

## TPM: PLANNED AND AUTONOMOUS MAINTENANCE: BRIDGING THE GAP BETWEEN PRACTICE AND RESEARCH\*

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Competitive pressures and changing production management paradigms have, in recent years, increased the importance of reliable and consistent production equipment. Initially, the Japanese, and now others, have espoused the virtues of a management philosophy known as total productive maintenance (TPM). We are interested in the maintenance-investment decisions for TPM. This paper (1) describes the basic elements of TPM programs, (2) categorizes the relevant research literature using a practitioner's framework for autonomous and planned maintenance activities, and (3) identifies the current gaps between practitioner needs and academic research in the area of TPM and offers suggestions to close the gaps.

(MAINTENANCE; TOTAL PRODUCTIVE MAINTENANCE; LITERATURE REVIEW)

### 1. Introduction

Substantial capital investments are required for manufacturing almost all goods of economic significance. The productivity of these investments is a fundamental element of competition among companies and nations. The maintenance of capital investments involves significant recurring expenses. For example, in 1991 the amount of money DuPont spent company-wide on maintenance was roughly equal to its net income (Sterman, Banaghan, and Gorman 1992). Maintenance expenses vary depending on the type of industry; however, maintenance expenses each year are typically 15–40% of production costs (Maggard and Rhyne 1992). Perhaps because maintenance is so expensive, companies attempt to control maintenance costs by keeping them at a specified budget level, a level often simply established based on the previous year's expenses. After all, equipment must be repaired in order to continue operations and therefore the related expenses are considered mandatory.

During the last decade, however, this approach has been insufficient. As companies have invested in programs such as just in time (JIT) and total quality management (TQM) in an effort to increase organizational capabilities, the benefits from these programs have often been limited because of unreliable or inflexible equipment (Garwood 1990; Tajiri and Gotoh 1992). In fact, the National Research Council (1991) estimated the average

\* Received October 1997; revised May 1998; accepted May 1998.

utilization of machines in the United States at less than 50%. Therefore, initiatives such as total productive maintenance (TPM), which address equipment maintenance, have become more commonplace in the drive for continual improvement. Rather than being seen simply as an expense that must be controlled, maintenance is now regarded as a strategic competitive tool.

TPM has resulted in significant improvements in plant performance. Constance Dyer, director of Research and TPM Product Development, Productivity Inc., says that companies that adopt TPM are seeing 50% reductions in breakdown maintenance labor, 70% reductions in lost production, 50–90% reductions in setups, 25–40% increases in capacity, 50% increases in labor productivity, and 60% reductions in costs per maintenance unit (Koelsh 1993, p. 64).

These successes indicate that TPM may play a significant role in improving manufacturing performance. Unfortunately, the academic research that supports the evaluation of investments in TPM is limited. In this paper, we identify opportunities for future research to support TPM investment decisions. Our goal is to encourage practically oriented, relevant research on TPM.

In this paper, we provide an overview of TPM by describing the origins of TPM, presenting a framework for TPM, and by explaining the basic elements of TPM. Then, using a popular TPM practitioner framework for autonomous and planned maintenance, we discuss the gaps between practitioner needs and the academic literature. We conclude by identifying opportunities and suggestions for future research to support investment decisions for TPM development activities.

## 2. An Overview of TPM

In this section, we present the history of TPM and typical TPM activities. Our aim is to introduce the reader to TPM and to present a framework for discussing TPM implementation. This overview provides a foundation from which we can discuss the academic literature and identify gaps between the problems that academic researchers have solved and the problems that practitioners are faced with during TPM implementation.

### 2.1. A Brief History of Maintenance Management

TPM originated from the fields of reliability and maintenance, a pair of closely related disciplines that have become standard engineering functions in many industries. The primary objective of these functions is to increase equipment availability and overall effectiveness.

There have been four major periods of maintenance management:

1. The period prior to 1950 was characterized by *reactive* maintenance. During this phase little attention was placed on defining reliability requirements or preventing equipment failures. Typically, equipment specifications included requirements for individual parts and failed to consider the reliability or availability of the entire system.
2. The second period, *preventive maintenance*, involved an analysis of current equipment to determine the best methods to prevent failure and to reduce repair time. This period resulted from the emergence of the military equipment industry during World War II. Emphasis was placed on the economic efficiency of equipment replacements and repairs as well as on improving equipment reliability to reduce the mean time between failures.
3. The third period, called *productive maintenance*, became well established during the 1960s as the importance of reliability, maintenance, and economic efficiency in plant design was recognized. Productive maintenance has three key elements: maintenance prevention, which is introduced during the equipment-design stages; maintainability improvement, which modifies equipment to prevent breakdowns and facilitate ease of maintenance; and preventive maintenance, which includes periodic inspections and repairs of

the equipment. General Electric Corporation is typically credited for initiating productive maintenance in the 1950s, but the approach did not gain popularity until the 1960s (Hartmann 1992). In the late 1950s, the concepts of productive maintenance were also promoted in Japan.

4. The most recent period is represented by *total productive maintenance*. TPM officially began in the 1970s in Japan. Seiichi Nakajima, vice-chairman of the Japanese Institute of Plant Engineers (JIPE), the predecessor of the Japan Institute of Plant Maintenance (JIPM), promoted TPM throughout Japan and has become known as the father of TPM. In 1971, TPM was described by JIPE as follows:

TPM is designed to maximize equipment effectiveness (improving overall efficiency) by establishing a comprehensive productive-maintenance system covering the entire life of the equipment, spanning all equipment-related fields (planning, use, maintenance, etc.) and, with the participation of all employees from top management down to shop-floor workers, to promote productive maintenance through motivation management or voluntary small-group activities. (Tsuchiya 1992, p. 4)

TPM provides a comprehensive company-wide approach to maintenance management.

In the late 1980s TPM was introduced in the United States. There are several reasons why American companies are utilizing TPM. Dominant, among other reasons, is that many organizations face competitive pressures from firms that have improved plant productivity, often through successful TPM implementation. One particular group of competitors, the Japanese, have demonstrated in many industries that maintenance is a critical component of their success. JIPM has emphasized the importance of maintenance and has awarded over 450 preventive-maintenance prizes to companies that have achieved a high level of success with TPM implementation.

It would, however, be a gross oversimplification to suggest that the Japanese influence is the only factor that has brought about the popularity of TPM. There are also several other changes in the manufacturing environment that have increased the importance of maintenance. JIT, TQM, and employee involvement (EI) programs have become more commonplace in industry; to address the increasing demands of customers, companies have attempted to reduce costs, shorten production lead time, and improve quality. These improvement programs all require reliable and consistent equipment throughout the entire plant. Moreover, as customers become more demanding and processes become more interrelated, the need for an effective maintenance strategy also increases. Figure 1 shows the interrelationships between TPM, JIT, TQM, and EI. From this diagram, it is clear that proper implementation of TPM will enhance the effectiveness of the other improvement programs.

Another important trend is that technology has changed within many plants and has also improved the tools that are available for maintenance management. As the technology of production equipment becomes more sophisticated, it is essential that operators and maintenance personnel are provided with the tools and training to support the new demands of the equipment. It is also important that production personnel take advantage of the new maintenance technologies, such as vibration analysis and infrared thermography, that have become useful means for predicting and diagnosing equipment problems.

These trends make it important for organizations to maintain manufacturing equipment in order to achieve the new performance criteria, produce maximum returns, and compete aggressively worldwide. TPM has emerged as a result of this heightened corporate focus on making better use of available resources.

## 2.2. A Brief Description of TPM

This section provides a framework for considering TPM activities (refer to Figure 2). The elements of the framework have been developed based upon popular TPM literature (Hartmann 1992; Nakajima 1988; Shimbun 1995; Suzuki 1995; Tsuchiya 1992; Gotoh

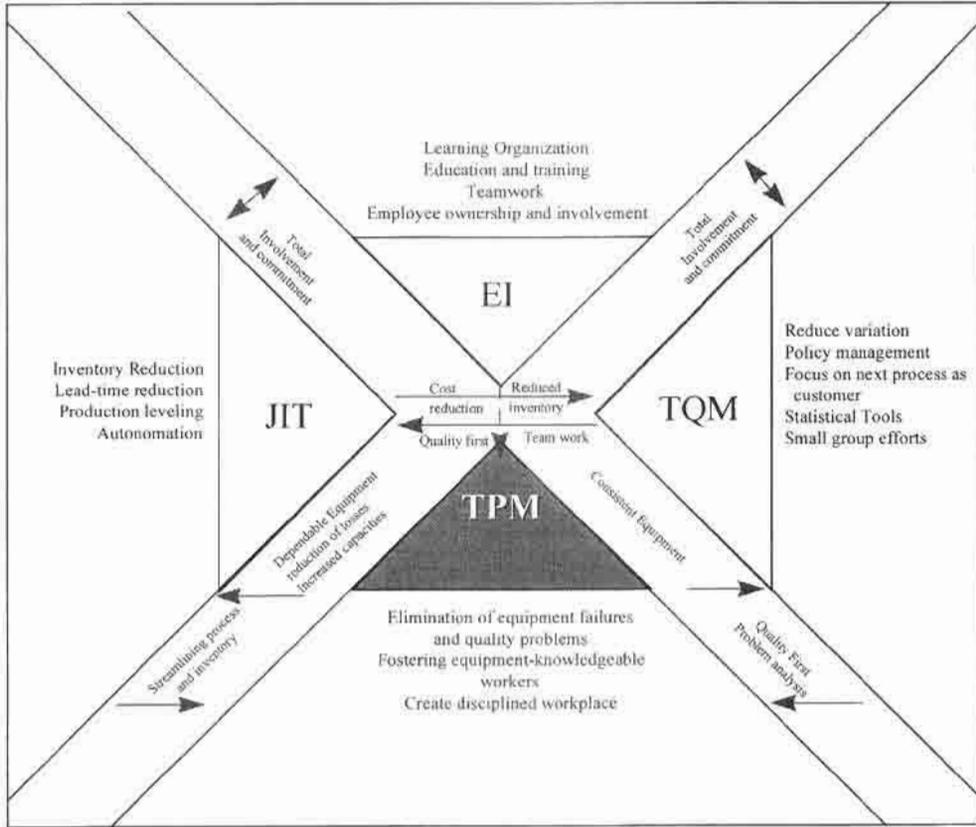


FIGURE 1. The Interdependence of JIT, TQM, TPM, and EI

1991) and a number of site visits and interviews with practicing managers. (These visits were conducted by the lead author and sponsored by a grant from Coopers and Lybrand).

While maintenance activities primarily focus on cost reduction and equipment effectiveness, TPM, which emphasizes a company-wide approach to maintenance, also plays a vital role in improving other manufacturing performance measures. Therefore, we consider improved cost, quality, delivery, flexibility, and innovativeness to be important goals of a TPM program and represent them in our framework. (These manufacturing priorities are discussed in Miltenburg 1996). We now discuss the elements of the TPM program that support these improvement efforts.

**2.2.1. TPM VALUES.** Critical to successful TPM implementation are its core operating values. Although these values should be tailored to any given organization, they offer a broad guide to the management of equipment. The following statements represent the general values of TPM:

- Process and product quality are a key part of every person's performance.
- Equipment failures and off-quality product can and will be prevented.
- If it ain't broke, fix it anyway.
- Equipment performance can be managed.

**2.2.2. EMPLOYEE INVOLVEMENT.** As indicated by the first value, every employee should be involved in the TPM process. Accountability for equipment performance is important to the success of the TPM program. However, employees cannot be accountable for quality and predictable production if they cannot impact equipment performance. Em-

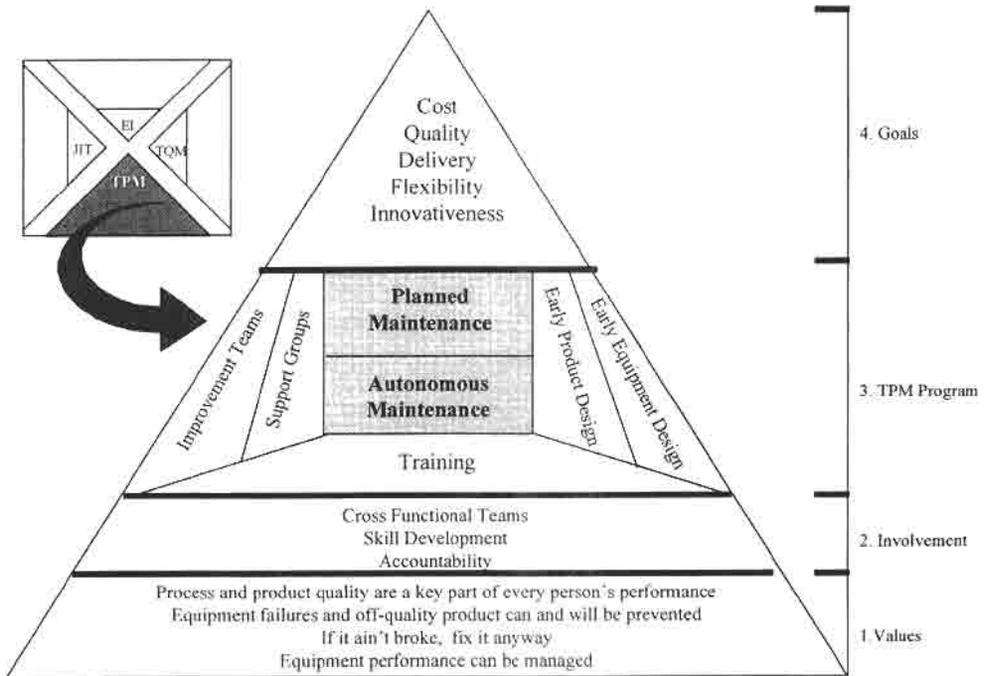


FIGURE 2. A Model of TPM

ployees' skills must be developed to meet the needs of their expanded roles. The core values and skills of the organization provide the foundation for TPM implementation.

Employee involvement is also encouraged by cross-functional teams. Teams help to break down the barriers that are inherent in the traditional approach to maintenance. Teams also help to identify problems and suggest new approaches for elimination of the problems, introduce new skills, initiate training programs, and define TPM processes.

**2.2.3. THE TPM PROGRAM.** While TPM is commonly associated with autonomous and planned maintenance activities, the program also includes other activities which help to improve equipment effectiveness over the entire life of the equipment. These activities include training, early equipment design, early product design, focused improvement teams, and support group activities (Tajiri and Gotoh 1992; Nakajima 1988; Gotoh 1991). Our literature review focuses on autonomous and planned maintenance activities, however, we briefly review the six major TPM activities in this section.

TPM training should be given to every employee. Although internal capabilities may not be sufficient to achieve the goals of TPM at the start of the program, the capabilities for continuation of TPM must be developed. Also, as needs develop, training should support new TPM activities such as inspection, periodic restoration, and prediction analysis.

Early equipment management activities are typically driven by the research and development or engineering functions within the organization. Early equipment management considers the tradeoffs between equipment attributes encompassing reliability, maintainability, operability, and safety. The engineering efforts involve the consideration of the life-cycle costing for equipment purchases as well as comprehensive commissioning periods prior to full production.

Early product design involves efforts to simplify the manufacturing requirements and improve quality assurance through product design. By considering these factors in the product-design stage, it is easier to meet the diversified needs of consumers in terms of product features, design, quality, and price. The shop-floor employees can focus on main-

taining the process and equipment rather than on working out the logistics of manufacturing the product.

Focused improvement team efforts help to eliminate the major equipment losses including breakdown losses, setup and adjustment losses, minor stoppage losses, speed losses, quality defects and rework losses, and start-up/yield losses. Typically, the major losses are eliminated by selecting a process-improvement team to resolve a particular problem. The team then identifies and analyzes the cause of the problem, plans and implements a solution, checks the results, and if improvement occurs, develops standards to ensure that the improved conditions will remain. The improvement team also documents its work so that other areas can learn from its improvement efforts.

Support group activities ensure that the production department does not produce useless or wasteful products and that orders are filled on time and at the quality and costs that the development and engineering departments prescribe. This is not the sole responsibility of the production department; it requires a TPM program that embraces the entire company, including the administrative and support departments.

While the first four activities are essential to developing a company-wide maintenance system, much of the day-to-day maintenance planning and execution is performed by the production and maintenance personnel. These efforts are represented by the autonomous and planned maintenance activities in Figure 2. Together production and maintenance groups help to improve the effectiveness of the maintenance program. As operators are trained, they begin to inspect and maintain the equipment and perform basic maintenance tasks. This allocation of maintenance tasks to production operators frees up time for maintenance personnel to perform long-term improvement efforts and plan maintenance interventions.

The autonomous and planned maintenance efforts are typically divided into four phases that correspond to the four stages of maintenance development. Nakajima (1980) was the first author to present this framework; it is frequently used in subsequent books (Tajiri and Gotoh 1992; Nachi-Fujikoski 1990; Suzuki 1994). We also include a fifth stage that hypothesizes the future direction of TPM efforts. This phase incorporates the many TPM activities that are not directly part of autonomous or planned maintenance roles. At this phase support functions become more critical to improving productivity. The phases are as follows:

- I. Reduce variability of life span.
- II. Extend the life span.
- III. Estimate the life span and restore or inspect parts periodically.
- IV. Predict life spans and restore parts when needed.
- V. Design the life span.

Figure 3 shows a five-phase framework for TPM autonomous and planned maintenance development and includes typical steps for implementation. This five-phase framework provides a useful tool for demonstrating how the maintenance research relates to the problems being faced by TPM practitioners. At each phase of TPM development there is a need to make different maintenance-investment decisions. In Section 3, we will utilize this five phase framework to describe the decisions made at each phase of TPM development and discuss the literature relevant to these planned and autonomous maintenance decisions.

### 3. A Review of the Research Literature

Competitive pressures and changing production-management paradigms have increased the importance of reliable and consistent production equipment and have led to the popularity of TPM. Academics need to lead the efforts to improve equipment-management practices. Research that evaluates the various decisions in TPM development will help to



	Phase I	Phase II	Phase III	Phase IV	Phase V
	Reduces Life Span Variability	Lengthen Average Life Span	Estimate Life Span	Predict Life Span	Design Life Span
Planned Maintenance	Step 1: Evaluate Equipment Step 2: Restore Deterioration	Step 3: Correct Design Weaknesses Step 4: Eliminate Unexpected Failures	Step 5: Build Periodic Maintenance System & Identify Symptoms of Deterioration	Step 6: Build Predictive Maintenance System Step 7: Prevent Quality Defects	Step 8: Technical Analysis of Any Deterioration & Design Step 9: Implement in All Support Areas
Autonomous Maintenance	Step 1: Basic Cleaning Step 2: Eliminate Source of Problems Step 3: Set Standards	Step 4: General Inspection of Equipment	Step 5: Autonomous Inspection	Step 6: Maintenance for Quality Step 7: Autonomous Maintenance	Step 8: Process Improvement & Design Team Step 9: Implement in all Support Areas

FIGURE 3. Five Phases of TPM Development

drive maintenance investments to improve equipment productivity. This section discusses the relationship of the maintenance management literature to TPM planned and autonomous maintenance investment decisions. We consider research conducted both pre- and post-TPM introduction and consider how it supports current decision-making by TPM practitioners.

Historically, maintenance management research has been based on the mathematical modeling and statistical analysis of equipment; the primary research areas that evaluate the management of equipment are reliability and maintenance. The fields of reliability and maintenance are concerned not only with equipment but also with the technical, operational, and management activities required to sustain the performance of manufacturing equipment throughout its entire lifetime. Both fields encompass a broad scope of research and a book could be dedicated to each; therefore, the reader should be aware that only a fraction of the possible topics are covered in this paper. We have chosen to mention the articles that relate most closely to TPM implementation. Because the reliability literature primarily provides a foundation for the maintenance literature (e.g., the type of failure distribution), it is not reviewed in this paper.

This review considers the relationship of academic maintenance literature to the practitioner's framework for autonomous and planned maintenance shown in Figure 3. We chose this popular framework because it is accepted by practitioners, is easy to understand, and closely depicts the managerial decisions made for maintenance on a day-to-day basis within the plant. While there are also important decisions required to support the other four TPM activities discussed in the previous section, we choose to focus on the decisions that directly impact the autonomous and planned maintenance activities. For each phase of TPM development, we describe the decisions faced by practitioners and then discuss the literature that supports the decision-making process. By categorizing the literature in this framework for autonomous and planned maintenance, we are able to identify gaps between current TPM practices and academic research.

### 3.1. Phases I and II: Equipment Improvement

The first phase of TPM involves efforts to reduce the variability of the equipment life span. This phase is analogous to the removal of assignable causes to achieve "control" of machinery in a quality program. These efforts include restoration and cleaning of the equipment. At this stage, practitioners must decide how much time and money to invest in restoring the equipment to a base condition.

The main objective of Phase II is to lengthen the equipment's life. In this stage, the cleaning and lubrication procedures become standardized and operators are educated to conduct detailed inspection of all equipment. Companies must decide how much time and money to invest in training operators and technicians. Cross-training personnel can make an organization more flexible and more responsive to maintenance needs; however, some tasks will still be too difficult or unsafe for all personnel to perform. Another Phase II decision is to make investments in eliminating the root causes of contamination and failure and to simplify the inspection and maintenance tasks. Finally, practitioners must decide how much time to invest in order to sustain the equipment at its base condition.

Both Phases I and II assume that it is possible to change the failure distribution of the equipment. This assumption is central to the TPM philosophy. In traditional maintenance, the assumption is made that equipment conditions deteriorate over time, leading to failure or the need for replacement. With TPM, investments are made to reduce equipment problems; the assumption is that a goal of zero failures and defects is achievable.

We have seen numerous examples of Phase I and II decisions. A Phase I policy investment was made by a large cigarette manufacturer when it made a commitment to improve its maintenance procedures. The company shut down one production line and essentially rebuilt the equipment. After establishing a base condition, the most frequent line stoppage, rod breaks, was reduced from one every 9 minutes to one every 24 hours, on average. After justifying the impact of its initial Phase I investment, the manufacturer shut down each production line in order to conduct further Phase I activities. A very effective Phase II investment decision was made at Tennessee Eastman. They decided to cross-train operators, electricians, and mechanics to de- and re-energize motors. This training effort helped to reduce the response time of electricians from 54 to 18 minutes and increase machine availability by 20,000 hours in the first year. We now consider the literature that supports Phase I and II decisions.

3.1.1. REVIEW OF THE LITERATURE. Most maintenance and reliability literature does not incorporate the important investment considerations present in Phases I and II of TPM development. Recent literature begins to address these improvement phases. McKone and Weiss (1997a) analyze the business decision to reduce the mean and variance of production cycle time through an investment in planned autonomous maintenance. The model provides an important extension to previous models; it treats planned maintenance as a decision variable that helps reduce the frequency of equipment problems. With this extension, managers can choose both the order quantity and the time investment in maintenance to manage the cycle time. The model provides evidence that there is an optimal investment in planned downtime to minimize expected cycle time. This model is expanded in McKone and Weiss (1997b) to consider the autonomous maintenance investment decision when the goal is to reduce inventory (both safety and cycle stock). These results demonstrate that the first phase of TPM can yield significant benefits to equipment.

Chitke and Desmukh (1981) and Anderson (1981) study systems subject to randomly occurring shocks that can be controlled by continuous preventive-maintenance expenditures. The problem is to determine a policy that schedules replacement and maintenance expenditures in such a way as to maximize the expected discounted net profit. They show the optimality of a control-limit policy, in which replacements are made after the equipment damage reaches the control limit. The maintenance-expenditure rate should be reduced as the deterioration level approaches the control limit. These maintenance expenditures could be coordinated with the TPM activities of Phases I and II.

Waldman (1983) incorporates an environmental process with the regular shock model. In his model, each shock causes a discrete or random amount of damage depending on the realization of a stochastic process describing the environment. According to Waldman, policies that minimize expected discounted total cost will require system replacement

whenever the accumulated damage exceeds a critical number, determined by the state of the environment. The model describes the relationship of the external environment to the failure of the system components. Therefore, it could serve as a useful tool for evaluating improvements made through TPM environment-maintenance activities.

Porteus (1986) evaluates models that consider the option of a one-time investment to improve process quality or reduce setup time. The first model he examines could be described as a technological-choice model in which a process with an optimal rate of producing defects is selected. His objective is to minimize cost per unit time (investment, inventory, and ordering costs). In his second model, he takes a similar approach but considers the investment to select the optimal setup time. Although this article is not directly related to maintenance, it does consider the ability to invest in improvements to reduce overall operating costs.

Another area of the literature investigates the learning benefits of maintenance (Fine 1988; Marcellus and Dada 1991; Dada and Marcellus 1994). By offering savings in operating costs, these models provide an economic incentive for gradually improving the maintenance process. In contrast to Porteus, these models assume that a given technology has already been acquired. Their research considers the benefit of interrupting the process in order to reap longer term benefits from improved operator skills. Fine (1988) determines when to undertake maintenance, and Marcellus and Dada (1991) determine how to choose between two types of maintenance. In Dada and Marcellus' model (1994), the decision maker has three choices when the process is out of control: continue production, perform routine maintenance that restores the process to control, or invest in more expensive maintenance to provide training to the operators and decrease the tendency of the process to go out of control. The decision problem is modeled by a Markov decision process in which the decision, at each point in time, is based on the probability that the process is out of control, as well as on the transition probability. The optimal policy is of the control-limit type with the property that learning is not optimal if the tendency of the process to go out of control is small enough. These models relate to the Phase I and II investment in training for production and maintenance personnel.

As mentioned in this review, researchers have made some progress in addressing the concerns associated with the early phases of TPM implementation. However, there is still a significant gap between the decisions that the literature support and the decisions that are being faced by practitioners. In particular, few models directly consider the ability to invest in restoring or improving equipment performance. Models are needed to evaluate the investments in time, capital, and employees to support TPM efforts. We will consider this gap in more detail in Section 4 when we recommend areas for future research.

### 3.2. *Phase III: Estimating Life Span (Inspection and Replacement Intervals)*

After implementing the first two phases, equipment conditions should be dependable and operating conditions consistent. Equipment life span can be accurately estimated, and mechanics and operators can plan periodic inspections and renovations. Phase III of TPM development begins to determine the best type and interval of inspections and repairs.

Phase III decisions are made frequently in organizations that establish a preventive maintenance program. One large paper-products company used historical data for equipment failures to estimate the failure distribution and establish periodic replacement policies. In addition, operators were trained on the cause-and-effect relationship between the process and product quality. Then, on-line tracking of process characteristics allowed the operators to detect equipment deterioration before it created product-quality problems.

It is interesting that much of the traditional maintenance literature support the decision involved in Phase III of TPM development. Essentially, the failure rate is assumed to be a function of the equipment, and little attention is given to the possibility of improving the equipment or restoring the equipment to a better condition (Phase I and II decisions).

The maintenance literature appears to have developed comparably to the lot-sizing literature. In the lot-sizing literature, the economic-order-quantity model was utilized for years, and various modifications were made to its formulation. Not until Porteus (1986) considered the ability to make an investment in setup reduction did the research begin to question the assumption that setup costs were fixed. Similarly, much of the research on maintenance has focused on Phase III decisions, where the failure distribution is assumed to be stable. The research focuses on simply restoring a failed system to its initial condition rather than improving long-term equipment effectiveness. We now discuss the literature that support Phase III of TPM development.

3.2.1. REVIEW OF THE LITERATURE. Because McCall (1965), Pierskalla and Voelker (1976), and Valdez-Flores and Feldman (1989) provide comprehensive reviews of literature relevant to this phase of maintenance management, we will not attempt to review this area exhaustively. We briefly mention the type of models supporting these investment decisions and then comment on opportunities for future research.

McCall discusses two main types of models in the classic maintenance literature: policies for which the failure distribution is known and those for which the distribution is unknown. When the failure distribution is known, there are two basic types of models. The first is the preparedness model in which the equipment fails stochastically and its actual state is unknown. Changes in the equipment condition can only be determined at the time of inspection or replacement. The uncertainty in the preparedness model is associated with the inability to predict the exact time of failure and to determine the state of equipment without intervention.

The second is the preventive model, in which the equipment fails stochastically and the actual state is known. Changes in equipment conditions are detected immediately and appropriate action can then be taken. The uncertainty in the preventive model comes from the inability to predict the exact time of state changes. It is this uncertainty that creates an opportunity to replace or repair equipment before it fails. Most preventive and preparedness models consider strictly periodic policies; however, this policy is only optimal for an infinite time horizon. Sequential maintenance policies, where the replacement interval is recalculated at each replacement maintenance, have also been analyzed for the finite time horizon.

There are several different methods for handling uncertainty with regard to the failure distribution. When nothing is known about the equipment-failure characteristics, the well-known minimax approximation procedures can be used. When there is some information regarding the stochastic behavior of the equipment, upper and lower bounds can be calculated for the expected costs. If there is some information about the form of the distribution but one or more parameters are unknown, then a Bayes Adaptive Method can be useful. As additional data are obtained, the unknown parameters are updated and the ensuing posterior distribution is used to recompute the maintenance policy. A summary of these techniques is provided in Jorgenson and McCall (1963).

Most of the Phase III literature compares the cost benefits of various maintenance policies: preparedness or preventive maintenance, and periodic- or sequential-replacement policies. More recent literature extends the base models to incorporate multi-component equipment and multi-state equipment conditions or to relax some of the assumptions of the early models.

Phase III models have been extremely effective in the development of a philosophy of preventive versus reactive maintenance. Most organizations realize that it can be beneficial to replace equipment prior to failure when the costs of breakdowns are high. However, in practice, the replacement interval is often chosen based on the equipment manufacturer's recommendations. Therefore, intervals are often established without considering the actual failure distribution (based on the environment in which it operates) or main-

tenance costs (based on the downtime costs associated with a particular plant). Efforts should be made to develop better estimates of the actual failure distribution and the associated maintenance costs. In Section 4, we will discuss other potential research areas that will help support decision making during Phase III of TPM implementation.

### 3.3. *Phase IV: Predicting Quality and Equipment Performance*

Phase III allows operators and technicians to gain a deeper understanding of the equipment and process. Phase IV permits personnel to use this new knowledge about equipment deterioration, together with diagnostic techniques, to predict failures of equipment and eliminate equipment-related quality problems. Condition-based maintenance helps get additional time out of the equipment as well as eliminate unexpected failures. The practitioner must thus decide where, when, and how to use prediction tools. In addition, maintenance policies must be coordinated with quality-control policies in order to reduce quality problems.

Few companies have reached this stage of TPM development. However, numerous companies attempt to utilize the basic predictive tools associated with this stage. For example, a large automotive company has one department dedicated to establishing predictive-maintenance tools and monitoring the equipment. This department is responsible for choosing prediction tools and for identifying the equipment to monitor; it also determines the monitoring frequency (continuous, daily, weekly) and schedules predictive replacements. Because predictive monitoring must be completed when the equipment is running, much of the maintenance technician's time is dedicated to proactive maintenance activities rather than fighting fires on an already inoperable line. We now review the literature that supports this and other Phase IV decisions.

3.3.1. REVIEW OF THE LITERATURE. Traditionally, equipment maintenance was treated as a method for increasing equipment availability. The goal of maintenance was to keep the equipment running. With the advent of quality-management efforts, however, the condition of the equipment became important to control the quality of the product. Several recent papers address the relationship between maintenance and quality. Tapiero (1986) considers the problem of continuous-quality production and maintenance of a machine. In his model, quality is assumed to be a known function of the machine-degradation state. He considers open-loop (based on quantity or age of equipment) and closed-loop (based on the equipment condition) stochastic control-maintenance problems. Rahim (1994) presents a model for jointly determining the economic production quantity, inspection schedule, and control-chart parameters for an imperfect production process.

Predictive maintenance is commonly discussed in trade journals; however, very little academic research focuses on this area. Paté-Cornell, Lee, and Tagaras (1987) begin to address some issues of predictive maintenance. They evaluate four maintenance policies: preventive maintenance, scheduled inspection of the process output, maintenance in response to equipment signals, and maintenance in response to output-quality signals. The authors test the various policies under different assumptions of the deterioration process, the signal accuracy, the risk aversion of the decision maker, and the reliability of maintenance. Based on the analysis, they recommend policies that perform best for certain environments. McKone and Weiss (1997b) consider the joint use of continuously monitoring prediction tools as well as periodic maintenance policies in order to minimize maintenance costs. They recommend that periodic tools *not* be abandoned for the use of predictive tools and provide decision rules for selecting the appropriate periodic policy when predictive tools are available.

Özekici and Pliska (1991) consider a system subject to catastrophic failures, deteriorating according to a delayed Markovian process, and subject to a series of binary tests that may yield negative or false-positive outcomes. Costs for inspection, corrective actions,

and failures are incurred, and dynamic programming is used to compute the optimal inspection schedule. This research helps to consider the optimal frequency of periodic predictive-maintenance tests. Like other inspection models, however, it assumes that the inspection reveals the current operating state and does not provide any information about the expected time to fail.

The quality literature clearly provides some support for this stage of TPM development. Tools and techniques that help to define, identify, and eliminate known and/or potential failures, problems, and errors in the system are important to equipment improvement efforts. For example, failure model and effect analysis (FMEA) (Stamatis 1995) helps to identify plant equipment and process problems that result in product quality problems. FMEA can help to link both maintenance and quality improvement efforts.

While this Phase IV research has considered the use of predictive maintenance tools, few models actually consider the capabilities and limitation of the available tools, such as vibration analysis, fluid analysis, infrared technology. Research needs to keep pace with the rapid advances made in predictive equipment. It also needs to provide recommendations for using the technology to increase equipment availability as well as to improve equipment operating performance.

#### 3.4. *Phase V: Design Life Span*

The fifth phase involves an organization-wide focus on plant productivity. First, design teams made up of engineers, maintenance workers, and operators prepare equipment so that cleaning and inspection standards are established and personnel are trained to produce effectively upon roll-out. Phase V decisions also consider other nonmaintenance systems, such as spare parts, raw materials, and production scheduling, that impact the equipment productivity and quality. Finally, efforts are made to eliminate losses in labor, energy, and materials in addition to equipment efficiency. The decisions in this phase primarily focus on organizational and systemic issues as different functional areas coordinate their efforts to improve productivity.

**3.4.1. REVIEW OF THE LITERATURE.** Few models truly describe Phase V decisions. Some research begins to address the coordination of decision making in maintenance and other functional areas. For example, Lee and Rosenblatt (1989) extend the classic lot-sizing problem by considering the effect of process deterioration and existence of defective items in the production lot. They address the problem of joint control of production cycles and maintenance by inspection and determine whether maintenance is worthwhile. When maintenance by inspection is adopted, it is shown that the optimal inspection schedule is equally spaced throughout the production run.

One area of the literature, most often referred to as life-cycle costing, considers the total costs of purchasing and maintaining the equipment over its lifetime. This literature is the first to indicate the need to incorporate maintenance decisions with equipment design and purchase decisions. Thompson (1968) considers the optimal maintenance policy and sale date of a machine to minimize the total cost. His approach, which has become a classic analytical model, evaluates the optimal initial investment and maintenance policy to minimize total life costs. The methodology minimizes the total costs of a system over its entire life. This model, however, ignores costs such as inventory, operating, and quality control.

Phase V involves a much more comprehensive approach to TPM. At this phase, functional areas within manufacturing must be carefully integrated. Essentially, all six TPM activities discussed in Section 2 must be coordinated for effective and efficient equipment operation. Studies that consider the long-term success of TPM programs and provide guidelines for effective implementation are important to reach and maintain Phase V performance.

### 3.4. *TPM Implementation*

Few maintenance studies have directly investigated current TPM maintenance activities. Thilander (1992) conducted a case study of two Swedish firms in an effort to define the benefits of the organizational aspects of TPM. The study shows the positive influence on productivity of having well-defined areas of responsibility, of appointing one individual who holds the overall responsibility for the maintenance of a machine line, and of establishing direct contact between the operators and maintenance technicians. McKone, Schroeder, and Cua (1997) study maintenance policies at 110 plants from Japan, Italy, and the United States. They identify contextual differences that help explain differences in TPM practices.

Other case studies of TPM have presented the TPM development story or examples of TPM improvement activities in plants (Varughese 1993; Shimbun 1995; Steinbacher and Steinbacher 1993, chapter 15; Hartmann 1992; Tsuchiya 1992; Suzuki 1992, chapter 4; Tajiri and Gotoh 1992). Each of these studies suggests steps for TPM implementation that are aligned with the TPM development phases. There is a further need, however, to tie the development process to the actual state of the plant and the abilities of the work force. For example, most organizations must determine how tasks should be allocated between maintenance and production resources.

Hartmann (1992) specifies many differences between TPM in Japan versus the United States. He emphasizes the need to customize the TPM process to work for the specific manager, in the specific environment, with the specific people. It would be interesting to consider the modifications that non-Japanese plants have made to the process.

In the future, empirical research should help identify successful TPM implementation policies. In particular, a large-scale survey of current maintenance practices would be useful for documenting the variety of program configurations. A study of autonomous and planned maintenance activities and their impact on manufacturing performance could help justify the investments in employees, time, and capital for TPM development.

## 4. Research Opportunities

The current maintenance literature does not sufficiently support the implementation of TPM for several reasons. First, the practitioner community does not have easy access to the research models. Few of the theoreticians who develop these models have made serious efforts to take the information from the journal (which practitioners generally do not read) to the plant floor.

Second, the methods described in this paper and other maintenance-review articles are often only optimal for very carefully specified scenarios that are not likely to occur in reality. To a considerable extent, the models solve the wrong problem. For instance, many of the problems are solved in a renewal-theory setting. The process fails, it is replaced, and the process is returned to its original condition. There are two problems with this assumption: (1) a system may deteriorate over the long haul and replacements may not return the system to its "like-new" condition and (2) after replacement, it is assumed that nothing is learned. This conflicts with the philosophy of continuous improvement.

Third, the existing literature takes a narrow focus of maintenance performance measures (typically limited to replacement, inspection, or failure costs or to equipment availability). In the past, much of the maintenance research has focused on cost management of inspection and repair activities. The models ignore other costs associated with maintenance, such as safety stock for unreliable equipment, the cost of poor quality due to inconsistent equipment, the cost of poor operating conditions, and the cost of equipment-improvement activities. Moreover, the models fail to relate maintenance management to the achievement of quality, delivery, and flexibility goals or to the improvement of employee safety and

morale. Future research should consider the relationship between maintenance management and other manufacturing priorities.

Fourth, there are significant gaps in the literature that supports TPM implementation. Figure 4 categorizes the research literature in this framework and demonstrates that major gaps exist between practice and research. Most of the maintenance literature has focused on Phase III. Practitioners clearly need assistance with decisions involving Phases I, II, IV, and V.

Decisions involving Phases I and II have generally not been supported by academic research. Additional research needs to provide justification for the substantial investment in time and resources needed for training and educating people in TPM principles and equipment tasks. Models that consider the opportunity to invest in cleaning and inspecting procedures or new equipment to change the form of the equipment-deterioration process will help provide this justification.

Most of the Phase III research has been developed prior to development of TPM and does not directly address TPM activities. An important goal of future research should be to relate the components of past research to actual TPM practices. The first step in this process will be to consider the benefits of particular types of TPM activities, such as continuous investment to maintain the environment, corrective-maintenance activities, periodic activities, and predictive activities. Models that help identify when each activity should be performed are vital to TPM development. Therefore, it will be important to develop models that simultaneously consider the use of multiple maintenance tools.

Another opportunity for Phase III research is to consider how to make transitions from Phase III to Phase IV. For example, many companies have become excited by the potential of predictive-maintenance diagnostic tools. This enthusiasm has led to quick adoption of the tools. Unfortunately, the transition from traditional preventive-maintenance policies to predictive-maintenance policies is not smooth. Problems arise because of imperfect prediction abilities, incompatible or nonstandard inspection intervals, or complete elimination of past preventive-maintenance procedures.

Phase IV research needs to consider how to incorporate the new predictive-maintenance tools into the current maintenance environment. The Phase III preventive-replacement and -inspection models will become outdated as companies progress in their TPM development. First, as equipment knowledge is broadened, prediction capabilities improve. Second, as the cost of predictive technologies decreases, companies are able to monitor equipment continuously. Future research should consider the nature (equipment, reliability, tracking information) and timing of the predictive information (when to inspect and respond to prediction signals).

	Phase I Reduce Life Span Variability	Phase II Lengthen Average Life Span	Phase III Estimate Life Span	Phase IV Predict Life Span	Phase V Design Life Span
Planned Maintenance	Waldman 1983	Chitke & Desmukh 1981 Anderson 1981	Reviews by McCall 1965, Pierskalla & Volker 1976 Valdez-Flores & Feldman 1989	Tapiero 1986 Rahim 1984 McKone & Weiss 1997 Ozekicic & Pliska 1991	Lee & Rosenblatt 1989 Thompson 1968
Autonomous Maintenance	Dada & Marcellus 1994 Fine 1988	McKone & Weiss 1995		Fate-Cornell, Lee, Tagarus 1987	

FIGURE 4. Categorization of Literature in TPM Development Framework

Research is also needed to evaluate the close relationship between equipment condition and product quality. Central to the reduction of final-product variability is the stability of the equipment process. For example, research that relates equipment performance to the Taguchi loss function for product quality could be important to the coordination of quality and maintenance policies.

A challenging issue for Phase V research is the coordination among maintenance planning, preventive and predictive activities, and scheduling. Past research has focused on the inspection/replacement interval and assumes that maintenance decisions can be easily implemented. This assumption needs to be challenged, and support for scheduling and planning should be provided.

This integration can also be taken a step further by evaluating the coordination of the maintenance function with production planning, inventory management, staffing support, engineering, and design. For example, one issue for Phase V is the ability to design equipment so that operators and maintenance personnel need not reimplement the first four phases of TPM development when new equipment is installed. Another issue is the design and coordination of process and quality control for equipment. Finally, to maximize plant effectiveness, it is important to consider applying TPM improvement concepts to increase the efficiency of the material and labor as well as the equipment.

Finally, although a scientific focus is important to TPM, the research discussed in this paper concentrates on the component tools rather than on the philosophical cornerstones of TPM. Like TQM, TPM requires two streams of research. The first stream should focus on analytical tools for decision making, control and measurement, and performance improvement. The second stream needs to focus on the organizational structure, the program methodologies, and the program design required for implementation. In the future, empirical research should attempt to establish a link between particular TPM practices and superior results.

In closing, we make several observations about TPM's challenge to researchers. First, we need to apply operations management research methodologies to TPM in order to put it on a firmer scientific footing than provided by the frameworks currently described in the numerous practitioners' books. Second, we must seek opportunities to translate theoretical results into practical implementation guidelines for the plant. While elegant mathematical models can be important to maintenance management, they must address issues that have a verifiable impact on plant performance.<sup>1</sup>

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<sup>1</sup> The authors acknowledge the support of Coopers and Lybrand in providing funding for a portion of this research.

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