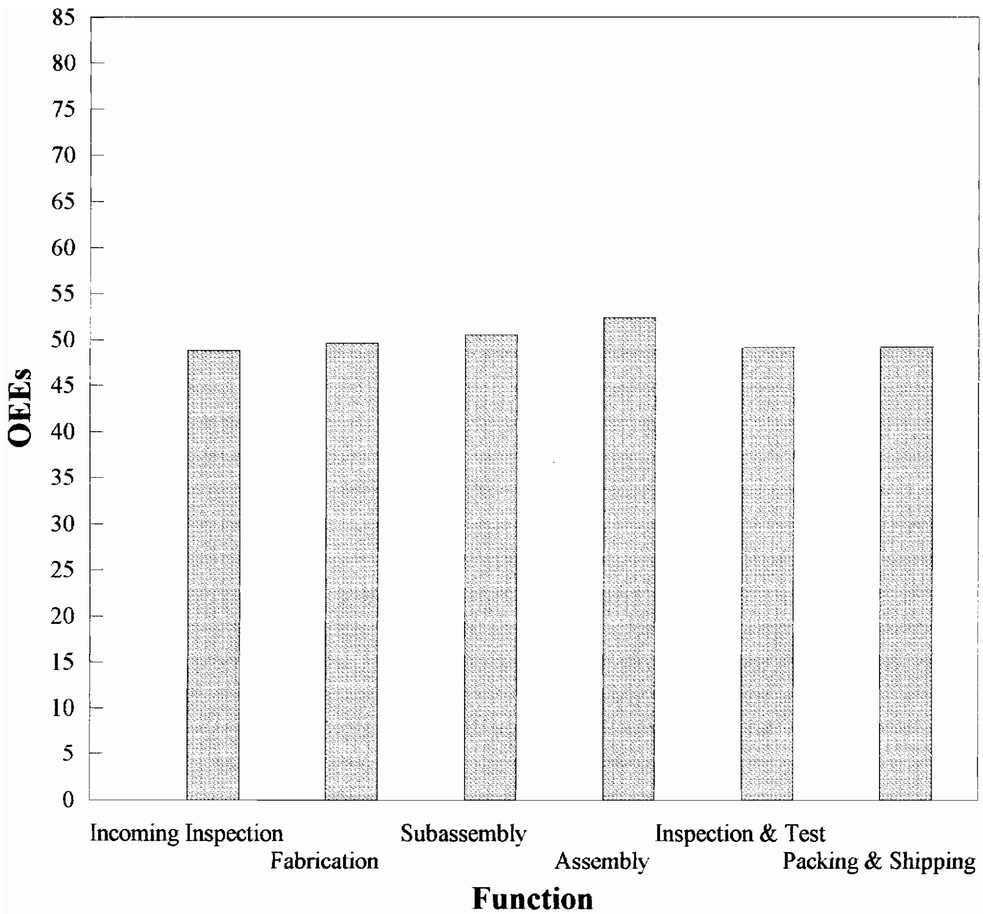

Figure 4.1 Impacts of Availability on OEE (Availability = 90%)

Table 4.10 presents the detail results of this analysis for each function block. Actually, when the availability is increased, the performance rate will be increased since the net operating rate is increased by the reduction in the operating time for a certain quantity of product. Increasing the availability of assembly function seems to have more influence on the system OEE value because of its longer loading time. If the availability of assembly function is increased to 90%, the system OEE will be increased to 52.38%. This is the largest impact of increasing the availability on the system OEE among all function blocks. This analysis shows that increasing the availability of assembly function results in the most significant improvement in enhancing the system OEE.

Performance rate is the product of the operating speed rate and the net operating rate. The net operating rate reflects losses resulting from minor stoppages. The operating speed rate reflects reduced speed losses. In this hypothetical factory, low performance rates are greatly caused by the low operating speed rate which ranged from 70.59% to 76.92%. In order to improve the performance rate, idling and minor stoppage losses must be completely eliminated in all equipment and all differences between the actual and ideal condition of the equipment must be eliminated. Figure 4.2, which assumes (1) the loading time is fixed for the current factory environment; (2) the net operating rate and the quality rate are unchanged; and (3) the operating speed rate of one function block is increased to 90%, illustrates the impacts of individually increasing the operating speed rate of each function block on the system OEE after eliminating all idling and minor stoppage. Actually, by eliminating the idling and minor stoppage, not only is the net operating rate increased, but also the availability is increased because of the decrease in the unplanned downtime. The detailed outcomes of this analysis for each function block are summarized in Table 4.11. For instance, the detailed procedures for this analysis in assembly function are given as follows:

Loading time (assembly) = 10620 (minutes)

$$\sum_{i=1}^{n} LT(i) = 35180 \text{ (minutes)}$$

Table 4.10 Results of OEE analysis for Availability

Function	Loading time	$\sum LT(i)$	Operating Time	$\sum OT(i)$
Incoming Inspection	3700	35180	3330	25870
Fabrication	5420	35180	4878	26293
Subassembly	7200	35180	6480	26795
Assembly	10620	35180	9558	27773
Inspection and Test	4560	35180	4104	26079
Packing and Shipping	3640	35180	3276	26091

Table 4.10 Results of OEE analysis for Availability (continued)

Function	A_S (%)	P_S (%)	Q_S (%)	OEE_S (%)
Incoming Inspection	73.54	71.44	92.86	48.78
Fabrication	74.74	71.44	92.86	49.58
Subassembly	76.17	71.44	92.86	50.53
Assembly	78.95	71.44	92.86	52.38
Inspection and Test	74.13	71.44	92.86	49.18
Packing and Shipping	74.16	71.44	92.86	49.20

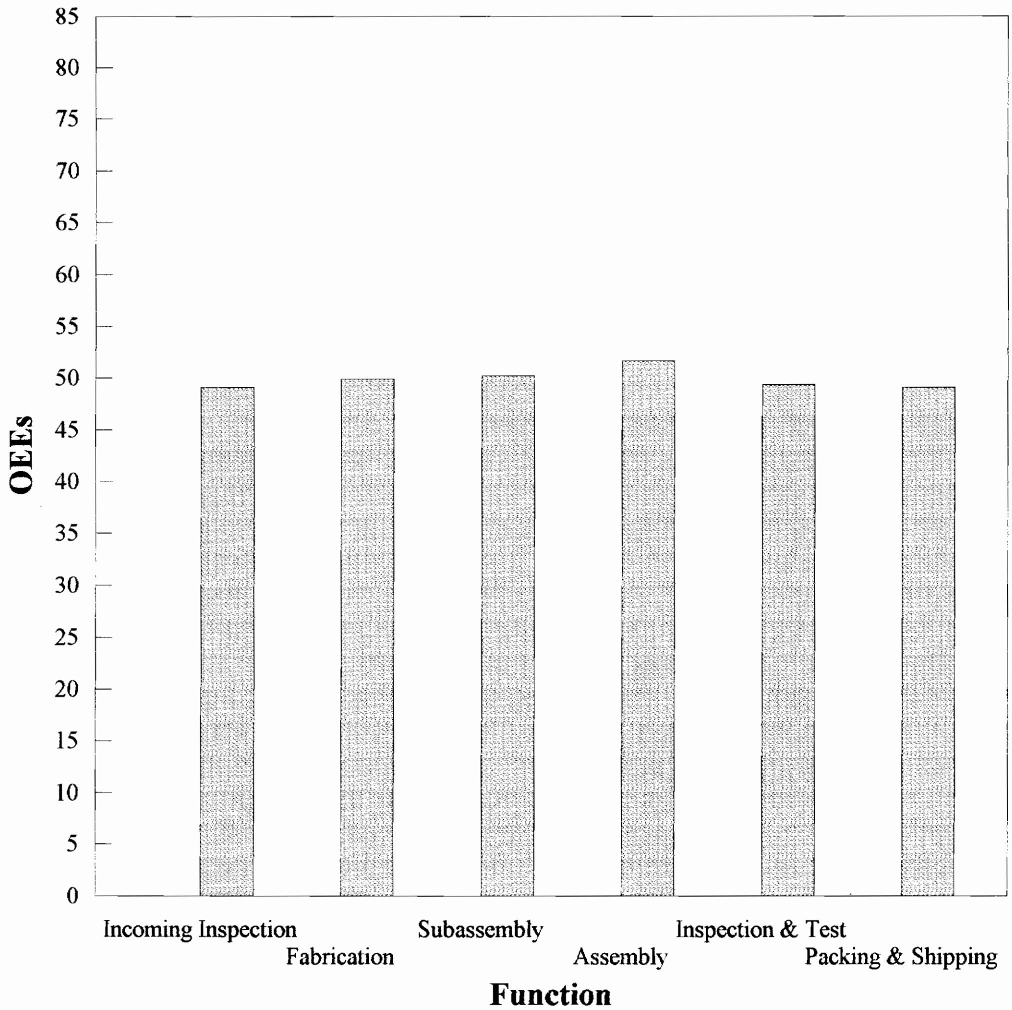

Figure 4.2 Impacts of Performance rate on OEE (Operating speed rate = 90%)

Table 4.11 Results of OEE analysis for Performance rate

Function	Loading time	$\sum LT(i)$	Operating Time	$\sum OT(i)$	$\sum ICT(i)$
Incoming Inspection	3700	35180	3075	25615	44.5
Fabrication	5420	35180	4230	25645	44.5
Subassembly	7200	35180	5420	25735	44.5
Assembly	10620	35180	7505	25720	44.5
Inspection and Test	4560	35180	3640	25615	44.5
Packing and Shipping	3640	35180	2775	25590	44.5

Table 4.11 Results of OEE analysis for Performance rate (continued)

Function	ACT	$\sum ACT(i)$	A_S (%)	P_S (%)	Q_S (%)	OEE (%)
Incoming Inspection	5.56	59.06	72.81	72.57	92.86	49.07
Fabrication	7.78	58.38	72.90	73.42	92.86	49.90
Subassembly	10.00	58.00	73.15	73.90	92.86	50.20
Assembly	13.33	56.33	73.11	76.09	92.86	51.66
Inspection and Test	7.22	58.72	72.81	72.99	92.86	49.35
Packing and Shipping	5.56	58.96	72.74	72.69	92.86	49.10

Operating time (assembly) = $10620 - 3115 = 7505$ (minutes)

$$\sum_{i=1}^{6} OT(i) = 25455 - 7240 + 7505 = 25720 \text{ (minutes)}$$

$$A_S = \frac{25720}{35180} = 73.11\%$$

$$\sum_{i=1}^{6} ICT(i) = 44.5 \text{ (minutes per unit product)}$$

Actual cycle time (assembly) = $\frac{12}{0.90} = 13.33$ (minutes per product unit)

$$\sum_{i=1}^{6} ACT(i) = 60 - 17 + 13.33 = 56.33 \text{ (minutes per product unit)}$$

Net operating rate (system) = 96.32%

$$P_S = 0.9632 \times \frac{44.5}{56.33} = 76.09\%$$

$$Q_S = 92.86\%$$

$$OEE_S = 0.7311 \times 0.7609 \times 0.9286 = 51.66\%$$

Increasing the operating speed rate of each function block will increase the system OEE. It results that the increase of operating speed rate in the assembly function has the largest impact on the system OEE.

In a word, through previously performing the assessment and evaluation of OEE on the current production process in the hypothetical factory, the causes of production losses can be identified as follow:

1. In each function, the breakdown and failure downtime constitutes the largest part of unplanned downtime and, in turn, significantly results in the low availability. Especially, in the assembly function, 1580 minutes of breakdown and failure downtime contribute 47% of unplanned downtime (3380 minutes) and cause the lowest availability among all function

blocks. The current preventive maintenance is not effective in preventing breakdown and failure in advance.

2. According to the summary of downtime records, it is found that setup downtime constitutes the averaged 29% of unplanned downtime excluding breakdown and failure downtime in all function. This loss reduces the operating time and also reduces the availability of each function.
3. The discrepancies between designed and actual speed of equipment in each function are so distinct that the operating rates are low and the equipment is not operated at the designed operating condition. These, in turn, cause the low performance rate. The largest distinction between ideal and actual speed of equipment also occurs in the assembly function.
4. The lowest net operating rate among all function blocks is found in the incoming inspection function. It represents that the incoming inspection function is experiencing the minor stoppage and idling losses. According to the assumed operational and maintenance records, the largest idling downtime is caused in the incoming inspection function. The reason may be the insufficient supplies of raw materials. This, in turn, makes the incoming inspection function have the second lowest performance rate among all functions.
5. Compared to the ideal condition for the quality rate which is greater than 99%, the quality rates for most of the functions look good. However, the quality rates of around 97% and 98% are found in both subassembly and assembly functions. The reason for this loss is that more amounts of defect products are produced in these two functions.

Once the causes of production losses have been identified, the company can recognize the areas where improvement can be made to help increase the OEE value and the productivity and plan countermeasures to eliminate those losses. The systematic improvement program for eliminating the big losses described in chapter three can be applied here for improving the OEE value of the hypothetical factory. When planning the countermeasures, the principle of setting the highest improvement priority to the assembly function because of its largest impact on the system OEE must be emphasized. The countermeasures for the hypothetical factory are recommended as follows:

1. Establish and maintain the basic equipment condition by three activities — cleaning, lubricating, and bolt tightening. Then, maintain the equipment to be operated at its correct condition and prevent and restore any deterioration occurring in the equipment. In the mean time, the company must train operators and maintenance staffs to enhance their skills. A review and upgrade of the current preventive maintenance is also necessary to detect and predict the occurrence of equipment failure. By these activities, the breakdown can be eliminated.
2. Study and analyze the setup data and work method in each function. Identify obstacles to stabilize setup times. Separate the internal and external setup and convert internal to external setup as much as possible. Then, the setup downtime can be minimized.
3. Investigate the processing theories, principles, and present operating situation. Identify the possible causes of reducing operating speed. Predict the remedial action against the possible obstacles. Take actual remedial action to eliminate the difference between the designed and actual speed of equipment.
4. Analyze the phenomena of minor stoppage and idling. Detect and correct all minor stoppages. Identify the bottleneck in the process and schedule the production process to avoid the idling; especially, the supplies of raw materials in this process must be compatible with the operating schedule of the incoming inspection function.
5. Investigate the defect occurrence to clarify defect phenomena. Analyze the defect phenomena to set control points for causes of phenomena. Then, upgrade the manufacturing process to eliminate such quality defect losses.

4.3.3 Total Cost Analysis

Since cost is a major parameter for evaluating system performance, it is necessary to address cost in the effectiveness evaluation and analysis. In order to accomplish a total cost analysis, a cost breakdown structure showing the numerous categories that are combined to provide the total cost must be developed. In this case study, the total cost value involves revenues and product cost category. The product cost category is broken down on a functional basis, into investment, operations, maintenance, and material disposal/phase-out subcategories as shown in Figure 4.3. The purpose of performing this total cost analysis is to increase profit by minimizing product cost. In order to decrease product cost, the high cost drivers must be identified and then the possible solutions to prevent those cost drivers should be introduced.

In an attempt to simplify the problem and be compatible with the assumed operational and maintenance records, this total cost analysis is performed for a given period and the following additional data are assumed:

1. To calculate the revenues, the sale price of product A is $1,000 per unit.
2. Capital equipment costs, such as the cost of new, expended, replaced, or revamped equipment, are $2,200 for the monitoring period.
3. The costs of computer resources, facilities, and data/documentation subcategories are assumed on the basis of a given period. They are $632, $1,000, $740, respectively.
4. Spare/repair parts are required on the facilities and equipment for replacement of the units that need repair. Assumed costs of spare/repair parts are determined by the maintenance actions. It costs $32 per preventive maintenance action and $105 per corrective maintenance action for the facilities. On the other hand, it costs $80 per preventive maintenance action and $185 per corrective maintenance action for the equipment. This cost includes material costs and inventory maintenance costs. The turnaround time on spares is ignored for the sake of simplicity.

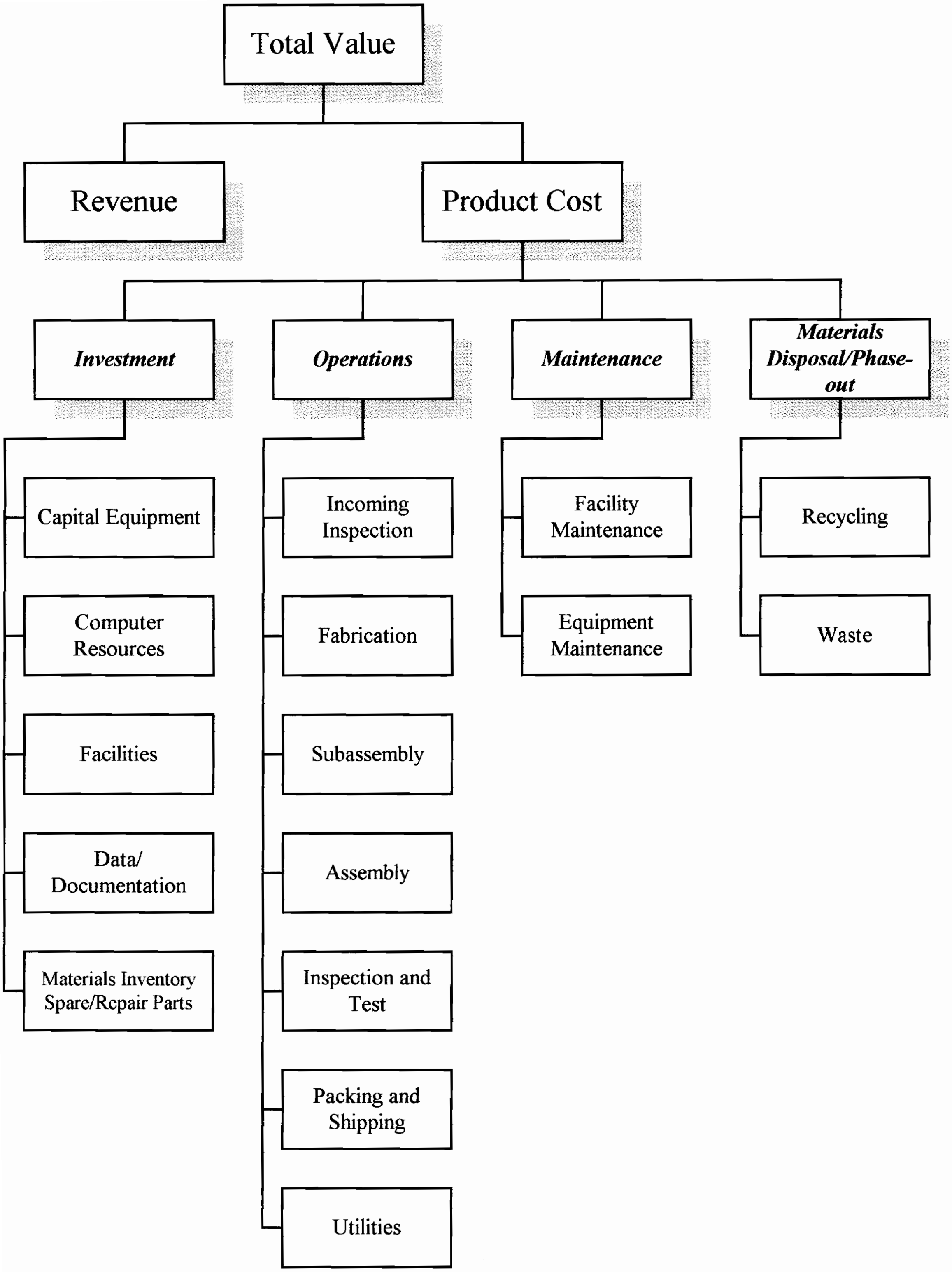

Figure 4.3 Cost Breakdown Structure

5. The costs of operation category are allocated to unit product for each function of the process. This includes the tooling and operation personnel cost. The associated costs of each function is the following:

- Incoming Inspection: $10/unit
- Fabrication: $24/unit
- Subassembly: $36/unit
- Assembly: $55/unit
- Inspection and Test: $18/unit
- Packing and Shipping: $20/unit
- Utilities: $6.4/unit

6. In this case study, the maintenance activities can be primarily divided into performing on both facility and equipment. Assume that the maintenance costs are based on the maintenance actions performed. For the facility maintenance, it costs $145 per preventive maintenance action and $500 per corrective maintenance action. For the equipment maintenance, it costs $235 per preventive maintenance action and $870 per corrective maintenance. This includes the costs for system maintenance and support and the maintenance personnel costs.
7. Assume that the recycling and waste cost is $30 and $15 per unit, respectively.

From the assumed operational and maintenance records, process data, and the above assumption of cost estimation, the total cost analysis can be performed. The revenue of company XYZ is $390,000 and the total cost is $287,390 for the given period. This make a profit of $102,610. The detailed product cost is presented as follows:

- Revenue = Sale price of product A × Amount of good product

  $= \$1{,}000 \times 390 = \$390{,}000$

- Cost of material inventory spare/repair parts

$= \$ \text{ per PM action} \times \text{PM action} + \$ \text{ per CM action} \times \text{CM action}$

Table 4.12 shows the results of this cost category for both facility and equipment.

- In operation cost category, the cost of each function is determined by the cost per unit times the processed amount. For example, in the incoming inspection function:

  $$\text{Operation cost in incoming inspection function} = \$ \text{ per unit} \times \text{processed amount}$$

  $$= \$10 \times 420 = \$4{,}200$$

- For both facility and equipment,

  $$\text{Maintenance cost} = \$ \text{ per PM} \times \text{PM action} + \$ \text{ per CM} \times \text{CM action}$$

  The maintenance costs of both facility and equipment are illustrated in Table 4.13.

- In material disposal/phase-out cost category, the recycling cost is computed by the recycling cost per unit times the number of good product and the waste cost is determined by the waste cost per unit times the number of defect product.

The total cost breakdown of company XYZ for the given period is presented in Table 4.14. It indicates that the maintenance cost, which constitutes 57.6% of total product cost, acts as the highest contributor of the product cost. Meanwhile, from Table 4.12 and 4.13, the costs of spare/repair parts and maintenance costs in the assembly function contribute above 30% of subtotal costs of each cost category. It shows that the costs spending on the assembly function are the highest cost driver of total product costs. Because both spare/repair part and maintenance costs are associated with maintenance activities, performing a reevaluation on the current maintenance approach is necessary. According to these cost analyses, analysts should review and update the current maintenance approach to minimize the occurrence of failure and breakdown and reduce the costs associated with the maintenance activities. Thereby, the revenue can be increased, the total product costs can be decreased, the profit can be substantially increased, and the OEE value can be improved. Furthermore, a cost-effectiveness analysis can be performed to make a trade-off between the effectiveness of maintenance approach and the total cost.

Table 4.12 Costs of Material inventory spare/repair parts ($)

Process	Incoming Inspection	Fabrication	Subassembly	Assembly	Inspection and Test	Packing and Shipping	Total
Facility	244	694	904	1324	484	379	4029
%	6.1	17.2	22.4	**32.9**	12.0	9.4	100
Equipment	2380	4785	6080	9410	4600	4230	31485
%	7.6	15.2	19.3	**29.9**	14.6	13.4	100

Table 4.13 Maintenance costs ($)

Process	Incoming Inspection	Fabrication	Subassembly	Assembly	Inspection and Test	Packing and Shipping	Total
Facility	1290	3290	4290	6290	2290	1790	19240
%	6.7	17.1	22.3	**32.7**	11.9	9.3	100
Equipment	10910	22220	28310	43970	21350	19610	146370
%	7.5	15.2	19.3	**30.0**	14.6	13.4	100

Table 4.14 Total product cost breakdown

Cost Category	Cost ($)	% of Total
1. Investment	$40,086	13.9
(a) Capital Equipment	2,200	0.8
(b) Computer Resources	632	0.2
(c) Facilities	1,000	0.3
(d) Data/Documentation	740	0.3
(e) Materials Inventory Spare/Repair Parts	35,514	12.3
2. Operations	$69,244	24.1
(a) Incoming Inspection	4,200	1.5
(b) Fabrication	10,008	3.5
(c) Subassembly	14,940	5.2
(d) Assembly	22,440	7.8
(e) Inspection and Test	7,128	2.5
(f) Packing and Shipping	7,840	2.7
(g) Utilities	2,688	0.9
3. Maintenance	$165,610	57.6
(a) Facility Maintenance	19,240	6.7
(b) Equipment Maintenance	146,370	50.9
4. Materials Disposal/Phase-out	$14,800	4.3
(a) Recycling	12,000	4.1
(b) Waste	450	0.2
Grand Total	$287,390	100.00

4.3.4 Cost-Effectiveness Analysis

Cost-effectiveness relates to the measure of the hypothetical production system in terms of OEE and total product cost. The objective of cost-effectiveness analysis is to balance both the necessary technical and performance requirement related to the equipment operation and maintenance and the total product cost in order to maximize the OEE value and profit at a minimum total product cost. In this case, the specific cost-effectiveness figure of metric (FOM) can be expressed as:

$$\text{FOM} = \frac{\text{OEE}}{\text{Total Product Cost}}$$

The FOM of company XYZ for the given monitoring period is:

$$\text{FOM} = \frac{0.48}{\$287{,}390} = 1.6702 \times 10^{-6}$$

During the "continue improvement" approach for the TPM implementation, analysts can evaluate the FOM value of improving maintenance approach to make a decision on implementing what kind of enhancing maintenance approach to use. If one new maintenance approach can increase the OEE value, reduce the total product cost, and, in turn, increase the FOM value, this maintenance approach should be implemented to upgrade the current maintenance approach. However, if one maintenance approach can increase the OEE value but significantly increase the total product cost, the FOM value will be decreased. From the cost-effectiveness standpoint, it is not an effective maintenance approach. In the hypothetical factory, any maintenance approach which provides the FOM value greater than the baseline FOM value (1.6702×10^{-6}) will be an enhancing maintenance approach. Thus, the greater FOM value represents the more cost-effective approach and is preferred. Cost-effectiveness analysis provides an excellent decision-making analysis to evaluate all alternative maintenance approaches. It is believed that the FOM value will be increased after implementing TPM program.

CHAPTER 5

SUMMARY AND FUTURE RESEARCH

This chapter presents a summary from this project and report. The future research for this project and report is also suggested in this chapter.

5.1 Summary

This project has focused on the new integrated maintenance approach — "Total Productive Maintenance (TPM)". The concept of TPM and the steps of TPM implementation have been presented, a specific measure of TPM effectiveness — overall equipment effectiveness (OEE) — has been defined, measured, and analyzed, and a computerized OEE model has been developed to measure the OEE value for a given manufacturing system. The countermeasures for eliminating the six big losses defined in TPM have been discussed to improve availability, performance rate, and quality rate. Application of the OEE measurement is illustrated through a case study assuming a hypothetical factory to measure the OEE value by applying the defined OEE model, analyze the production losses from the OEE value, and plan the possible countermeasures to prevent production losses. The computerized OEE model has been used to calculate the OEE value for each function block in the hypothetical production process. The cost-effectiveness approach using the total product cost and OEE value has also been illustrated through the case study.

TPM is an integrated life-cycle approach to factory maintenance and support. The complete implementation of such maintenance approach will lead to increased efficiency and greater productivity for any given manufacturing system. Throughout the introduction of TPM, the characteristics and the development steps of TPM can be completely realized and the implementation can be employed in every department at every level of factory. Overall equipment effectiveness is an important measure of TPM effectiveness. It involves all of the operation and maintenance parameters: availability; performance; and quality to evaluate the overall operating condition of equipment. Availability indicates breakdown losses and setup and adjustment losses. Performance rate shows speed losses and minor stoppage and idling losses experienced in equipment. Quality rate points out quality defects and reworks losses and startup losses. The evaluation of OEE value provides a measurement to investigate the current maintenance approach and to assess the effectiveness of improving maintenance approach. Moreover, from the OEE value, all production losses can be identified to lead to plan countermeasures to eliminate those losses, and then the effectiveness and performance of factory can be improved.

A hypothetical factory experiencing low OEE value and high maintenance cost is used as a case study to perform OEE calculation, OEE analysis, total cost analysis, and cost-effectiveness analysis. By applying the assumed operational and maintenance records into the OEE model, the OEE value of company XYZ is only 48%. It shows that there is a lot of room to improve the current maintenance approach at company XYZ. The OEE analysis for availability and performance rate is performed to establish the priority of improving approach, identify the causes of production losses, and plan the possible countermeasures to eliminate production losses. It is found that the improvement of availability in assembly function block has the largest influence on the system OEE value. Therefore, company XYZ should set the highest priority to improve the availability of assembly function and plan the countermeasures to eliminate the causes of affecting the availability of assembly function. The total cost analysis on company XYZ indicates that the cost associated with maintenance activities (especially, the maintenance cost in assembly function) are the cost driver for the total product cost of product "A". To reduce the total cost of product "A" and increase the profit of company XYZ, the occurrences of equipment failure and breakdown must be eliminated to reduce the maintenance costs. A specific cost-effectiveness figure of metric is expressed as the ratio of OEE value to the total product cost in this case study. The current FOM value is 1.6702×10^{-6} at company XYZ. Analysts can use this FOM value as a index to evaluate the FOM value of improving maintenance approach to make a decision on implementing what kind of enhancing maintenance approach.

The objective of studying and analyzing the measurement of TPM effectiveness has been met in terms of OEE. The analysis on factors affecting OEE value negatively has been achieved by understanding the relationship between six big losses and OEE value. The developed computerized OEE model has enabled OEE calculation more quickly. The suggested countermeasures for the hypothetical factory has been planned from the OEE calculation and analysis.

5.2 Future Research

TPM approach has been widely implemented around the world. Although the major fundamental development steps of TPM have been established, companies intending to implement TPM must "tailor" the current approach to be compatible. There are several ways to further improve the work in this project and report. These include:

1. Apply the principles of implementing autonomous maintenance, the steps of TPM development, the countermeasures of eliminating six big losses in a real factory to establish the practical approach of those concepts and steps and understand how they work in the field.
2. Integrate some system design methods such as failure mode, effects, and criticality analysis (FMECA), reliability centered maintenance (RCM), and so on, into the activities of TPM implementation to create an effective realistic implementation approach.
3. Apply the OEE model in a real factory to present how the OEE value assist in evaluating the effectiveness of maintenance approach and identifying the current experiencing losses in the factory.
4. Establish a system OEE evaluation model to measure the OEE value for the different configuration of manufacturing system.

5. Expand the model to consider additional system parameters from the logistics perspective in order to achieve an optimal balance among those system parameters and life-cycle cost.
6. Expand the developed computerized OEE model to perform OEE evaluation and analysis, and combine with the life-cycle cost analysis for the purpose of diagnosing and evaluating the cost-effectiveness of maintenance approach.
7. Develop an expert system to integrate operational and maintenance figures, OEE calculation, OEE analysis, life-cycle cost, etc. throughout the life cycle of equipment in the factory.

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APPENDIX A

COMPUTER PROGRAM CODES AND OUTPUT

File Name: OEE.C

```
#define extflg  1
#include "struct.h"    /* Include file with data structures and the operations on them.    */

extern OEE_Calculation();

void startingmessage()

{
  _settextposition(4,21);
  _outtext("OVERALL EQUIPMENT EFFECTIVENESS");
  _settextposition(6,35);
  _outtext("VER 1.0");
  _settextposition(11,32);
  _outtext("Chyi-Bao Yang");
  _settextposition(14,29);
  _outtext("Copyright, May, 1995");
  _settextposition(18,15);
  _outtext("Virginia Polytechnic Institute and State University");
  _settextposition(19,30);
  _outtext("Blacksburg, Virginia");
  _settextposition(21,27);
  _outtext("Press enter to continue");
  _getch();
}

void main()
{

   _clearscreen(_GWINDOW);
   startingmessage();
   _settextwindow(1,1,25,80);
   _clearscreen(_GWINDOW);
   OEE_Calculation();
   system("cls");
}
```

File Name: OEE_CAL.C

```
#include "struct.h"          /* Include file with data structures and the operations on them. */

extern  void    EventHandler_start();
extern  int     get_file_name();

void Show_Calculation_Form()
{
  _settextwindow(1,1,25,80);
  _setbkcolor(BLACK);
  _settextcolor(WHITE);
  _clearscreen(_GWINDOW);          /* clear the text window by default a 80 x 25 mode) */
  _settextposition(1,33);
  _outtext("OEE Calculation");
  _settextposition(2,33);
  _outtext("===============");
  _settextposition(3,21);
  _outtext("Working Time (min.):");
  _settextposition(5,29);
  _outtext("Planned Downtime Data" );
  _settextposition(6,29);
  _outtext("———————————" );
  _settextposition(7,5);
  _outtext("Meeting (min.):" );
  _settextposition(7,39);
  _outtext("Preventive Maintenance (min.):" );
  _settextposition(8,5);
  _outtext("Break and Holiday (min.):" );
  _settextposition(9,5);
  _outtext("Lunch (min.):" );
  _settextposition(9,43);
  _outtext("Others (min.):" );
  _settextposition(11,28);
  _outtext("Unplanned Downtime Data" );
  _settextposition(12,28);
  _outtext("————————————");
  _settextposition(13,5);
  _outtext("Setup (min.):" );
  _settextposition(13,47);
  _outtext("Startup (min.):" );
  _settextposition(14,5);
  _outtext("Adjustment (min):" );
```

```
  _settextposition(14,47);
  _outtext("Minor Stoppage (min.):" );
  _settextposition(15,5);
  _outtext("Breakdown and Failure (min.):" );
  _settextposition(15,47);
  _outtext("Idling (min.):" );
  _settextposition(16,5);
  _outtext("Changeover (min.):" );
  _settextposition(16,47);
  _outtext("Others (min.):" );
  _settextposition(18,33);
  _outtext("Process Data" );
  _settextposition(19,33);
  _outtext("————————" );
  _settextposition(20,5);
  _outtext("Process Amount (units):" );
  _settextposition(20,49);
  _outtext("Actual Cycle Time " );
  _settextposition(21,5);
  _outtext("No. of Quality Defect (units):" );
  _settextposition(21,45);
  _outtext("(min. per product unit):" );
  _settextposition(22,5);
  _outtext("No. of Startup Defect (units):" );
  _settextposition(22,49);
  _outtext("Design Cycle Time " );
  _settextposition(23,5);
  _outtext("No. of Rework (units):" );
  _settextposition(23,45);
  _outtext("(min. per product unit):" );
  _settextposition(24,4);
  _setbkcolor(BLUE);
  _settextcolor(RED);
  _outtext("ÇESC: Quit¶ Ç^N: New¶ Ç^L: Load¶ Ç^A: Save As¶ Ç^W: "Save¶ Ç^E:
           Calculation¶");"
}

void Define_Position()
{
  Field_Pos[0][0] = 3; Field_Pos[0][1] = 42;
  Field_Pos[1][0] = 7; Field_Pos[1][1] = 21;
  Field_Pos[2][0] = 7; Field_Pos[2][1] = 70;
  Field_Pos[3][0] = 8; Field_Pos[3][1] = 31;
```

```
  Field_Pos[4][0] = 9; Field_Pos[4][1] = 19;
  Field_Pos[5][0] = 9; Field_Pos[5][1] = 58;
  Field_Pos[6][0] = 13; Field_Pos[6][1] = 19;
  Field_Pos[7][0] = 13; Field_Pos[7][1] = 63;
  Field_Pos[8][0] = 14; Field_Pos[8][1] = 23;
  Field_Pos[9][0] = 14; Field_Pos[9][1] = 70;
  Field_Pos[10][0] = 15; Field_Pos[10][1] = 35;
  Field_Pos[11][0] = 15; Field_Pos[11][1] = 62;
  Field_Pos[12][0] = 16; Field_Pos[12][1] = 24;
  Field_Pos[13][0] = 16; Field_Pos[13][1] = 62;
  Field_Pos[14][0] = 20; Field_Pos[14][1] = 29;
  Field_Pos[15][0] = 21; Field_Pos[15][1] = 36;
  Field_Pos[18][0] = 21; Field_Pos[18][1] = 70;
  Field_Pos[16][0] = 22; Field_Pos[16][1] = 36;
  Field_Pos[17][0] = 23; Field_Pos[17][1] = 28;
  Field_Pos[19][0] = 23; Field_Pos[19][1] = 70;
}

void OEE_Calculation()
{

  Show_Calculation_Form();
  Define_Position();
  has_changed = 1;
  EventHandler_start(No_Cal_Fields);
  return;
}
```

File Name: EV_HNDLR.C

```
#include "struct.h"

extern  int     quit_from_view();
extern  int     get_file_name();
extern  int     save();
extern  int     print_view();
extern  int     clear_data();

void EventHandler_start(No_Cal)
int     No_Cal;
{
int     c, i, j;
int     length;                         // Current Field Index
int     Activate_Key_Press;
int     CFNdx;
   Activate_Key_Press = 1;
   CFNdx = 0;
   for (i = 0; i < No_Cal; i++)
   {
     _settextposition(Field_Pos[i][0], Field_Pos[i][1]);
     _cprintf("%-9s",Field_Value[i]);  // display default value
   }
   j = 0;
   length = 0;
   while(Activate_Key_Press)
   {
      _settextposition((int)Field_Pos[CFNdx][0], (int)Field_Pos[CFNdx][1]+j);
      if(kbhit())                       // Check if there is a keypress?
      {
         c = _getch();                  // Get character without echoing
         if (c == Ctrl('['))
           Activate_Key_Press = quit_from_view();
         ef (c == Ctrl('L'))
           Activate_Key_Press = get_file_name(0);
         ef (c == Ctrl('N'))
         {
           Activate_Key_Press = clear_data();
           CFNdx = 0;
           j = 0;
         }
         ef (c == Ctrl('A'))
```

```
  Activate_Key_Press = get_file_name(1);
ef (c == Ctrl('W'))
  Activate_Key_Press = save();
ef (c == Ctrl('E'))
  Activate_Key_Press = print_view();
ef (c == 8)                              // Backspace
{
  if (length >= 0)
  {
    _cputs(" ");
    Field_Value[CFNdx][j] = (char)32;        //" "
    if (j > 0)
      j--;
    length--;
  }
  else
  {
    _cputs(" ");
    BELL();
  }
  has_changed = 1;
}
ef (c == 75)                             // Left Arrow
{
  if (length > 0)
  {
    j = j - 1;
    length--;
  }
  else
  {
    BELL();
  }
}
 ef (c == 77)                            // Right Arrow
{
   if (length < 8)
  {
    j++;
    length++;
  }                                      //move cursor position
  else
    BELL();
```

```
        }
        ef (c == 15)                              // Shift TAB
        {
          if (CFNdx == 0)
            CFNdx = No_Cal-1;
          else
            CFNdx--;
          j = 0;
          length = 0;
        }
        ef ((c == 13) || (c == 9))                // Enter & TAB
        {
          _settextposition(Field_Pos[CFNdx][0], Field_Pos[CFNdx][1]);
          _cprintf("%-9s",Field_Value[CFNdx]);  // display new value
          if (CFNdx >= 19)
             CFNdx = 0;
          else
             CFNdx++;
          j = 0;
          length = 0;
        }
        ef ((c >=48 && c <= 57) || (c == 46))
        {
          if (length < 9)
          {
            _putch((char)c);
            Field_Value[CFNdx][j]=(char)c;
            j++;
            length++;
            has_changed = 1;
          }                                       //move cursor position
          else
            BELL();
        }
        else
        ;
      }
      else                                        // Handle other events if no keypress
      {
        ;                                         // You can look for mouse events in this block
}
   }
}
```

File Name: CNTLKEY.C

```
#include "struct.h"

extern      void    Show_Calculation_Form();
extern      void    Define_Position();
extern      void    Calculation();
extern      void    display_results();
extern      void    print_results();

void repaint()
{
int i;
// Clear the text window (by default, a 80x25 one)
   Show_Calculation_Form();
   for (i = 0; i < No_Cal_Fields; i++)
   {
     _settextposition(Field_Pos[i][0], Field_Pos[i][1]);
      _cprintf("%-9s",Field_Value[i]);    // display default value
   }

}

int clear_data()
{
int i;
   i = 0;
   for (i = 0; i < No_Cal_Fields; i++)
   {
     strcpy(Field_Value[i]," ");
   }
   New_File = 1;
   Show_Calculation_Form();
   Define_Position();
   return 1;
}

int Save_As()
{
int i;

   OEE_File = fopen(filename,"w");
   for (i = 0; i < No_Cal_Fields; i++)
```

```
    fprintf(OEE_File,"%9s\n",Field_Value[i]);
    fclose(OEE_File);
    repaint();
    has_changed = 0;
    return 1;
}

int Load()
{
int c,i;
  if (!(OEE_File = fopen(filename,"r+")))      // read_data into Field_Value
  {
    _settextposition(1,1);
    _outtext("cannot open ");
    _outtext(filename);
    BELL();
    _settextwindow(10, 10, 15, 70);
    _setbkcolor(RED);
    _settextcolor(WHITE);
    _clearscreen(_GWINDOW);
    _settextposition(5,1);
    _outtext("Press 'y' to create a new or 'n' to exit ");
    _settextposition(3, 1);
    _outtext("Create a new file? [y/n]:");
    _setbkcolor(BLACK);
    c = 0;
    while(1)
    {
      c = _getch();
      if (c == 'y' || c == 'Y')
      {
        break;
      }
      if(c == 'n' || c == 'N')
      {
        repaint();
        return 1;
      }
    }
    New_File = 1;
  }
  else
  {
```

```
      for (i = 0; i < No_Cal_Fields; i++)
      fscanf(OEE_File,"%9s",Field_Value[i]);
      New_File = 0;
    }
    fclose(OEE_File);
    has_changed = 0;
    repaint();
    return 1;
}

int get_file_name(Load_or_Save)
int Load_or_Save;
{
int       c, numchar;

    _settextwindow(10, 10, 16, 70);
    _setbkcolor(RED);
    _settextcolor(WHITE);
    _clearscreen(_GWINDOW);
    _settextposition(1,1);
    _outtext("Enter OEE filename: ");
    _settextposition(5,1);
    _outtext("Press <Enter> to continue");
    _settextwindow(12, 15, 12, 65);
    _setbkcolor(BLACK);
    _settextcolor(WHITE);
    _clearscreen(_GWINDOW);
    _settextposition(1,1);
    c = 0;
    numchar = 0;
    while(c != '\r')
    {
      c = _getch();
      switch(c)
      {
        case '\r': // <Enter>
          break;
        case '\b':  // backspace
          if(numchar > 0)
          {
            filename[--numchar] = '\0';
          }
          break;
```

```
          default:  // all other characters
             filename[numchar++] = c;
             filename[numchar] = '\0';
        }
        _clearscreen(_GWINDOW);
        _settextposition(1, 1);
        _outtext(filename);
    }
    switch (Load_or_Save)
    {
         case 0: return Load();           break;
         case 1: return Save_As();        break;
         default: break;
    }
}

int save()
{
int done;
int      i;

    if (has_changed)
    {
      if(New_File)
         done = get_file_name(1);
      else
      {
       OEE_File = fopen(filename,"w");
       for (i = 0; i < No_Cal_Fields; i++)
       fprintf(OEE_File,"%9s\n",Field_Value[i]);
       fclose(OEE_File);
      }
      has_changed = 0;

    }
    return 1;
}

int quit_from_view()
{
int c;
int return_value;
     if(has_changed)
```

```
    {
        _settextwindow(10, 10, 15, 70);
        _setbkcolor(RED);
        _settextcolor(WHITE);
        _clearscreen(_GWINDOW);
        _settextposition(5,1);
        _outtext("Press 'y' to save file or 'n' to exit without saving file.");"
        _settextposition(3, 1);
        _outtext("File changed. Save? [y/n]:");
        _setbkcolor(BLACK);
        c = 0;
        while(1)
        {
        c = _getch();
        if(c == 'y' || c == 'Y')
        {
                repaint();
                return_value = save();
                break;
        }
        if(c == 'n' || c == 'N') break;
        }
    }
    return 0;
}

int print_view()
{
int c;

    _settextwindow(10, 10, 15, 70);
    _setbkcolor(RED);
    _settextcolor(WHITE);
    _clearscreen(_GWINDOW);
    _settextposition(5,1);
    _outtext("Press 'y' to do OEE calculation or 'n' to exit ");
    _settextposition(3, 1);
    _outtext("OEE Caluation? [y/n]:");
    _setbkcolor(BLACK);
    c = 0;
    while(1)
    {
        c = _getch();
```

```
        if(c == 'y' || c == 'Y')
        {
           Calculation();
           _settextwindow(10, 10, 15, 70);
           _setbkcolor(RED);
           _settextcolor(WHITE);
           _clearscreen(_GWINDOW);
           _settextposition(5,1);
           _outtext("Press 's' to send results to screen or 'p' to printer ");
           _settextposition(3, 1);
           _outtext("Screen or Printer? [s/p]:");
           _setbkcolor(BLACK);
           c = 0;
           while(1)
                {
                          c = _getch();
                          if(c == 's' || c == 'S')
                          {
                          display_results();
                          break;
                          }
                          if(c == 'p' || c == 'P')
                          {
                             print_results();
                             display_results();
                             break;
                   }
                }
        break;
        }
        if(c == 'n' || c == 'N') break;
  }
  repaint();
  return 1;
}
```

File Name: CAL_OPER.C

```
#include "struct.h"

void display_results()
{
int c;

  system("cls");
  printf("\n");
  printf("\n");
  printf("                Overall Equipment Effectiveness Report");
  printf("\n\n");
  printf("                     Working Time (min.): %9.2f\n", WH);
  printf("                Planned Downtime (min.): %9.2f\n", PD);
  printf("                     Loading Time (min.): %9.2f\n", LT);
  printf("             Unplanned Downtime (min.): %9.2f\n", UPD);
  printf("                  Operating Time (min.): %9.2f\n", OT);
  printf("\n\n");
  printf("       Number of Good Product (units): %9.2f\n",(float) GP);
  printf("                    Net Operating Rate: %9.2f %%\n", NOR*100);
  printf("                 Operating Speed Rate: %9.2f %%\n", OSR * 100.0);
  printf("\n\n");
  printf("                           Availability: %9.2f %%\n\n", A*100.0);
  printf("                     Performance Rate: %9.2f %%\n\n", P*100.0);
  printf("                          Quality Rate: %9.2f %%\n\n", Q*100.0);
  printf("       Overall Equipment Effectiveness: %9.2f %%\n\n", OEE*100.0);
  printf("                    Press any key to continue");
  c = _getch();

}

void Calculation()
{

 // Calculate Working Time (WH)

   WH = (float) atof(Field_Value[0]);

 // Caculate Planned Downtimes (PD)

   PD = (float)(atof(Field_Value[1]) + atof(Field_Value[3]) + atof(Field_Value[4])
         + atof(Field_Value[2]) + atof(Field_Value[5]));
```

```
// Calculate Unplanned Downtimes (UPD)

  UPD = (float)(atof(Field_Value[6]) + atof(Field_Value[8]) + atof(Field_Value[10])
           + atof(Field_Value[12]) + atof(Field_Value[7]) + atof(Field_Value[9]) +
           atof(Field_Value[11]) + atof(Field_Value[13]));

// Calculate Defect AMount (DA)

  DA =  (float)(atof(Field_Value[15]) + atof(Field_Value[16]) + atof(Field_Value[17]));

// Calculate Loading TIme (LT)

  LT = WH - PD;

// Calculate Operating Time (OT)

  OT = LT - UPD;

// Calculate Net Operating Rate (NOR)

  NOR = (float)(atof(Field_Value[14]) * atof(Field_Value[18]) / OT);

// Calculate Operating Speed Rate (OSR)

  OSR = (float)(atof(Field_Value[19]) / atof(Field_Value[18]));

// Calculate Number of Good Product

  GP = (float) (atof(Field_Value[14]) - atof(Field_Value[15]) - atof(Field_Value[16])
        - atof(Field_Value[17]));

// Calculate Availability(A), Performance Rate(P), Quality Rate(Q)

  A = OT / LT;
  P = NOR * OSR;
  Q = (float)((atof(Field_Value[14]) - DA) / atof(Field_Value[14]));

// Calculate Overall Equipment Effectiveness (OEE)

  OEE = A * P * Q;
}
```

```
void print_results()
{
file *fp;

  fp = fopen("oee_out.rpt","w");
  fprintf(fp,"\n");
  fprintf(fp,"\n");
  fprintf(fp,"                Overall Equipment Effectiveness Report");
  fprintf(fp,"\n\n");
  fprintf(fp,"                      Working Time (min.): %9.2f\n", WH);
  fprintf(fp,"                 Planned Downtime (min.): %9.2f\n", PD);
  fprintf(fp,"                      Loading Time (min.): %9.2f\n", LT);
  fprintf(fp,"              Unplanned Downtime (min.): %9.2f\n", UPD);
  fprintf(fp,"                   Operating Time (min.): %9.2f\n", OT);
  fprintf(fp,"\n\n");
  fprintf(fp,"       Number of Good Product (units): %9.2f\n",(float) GP);
  fprintf(fp,"                     Net Operating Rate: %9.2f %%\n", NOR*100);
  fprintf(fp,"                  Operating Speed Rate: %9.2f %%\n", OSR * 100.0);
  fprintf(fp,"\n\n");
  fprintf(fp,"                              Availability: %9.2f %%\n\n", A*100.0);
  fprintf(fp,"                     Performance Rate: %9.2f %%\n\n", P*100.0);
  fprintf(fp,"                           Quality Rate: %9.2f %%\n\n", Q*100.0);
  fprintf(fp,"    Overall Equipment Effectiveness: %9.2f %%\n\n", OEE*100.0);
  fclose(fp);
  system("cls");
  system("print oee_out.rpt");
}
```

File Name: STRUCT.H

```
#include <stdio.h>          /* input output utilities       */
#include <string.h>         /* string declaration           */
#include <time.h>           /* time-conversion routines     */
#include <math.h>           /* math functions               */
#include <stdlib.h>         /* memory allocation            */
#include <process.h>        /* system functions             */
#include <graph.h>          /* text window functions        */
#include <conio.h>          /* console I/O functions        */

#ifndef extflg
#       define extdef extern
#else
#       define extdef
#endif

#ifndef TRUE       /* If TRUE has not been defined, TRUE = 1  */
#define TRUE    1
#endif

#ifndef FALSE      /* If FALSE has not been defined, then FALSE = 0 */
#define FALSE   0
#endif


#define BLACK              0
#define BLUE               1
#define GREEN              2
#define CYAN               3
#define RED                4
#define MAGENTA            5
#define BROWN              6
#define WHITE              7
#define GRAY               8
#define LIGHTBLUE          9
#define LIGHTGREEN         10
#define LIGHTCYAN          11
#define LIGHTRED           12
#define LIGHTMAGENTA       13
#define YELLOW             14
#define BRIGHTWHITE        15
#define Ctrl(X)       (X-0x40)          /* control character */
```

```
#define ef        else if
#define BELL()          _putch((char)7)          /* Bell sound */
#define No_Cal_Fields 20
extdef int      Field_Pos[20][2];
extdef char     Field_Value[20][9];
extdef int      has_changed;
extdef int      New_File;
extdef FILE     *OEE_File;
extdef char     filename[80];

// Calculation Variables

extdef float  WH;
extdef float  PD;
extdef float  UPD;
extdef float  DA;
extdef float  LT;
extdef float  OT;
extdef float  NOR;
extdef float  OSR;
extdef float  A;
extdef float  P;
extdef float  Q;
extdef float  OEE;
extdef float  PA;
extdef float  ACT;
extdef float  GP;
```

```
                          OEE Calculation
                          ===============
                  Working Time (min.): 480

                      Planned Downtime Data
                      _____________________
Meeting (min.): 0                  Preventive Maintenance (min.): 20
Break and Holiday (min.): 0
Lunch (min.): 0                        Others (min.): 0

                      Unplanned Downtime Data
                      _______________________
Setup (min.): 20                           Startup (min.): 0
Adjustment (min): 20                       Minor Stoppage (min.): 0
Breakdown and Failure (min.): 20           Idling (min.): 0
Changeover (min.): 0                       Others (min.): 0

                          Process Data
                          ____________
Process Amount (units): 400                  Actual Cycle Time
No. of Quality Defect (units): 8         (min. per product unit): 0.8
No. of Startup Defect (units): 0             Design Cycle Time
No. of Rework (units): 0                 (min. per product unit): 0.5
||ESC: Quit|| ||^N: New|| ||^L: Load|| ||^A: Save As|| ||^W: Save|| ||^E: Calculation||
```

Figure A-1. Input Screen of Computerized OEE model

Overall Equipment Effectiveness Report

Working Time (min.):	480.00
Planned Downtime (min.):	20.00
Loading Time (min.):	460.00
Unplanned Downtime (min.):	60.00
Operating Time (min.):	400.00
Number of Good Product (units):	392.00
Net Operating Rate:	80.00 %
Operating Speed Rate:	62.50 %
Availability:	86.96%
Performance Rate:	50.00%
Quality Rate:	98.00%
Overall Equipment Effectiveness:	42.61%

Figure A.2 Output of Computerized OEE model