Improving Maintenance Work Flow Processes in a Volatile Assembly Factory Environment: Maintenance People and Processes, Spares Inventory, and Equipment Reliability

by

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Submitted to the Department of Materials Science and Engineering
and the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of
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and
Master of Science in Materials Science and Engineering

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ABSTRACT

Many manufacturing companies face significant challenges in maintaining their factory equipment in a cost efficient manner so as to provide reliable production capacity. CEI (Consumer Electronics, Inc., a pseudonym for an electronics marketing, sales, and assembly company that this work is based on) is no exception. The factory maintenance organization at CEI, similar to many other companies, had been relegated to the status of necessary evil, a cost center that was necessary but not always effective or efficient. Historically, the maintenance organization had been almost entirely reactive in its approach to maintenance. This study reviews many ideas for how CEI could, consistent with management objectives, become more proactive in its approach to maintenance.

This work presents an investigation into the work flow processes inherent in CEI's factory maintenance organization and suggests improvements to the processes and the software infrastructure to support those processes that might be appropriate. Specifically the reactive (emergency) and preventative maintenance work processes are analyzed and suggestions to improve data integrity and to improve communication are presented - providing the maintenance technicians with better information with which to do their jobs. Improvements for factory spare parts management are also suggested describing how CEI could potentially improve its fill rate while holding significantly less inventory. The role of equipment analysis technology and materials analysis in predicting equipment reliability is also discussed.

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Chapter 1 Introduction

Many manufacturing/assembly companies face significant challenges in maintaining their factory equipment. The company, CEI (Consumer Electronics, Inc., pseudonym for an electronics marketing, sales, and assembly company) that this thesis is based on is no exception. The factory maintenance organization investigated at CEI, similar to many other companies, had been relegated to the status of necessary evil, a cost center that was necessary but not always effective or efficient. CEI placed large amounts of effort on getting product assembled and tolerated little that would hinder product shipment. There had been some cases where the maintenance organization would be blamed for missed production/shipment targets even when they were not or were only in part to blame. Also, historically the maintenance organization had also been almost entirely reactive in its approach to maintenance. The most recent maintenance management had come from the production operations organization and desired to change the perception of the maintenance organization and to improve the effectiveness and efficiency of the maintenance group.

Although the maintenance and other management at CEI had made some positive changes to the organization, some deficiencies in the information management systems and work flow processes were thought to exist. Specifically, improvement opportunities were thought to be available in the reactive maintenance, preventative maintenance, and spare parts inventory work flow processes. The performance metrics used in the organization were also shown to be thought to warrant improvement. The maintenance group had been experiencing situations were their current work processes were inadequate and those in the group reverted to crisis management, doing whatever they could to get the equipment running so that product could be shipped. The group knew there was a better way, wanted to find that better way, and wanted to implement it.

This thesis is based on a project associated with an internship at CEI undertaken as part of the Leaders for Manufacturing (LFM) program at the Massachusetts Institute of Technology. The project was to investigate the work flow processes mentioned above inherent in the factory maintenance organization and determine what improvements to the processes and the infrastructure to support those processes might be appropriate. This thesis contains that investigation and a number of work flow process improvement suggestions as well as suggestions for implementing those improvements. Discussion of the work flow processes, their problems, and potential solutions can be found in chapters 4, 5, and 6. Chapters 4 and 5 describe the reactive and preventative maintenance processes – current and proposed states. Chapter 6 describes the proposed improvements for spare parts management at CEI. This thesis also describes other ideas in the literature that would also be useful to a maintenance organization for becoming more proactive in its approach to maintaining the equipment for which it is responsible. A discussion of these ideas as background information and some of the materials aspects of maintenance and reliability can be found in chapters 2, 3, and 7. Chapters 2 and 3 deal with the history and thought regarding factory and capital equipment maintenance and supporting information management infrastructure. Chapter 7 describes the role of materials and equipment analysis technology in predicting equipment reliability.

Chapter 2 The History and Spectrum of Maintenance Philosophies

Reviewing some of the historical and current thought regarding maintaining factory equipment will provide context for later discussions of the specifics of the maintenance work flow processes and the general state of the maintenance organization encountered at CEI.

History of Industrial Maintenance

Figure 2-1 below describes some of the historical maintenance philosophies and methods used in maintaining factories. In the period leading up to World War II the prevalent maintenance philosophy was to only fix equipment when it broke. During this period factories tended to be more dependent on manual labor than on complex equipment to produce products. As such there was less focus on maintaining equipment. With the changes in the work force and production needs brought about by World War II these ideas changed. With the labor shortage due to the war came an increased dependence on mechanized equipment as well as more serious implications for equipment downtime. The concept of preventative maintenance emerged to help mitigate some of the risks of equipment downtime. Complex mathematical models also emerged to try to optimize preventative maintenance intervals. As capital and maintenance costs continued to rise and the safety concerns associated with some equipment (airline aircraft, etc.) became more important, other innovations came to the maintenance field. Some of these included condition monitoring or predictive maintenance and design for reliability or maintainability. (Moubray, p1-6 and Shenoy, p1-2)

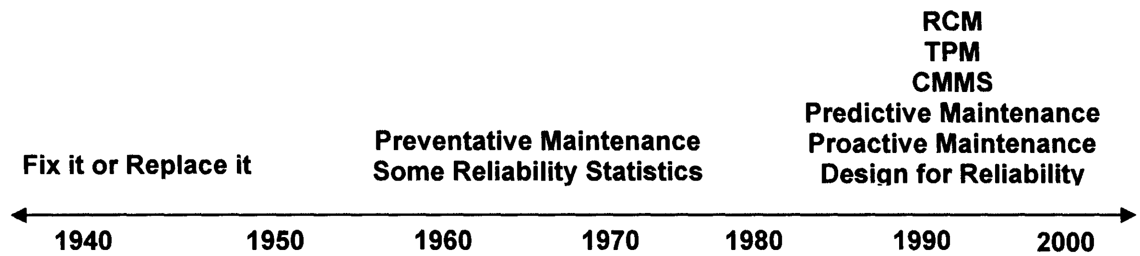

Figure 2-1 Maintenance Methods and Philosophies over Time (adapted from both Moubry and Shenoy)

Reactive Maintenance

Today, even though there are many tools and techniques available to the modern maintenance organization many maintenance groups are still operating with the "fix it when it breaks" or reactive maintenance philosophy. The obvious disadvantage of this philosophy is that the maintenance group cannot plan or predict the condition of its equipment well. They only touch the equipment when it has a problem. They have no control over their costs (expedited repairs and production typically are more expensive than planned maintenance and planned production) and can provide little guidance to their management about the condition of their equipment and hence have relatively unpredictable production capacity – the result of effective maintenance being capacity or higher probability of reliable capacity (Palmer, p4.2). Hence reactive maintenance organizations are on the far left of the spectrum of maintenance effectiveness as seen in the figure below:

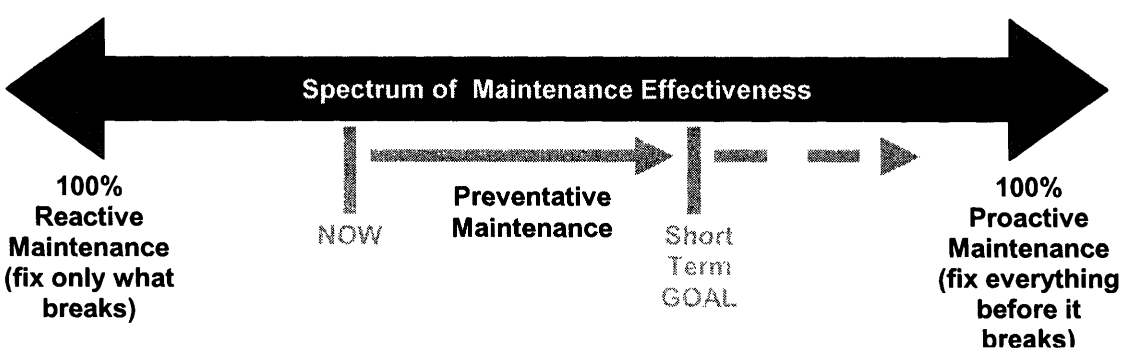

Figure 2-2 The Spectrum of Maintenance Effectiveness

Preventative Maintenance

The spectrum shown above corresponds generally to the history of maintenance – less sophisticated and perhaps less effective in years past and potentially more involved and effective now. Some firms still find themselves completely reactive with respect to their maintenance problems – they may be operating with outdated maintenance methods. Other firms have preventative maintenance programs organized to some degree for their factory equipment. These programs usually involve cataloguing some or all of the equipment in the plant and identifying tasks (inspections, replace/repair tasks, lubrication, calibration, or other adjustment/service tasks) to be done on the equipment at regular intervals. Preventative maintenance (PM) programs are generally better than purely reactive maintenance programs if they are well thought out to meet the real needs of the equipment and if they are consistently executed. There is some evidence however that over-zealous PM programs can actually increase the reactive repairs that are needed to maintain equipment due to tampering or other defect introduction (Moore, p232-233 and Moubray, p143). The costs associated with planned maintenance work should generally be lower than those associated with unplanned work (assuming that the equipment is in better health because of the preventative maintenance work) and as such there should be less need for reactive unplanned maintenance work. This is discussed in more detail later.

It should be stated that although a well executed preventative maintenance program is usually better than a purely reactive maintenance program (moving further to the right on the spectrum of effectiveness) it is not completely effective and in many cases does not completely address the maintenance needs of the equipment. The preventative maintenance philosophy is based on the assumption that all equipment failures can be properly addressed with regular and adequate servicing of the equipment, that a vast majority of failures can be addressed before some critical component of the equipment wears out or fails due to age. This assumption has been shown to not necessarily always be valid.

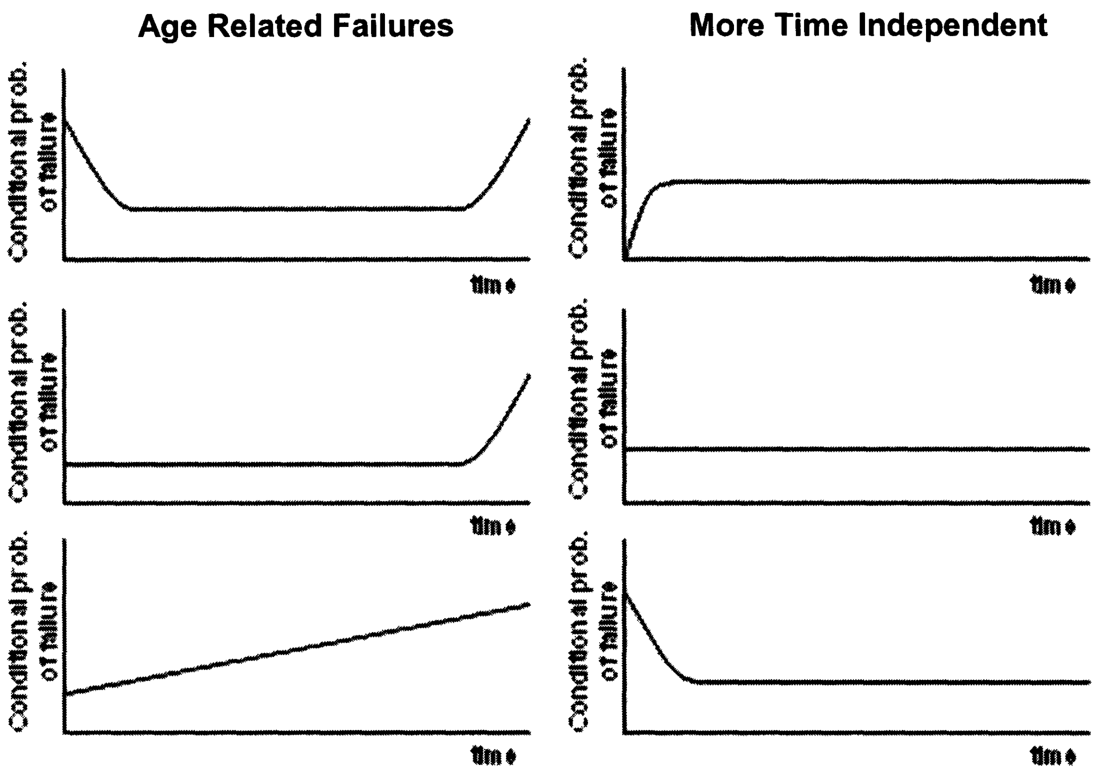

Figure 2-3 Observed Conditional Failure Probabilities Over Time (after Moore quoting Nowlan and Heap among others, p229)

Studies in the last 35+ years have shown that the conditional probability of failure of complex equipment as a function of time may or may not exhibit the behavior traditionally used as the basis for many reliability models, namely the top two "bathtub" or "wear-out" curves in the upper left of figure 3 above. This seems reasonable if we consider an example many are familiar with – automobiles. Even if the oil is regularly changed every 3 months or 3000 miles and other regularly scheduled maintenance is done on cars they still have some unexpected maintenance problems.

Two causes of time-independent failures are variable stress and complexity of equipment. Variable stress on equipment components whether due to operating conditions the machine was not designed for, incorrect installation, or unintended external stresses (i.e., forklift hits the equipment accidentally) all can contribute to increasing the likelihood of a piece of equipment failing. Abnormal non-design applied stresses to components can change their resistance to failure such that when another perhaps less severe abnormal non-design stress is applied to the component it fails (perhaps best described by the curve on the top right above). Complexity of the equipment can also affect the failure behavior of equipment. With more complexity comes more linkages, connections, and general opportunities for component and equipment failure. It is therefore relatively difficult to know all the failure probabilities of each component whether or not they are time-independent. The failure of the equipment can be thought of as time-independent perhaps best illustrated by the right-middle curve above. (Moubry, p140-143)

It should also be noted that in order to build reliability models that help maintenance managers understand how to predict when failures occur, a sizeable amount of historical failure data (or accelerated stress test data) is necessary. It is also highly desirable that the conditions under which the data is collected be controlled or consistent. These data or the circumstances to allow controlled collection of such data may not be available or practical given the variability associated with many production schedules in a real production environment. Basically, even if the probability of failure always increased with time as traditionally thought, the preventative maintenance intervals produced from those models would be guidelines at best (with some kind of confidence intervals depending on the data set and the confidence in that data set). Practically speaking using the experience of the operators and the equipment manufacturer's recommendations for PM tasks and frequencies may be the best path for initial implementation of a PM program. Once a consistent PM program is in place, data collection for reliability modeling can be done and data based refinements to PM frequencies can be made.

Proactive Maintenance

It can also be concluded based on the preceding section that something in addition to preventative maintenance tasks done at regular intervals is necessary to provide the most effective and consistent maintenance of industrial equipment. Many of the "beyond PM" ideas can be placed in the category of proactive maintenance. (However, it should be noted that PM programs are sometimes referred to as proactive maintenance as they are not reactive in nature.) Proactive maintenance can refer to any number of activities associated with proactively addressing the maintenance needs of equipment before it fails. Some of these proactive activities involve actively dealing with the equipment and other activities are associated with organizing the overall maintenance activities. Three areas of proactive maintenance will be considered in turn: Predictive Maintenance, Total Productive Maintenance, and Reliability Centered Maintenance.

Predictive Maintenance

The premise behind predictive maintenance, as the name implies, is that some measurable condition of the equipment can be used to predict when a piece of equipment is more likely to fail. Depending on the piece of equipment of concern many different parameters can be used. If we return to the automobile example predictive maintenance (sometimes abbreviated PdM) could, perhaps, be analogous to the "service engine now" light that illuminates on some dashboards indicating that some kind of action should be taken to prevent the engine from breaking down. Predictive maintenance techniques (also called condition-based monitoring or CBM) can be used to address some of the age-independent failure behavior seen in figure 2-3 previously. More will be said about predictive maintenance in chapter 7.

Total Productive Maintenance

Total Productive Maintenance (commonly referred to as TPM) is a maintenance philosophy and organizational concept made prominent by Seiichi Nakajima about the same time that TQM and other quality related initiatives were being popularized. In some ways TPM and TQM are quite similar. Both initiatives use the word "total" meaning that the whole company is to be committed to the effort. The basic philosophy involves getting operators and operations more involved in maintaining equipment in ways other than just notifying the maintenance group of broken equipment. The concept involves driving increased cooperation between operations and maintenance such that equipment operators take a role in maintaining the equipment (referred to as "autonomous maintenance"). Equipment operators are involved in equipment cleaning (potentially more rigorous than 5S* activities), completing simple equipment health checklists, and other simple maintenance activities (bolt tightening or simple lubrication are typical examples). This builds the operators' awareness of the health of the equipment, encourages the operations management to work more cooperatively with the maintenance organization, and basically puts more sets of eyes on the equipment looking for abnormal operating conditions.

TPM's goal is to get to zero breakdowns and zero defects. TPM focuses organizational effort into reducing production losses due to equipment downtime, equipment slow time, and process defects or yield. One of the key metrics used, "overall equipment effectiveness" or OEE, is basically an amalgamation of the three losses.

OEE = (equipment availability) x (performance efficiency) x (yield)

OEE essentially is the product of a downtime linked metric, a slow time or production rate metric, and a process quality yield metric. TPM activities are to drive an increase in OEE. (Nakajima, p1-2, 14, 27)

* "5S" refers to a set of factory organization and general cleanliness practices popularized first in Japan. 5 Japanese words that all start with the letter "s" describe the practices. The words and their translations are: *seiri* – organization, *seiton* – tidiness, *seiso* – purity, *seiketsu* – cleanliness, *shitsuke* – discipline. (Nakajima, p4)

Reliability Centered Maintenance

Moore's comparison of reliability-centered maintenance and TPM is instructive: "Total productive maintenance implies that all maintenance activities must be productive and that they should yield gains in productivity. Reliability-centered maintenance implies that the maintenance function must be focused on ensuring reliability in equipment and systems." (Moore, p316)

Similar to TPM reliability-centered maintenance (or RCM) is a holistic maintenance philosophy. Unlike TPM, RCM has its roots in the United States, in the airline industry. In 1978 Nowlan and Heap (employees of United Airlines) summarized the initial RCM principles. The approach focused on using a structured and logical approach to implementing an effective PM program. The program, as described could include "on-condition inspections" and "failure-finding inspections" which can be considered to fall under the heading of predictive maintenance. It is interesting to note that the logical approach to addressing maintenance for equipment (see Appendix 1) first focuses on safety, then "on-condition inspection", then "scheduled rework" and "scheduled discard", and lastly suggests redesign of the equipment as an option to increase equipment reliability/safety. RCM uses failure mode effects analysis (FMEA) to determine where the PM and PdM effort should be focused. RCM tries to assess what equipment is most critical and what failure modes are most severe and focuses reliability improvement efforts in those directions. The original RCM philosophy concentrated on equipment reliability. More recently the RCM philosophy (sometimes called RCM II) has come to include environmental concerns associated with equipment failures and equipment conditions. The originators of RCM, Nowlan and Heap, were instrumental in moving the maintenance field beyond the strictly preventative maintenance mindset (pointing out for example that many failures are age-independent).

Cost Considerations

Much has been said about equipment reliability and availability but it is clear that setting up and sustaining a consistent maintenance program costs money. For some, reactive maintenance may make sense if equipment is relatively inexpensive and quick to replace without dire consequences to the business, (Moubray, p13). Time required to set up an effective maintenance program and the manpower to sustain the maintenance effort are significant. Clearly some effort must be made to quantify the benefits of the potential increase in production capacity and reliability (reduced downtime) that a sustained effective maintenance program can bring.

Most of the benefits of a quality maintenance program can be seen in terms of cost avoidance – avoidance of costs tied to loss of production capacity (downtime) and the associated need to make up lost production time with overtime. The cost avoidance can also come in the form of avoidance of spare parts costs associated with poor equipment health or in the form of needing fewer technicians to maintain equipment. While financial justifications based on cost avoidance may not be desired at some firms they are a reality for most projects considered by a maintenance organization.

To understand the magnitude of the benefits of a more proactive approach to maintenance, it may be helpful to consider the following table.

	Base Case Profile	**Effects of Various Practices**							
Reactive	58%	<30%	<15%						
Preventative	27%			>50%	>60%				
Predictive	7%					>10%	>25%		
Proactive	8%							>10%	>20%
Maintenance Costs (as a % of Plant Replacement Value)	100%	78%	44%	72%	59%	75%	42%	58%	47%

Table 2-1 Maintenance Costs (adapted from Moore, p224)

The left most column is the base case that describes average percentage of effort spent in the average plant. The study this table comes from assessed maintenance costs as a percentage of plant replacement value. The average plant replacement value was normalized to 100%. It can be seen that as less effort is put into reactive activities or conversely more effort is put into proactive activities the relative costs of maintaining production reliability decrease. For example, plants that put <15% of their effort into reactive maintenance have only 44% of the base case maintenance costs in terms of plant replacement value. The same study indicated that those plants with more proactivity did better at spreading their maintenance effort around – those plants with more than 25% predictive maintenance had less than 25% reactive.

Organizational Considerations of Different Maintenance Philosophies

The values of any culture can be seen in where and how the people in that culture spend their time. Maintenance organizations are no different. Benchmark maintenance organizations spend less on reactive repairs - largely because they don't need to. Their equipment is typically more healthy. A comparison between typical and benchmark maintenance organizations is shown in figure 2-4 below.

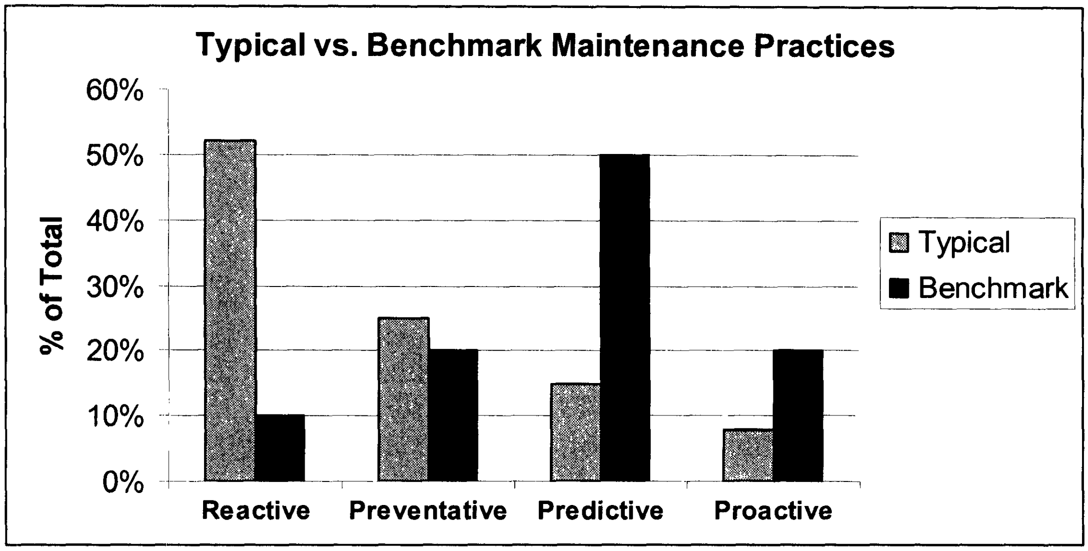

Figure 2-4 Typical vs Benchmark Maintenance Work Content (adapted from Moore, p223)

It can be seen that benchmark maintenance organizations expend a majority of their maintenance effort on things other than reactive maintenance. About 90% of maintenance is planned, scheduled, or proactive compared to less than 50% of maintenance being planned, scheduled, or proactive at typical factories. Being able to plan and hence schedule the preventative, predictive, and other proactive maintenance activities allows a less disruptive and more cost effective approach to delivering manufacturing capacity reliability.

Making the transition from being a reactive maintenance organization to a proactive maintenance organization is a significant challenge. Typically, those in the reactive mode complain of thing like never having the time to do preventative maintenance activities or even think about doing predictive maintenance activities or start other proactive efforts. As the culture focuses on reactive effort its attitudes are also very reactive – finger pointing and assigning blame for equipment downtime are not unusual.

It would be reasonable to assume that more proactive organizations focus on working together with all stakeholders (technicians, planners, engineers, and operations as appropriate through TPM efforts and work scheduling, etc.) to deliver reliable production capacity. It would also not be surprising to learn that these maintenance organizations tend to have healthy relationships with their operations or production management groups. The production management group recognizes the value of an effective maintenance group and the maintenance organization recognizes that they support the revenue-providing production group in delivering product to the customer. The two organizations would work effectively together without acrimony.

Current Philosophy and Culture of the Maintenance Organization at CEI

In the years prior to this study, the maintenance organization at CEI had had a number of senior managers. Some of these managers were more effective than others. The group had little consistency in its effort other than being reactive in its approach to maintenance.

Shortly before the beginning of this study at CEI the relatively new PM planning and scheduling team, had expended much time and effort in cataloguing, organizing, and labeling all the equipment they were responsible for in the most equipment-dense factory for which they had responsibility. They had also begun performing selected PMs (those thought to be most necessary) on their equipment on a regular basis. The result was that the organization had begun to move away from being purely a reactive organization. They were moving to the right on the spectrum of maintenance effectiveness.

Both the senior manager of the maintenance organization and the person in charge of the PM effort had come from operations/production-control and had personal relationships with the management in the operations/production-control groups. Thus they could more easily facilitate the scheduling of what were thought to be the most necessary PMs in gaps in the production schedule. All that being said there were still semi-regular conflicts between maintenance and operations in scheduling work – operations still, in many cases, did what it wanted to do when it wanted to to meet the production schedule.

The senior manager had been stressing proactive maintenance work and applauded the efforts of the people that put the PM program in place. He regularly stressed his desire that the group move to a more proactive stance and was trying to gain resources (money and headcount) to move the organization in that direction. It was in this environment that this study began at CEI.

Chapter 3 Computer Assisted Maintenance Management

Many larger manufacturing companies use computers to help manage some of their maintenance activities. Some use simple spreadsheets but many use what is called a CMMS (Computerized Maintenance Management System) or EAM (Enterprise Asset Management) system. There are over 300 CMMS applications available (www.plant-maintenance.com). They range in price from hundreds or thousands of dollars to many hundreds of thousands of dollars depending on the application's capabilities and the scope of the implementation – number of users and number of facilities.

As shown in figure 3-1 below CMMS applications are essentially a software tool that assists in storing data relevant to the maintenance organization and facilitates the flow of that information according to the users' needs. As the figure indicates a CMMS will typically contain a database of all the equipment maintained in the factory. This database will contain all relevant information associated with the equipment (PM tasks and frequencies, associated spare parts, work order history, etc.). The application will also allow the user to generate many types of what are typically called "work orders" to record work performed on the equipment. These work orders will contain information on the nature of the work performed (planned or unplanned), spare parts consumed, the technician who performed the work, and the time required for the job. Many modern CMMS packages also allow the users to quickly retrieve desirable information about the performance of equipment and the performance of the maintenance organization. The more advanced packages use 3rd party reporting software to query the database tied to the CMMS and clearly represent the desired data.

The effectiveness of a CMMS is directly related to the quality and quantity of information contained in the system. Because of these and other factors many new CMMS implementations are not considered successful – some put the number of implementations perceived as successful at or below 50%. (Moore, p277-279 and Palmer, p8.1)

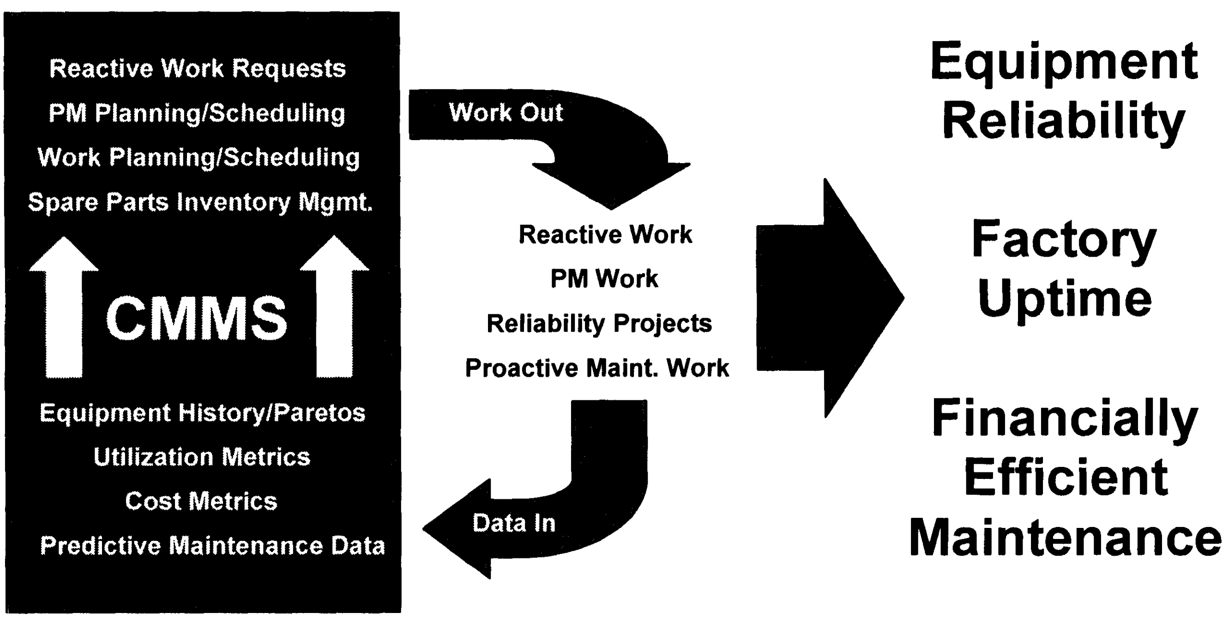

Figure 3-1 The Purpose and Functions of a CMMS

CEI also had a CMMS. The system had been used with various levels of intensity since its purchase in the late 1990's. A majority of the maintenance work flow processes were tied in some way to some kind of software package – but not all work flows were tied to the CMMS. The emergency (hereafter referred to as "reactive" or "unplanned") maintenance work was managed by a software application that CEI had developed internally. The PM work flow processes were managed in CEI's CMMS. The spare parts inventory was catalogued in the stock room system with weekly updates to CEI's CMMS. There was also a web-based "stock-out" application to record and track spare parts stock-outs. Because of the many disparate software applications it was tedious to compile all the desired maintenance performance metrics in one place. For example, failure data about equipment was available to some degree but that data and the PM records were not available in the same system making large scale analysis difficult. Equipment histories could not be easily obtained despite the fact that many of the equipment engineers interviewed expressed interest in getting equipment histories. Many of these factors (along with others) drove the management at CEI to consider replacing the existing CMMS with a new CMMS.

Because a majority of the maintenance work flow processes were tied to a software application it naturally follows that the implementation of a new CMMS would provide opportunity to implement a new set of work flow processes. The management wanted to create more effective and more robust work flow processes that would be then "hard-wired" into the new CMMS. Many advanced CMMS packages allow the user, as part of the software implementation process, to configure and/or customize the software to the business needs of the implementing organization (instead of having the CMMS dictate the business process completely). Because the replacement CMMS was integral to the implementation of many of the proposed improvements to the work flow processes the author compiled a CMMS configuration/customization specification left for CEI to be used in the implementation of the replacement CMMS.

What follows is a discussion of the analysis of the "as-found" maintenance work flow processes (chapter 4) and then a discussion of the changes thought to make the processes more effective and robust (chapter 5).

Chapter 4 "As-found" Work Flow Process Analysis

As previously discussed, CEI's maintenance organization had devoted a significant amount of effort to cataloguing and organizing the equipment information before this study began. This had been done by correcting and populating their CMMS. Numerous previous maintenance managers had tried to clean up the CMMS equipment database but had never put enough consistent effort into it to see any results. The maintenance group had begun to consistently work with their CMMS and had been doing selected preventative maintenance (PM) tasks regularly. However, their PM process was different for different factory buildings. The PM process was also paper based. The organization's process for handling emergency equipment problems was completely handled outside the CMMS as were a majority of their non-PM related performance metrics.

What follows is a discussion of the “as-found” work flow processes for reactive/emergency work orders, preventative maintenance work orders, and spares inventory. There will also be a brief discussion of the performance metrics being used at the time of the study. Following the process descriptions will be a discussion of the methods used to understand the potential weaknesses of the processes.

Reactive Work Order Process

Even world-class maintenance organizations deal with some reactive maintenance. This company, even with its recent improvements, was still dealing with more reactive maintenance than it desired. The reactive maintenance work flow process was completely separate from the organization’s CMMS. The organization had a web-based internally produced program that tracked what CEI called “trouble tickets” (reactive work orders). As shown in the figure below, when operations experienced an equipment problem they would call the maintenance dispatcher on the phone. Based on the information given from operations, the dispatcher would input a trouble ticket into the system and give the operations person a trouble ticket number for their reference. The maintenance technicians on the factory floor could take tickets if they were not assigned them automatically by the system. The ticket’s age would be indicated by the color displayed in the software interface (red for the trouble ticket that had been open for a lengthy period of time). High criticality tickets would be indicated by the severity level assigned the ticket. The management was notified of high criticality tickets by text page. If spare parts were needed the technician went to the tool crib and got them from the 3rd party inventory service provider. Once the repair was complete the technician filled out and corrected (if necessary) the needed trouble ticket information (time to resolve the ticket, trouble code, and location, etc.).

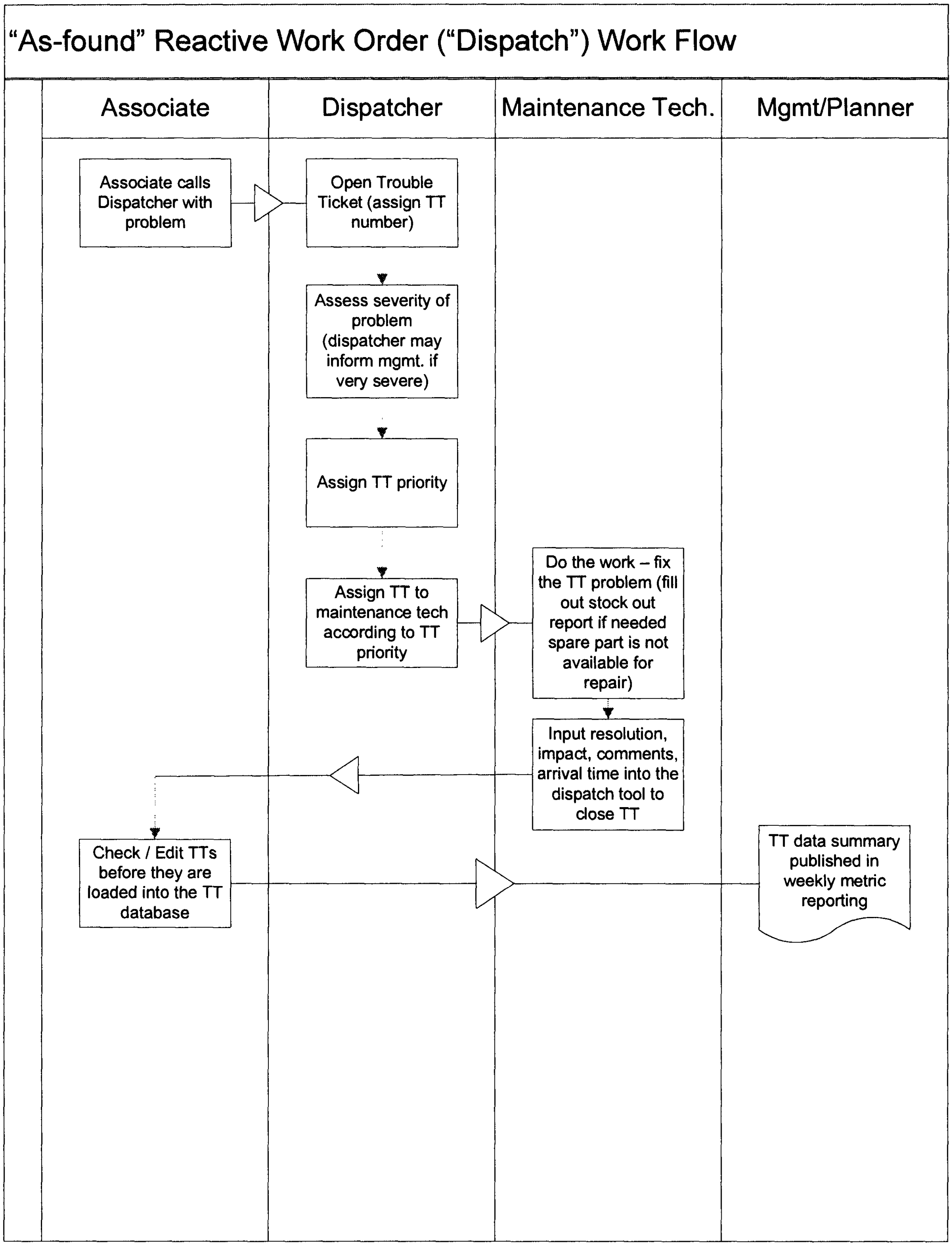

Figure 4-1 "As-found" Reactive Work Order Process

Preventative Maintenance Work Order Process

Preventative maintenance work order planning and execution was somewhat different for different buildings for which the group had responsibility. The preventative maintenance planner for one building would consider the whole quarter's PM work orders when planning the PM activities. The PM planner for another building would look only at the PMs shown to be due in the CMMS for the relevant week. The PM planners would sometimes check with inventory control to make sure that potentially needed parts were available to help facilitate PMs (although fewer than 10 PM tasks required consumption of spare parts there were many instances where PM tasks revealed issues that would be prudent to address especially when the PM program was first started in earnest). The planners would *print out* the PM work orders to be transferred to the relevant maintenance shift manager, PM champion, or contractors for completion. The PM technicians or other assigned technicians would complete the PM work orders (if they were not called on or told to do something else by management) and arrange for the paperwork to be returned to the PM planners. The planners would then manually enter the completed PMs in the CMMS (completion time, materials consumed, technician comments, etc.). There had been numerous instances where paperwork had been delayed or lost or not filled out correctly despite numerous attempts by the planners and their management to address these problems.

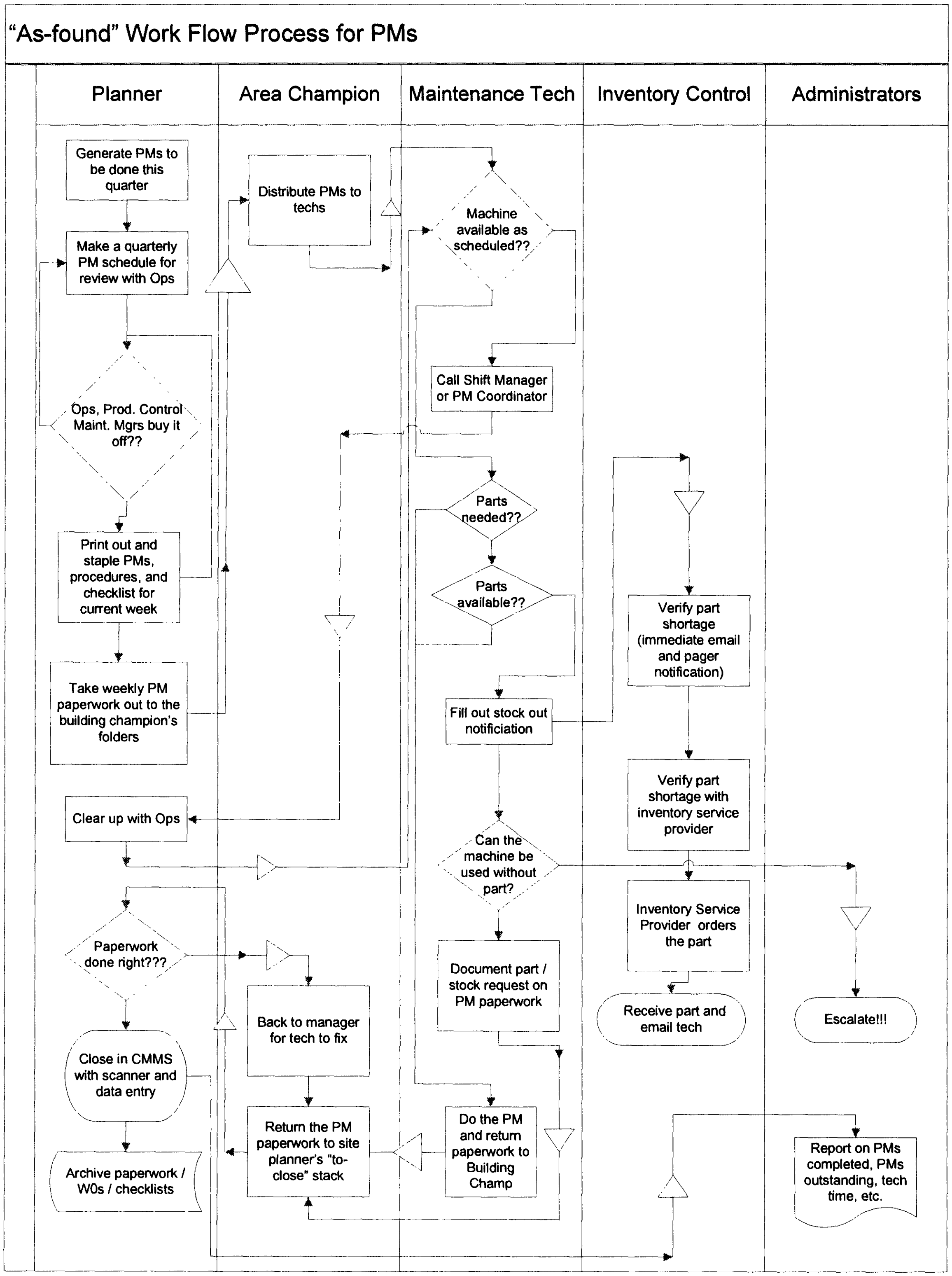

Figure 4-2 "As-found" PM Work Flow Process

Spare Parts Inventory Work Process

As mentioned previously the spare parts management function was largely handled by a 3rd party inventory service provider although CEI had one person devoted to handling spare parts issues. This individual would work with the service provider to track down part information for stock-outs, create part numbers for spare parts for new pieces of equipment, and work on other special parts related projects. The 3rd party service provider would do all of the part ordering (using information and re-order points provided by CEI), receiving, and storage as well as cycle counting. The service provider tracked parts as they left the tool crib with barcode scans. As was seen in the previous figures the inventory processes were integral to the other maintenance work flow processes. Two of the main work flow processes not totally integrated to the trouble ticket or PM processes were the stock-out and repairable spares processes.

The stock out process involved using an internally developed, web-based software application to record the spare part deficiency. The technician had to go to a computer and enter the part information. This information would then get passed to CEI inventory person and the service provider to work on getting the parts in. If multiple stock-outs came in for the same part in a short time window it was counted as only one stock-out.

Assessing the processes

CEI management was interested in developing improved and more robust work flow processes. As such FMEA (Failure Mode Effects Analysis) was chosen as the analysis tool for the processes of concern. Initially, it was thought best to work on FMEA for proposed future processes but as the work went on it became more clear that it would be better to work through FMEA on the current processes and use the results to help finalize the recommended future processes. FMEA-type exercises were completed with not only the PM planners but with one of the PM crew members. FMEA-type feedback was also solicited from the dispatcher and from a few of the dedicated trouble ticket technicians. FMEA feedback was also obtained from CEI spare parts inventory owner and the 3rd party inventory service provider. In addition to requesting FMEA type feedback targeted interviews with maintenance technicians (management suggested technicians) were conducted concerning the reactive work order process and the spare parts management processes.

It should be noted that not all of those who contributed to the FMEA feedback were familiar with FMEA or necessarily knew that they were contributing FMEA feedback. Some of the technicians interviewed were not told how the data they were contributing would be compiled although it was explained or implied that the goal was to improve the work flow processes. Some may think this tactic less than forthright but it was done in an effort to minimize the bias in the information gathered. As will be discussed later even though the data compilation method was not completely explained there were some significant differences in the responses depending on the standpoint of the individual contributing the information.

Analysis of the Reactive Work Order Process

Based on information gathered on the reactive work order process, a number of potential failure modes were generated. Following typical FMEA technique, severities, occurrence rates, and detectabilities for each failure mode were assigned. Using this as a baseline the dispatcher as well as one senior technician were approached for confirmation of the assessment of the process. Email feedback from two technicians on the assessment was also received. They were asked to validate or propose changes to the severity, occurrence rate, and detectability values for each of the failure modes and contribute any other failure modes that had not been considered. A number of changes were requested. The changes requested in a number of cases effectively deprioritized or de-emphasized failure modes that had to do with their job function or prioritized failure modes that caused them aggravation.

The ratings associated with each failure mode were averaged and the risk priority number (figure of merit used to assess failure modes with the most risk – a higher number indicates more risk) for each potential failure mode were calculated. The 6 failure modes with the highest risk associated with them according to the FMEA assessment can be seen in the table below:

Potential Failure Mode	RPN
inaccurate equipment identification	576
incomplete or inaccurate data used in reporting or reported	343
operator gives the dispatcher the wrong information	336
inaccurate hours allocated in repair	336
incomplete work order comments	294
equipment not set up in the system properly - hard to assign equipment to work orders correctly	280

Table 4-1 Reactive Work Flow Process Highest Risk Potential Failure Modes

A common theme in the most serious problems listed above is data integrity. This theme repeats itself throughout this study. It is problematic for executing a timely and effective repair if the technician is given the wrong information about the nature of the problem (location, problem description, etc.). It is also problematic for record keeping and data gathering for proactive activities if accurate information is not recorded. (It should be noted that senior technicians "audited" the work order records and corrected them on a regular basis – nearly all of the 40+ work orders the author saw audited needed some kind of correction).

Some of the process problems were further investigated in subsequent interviews (the email sent to set up the interviews included a scaled back version of some of the failure modes listed above that didn't implicate the technicians' actions directly as the source of process problems). Technicians interviewed expressed concerns recording how time ("wrench" time, "observation" time, "parts" time, etc.) was dealt with in the trouble ticket application. Modifying the trouble ticket application to be completely web-based (allow web-based entry of trouble tickets directly by operations people) was also raised as a possibility – under the assumption that by eliminating the information middle man (the Dispatcher) the data might flow more cleanly or at least there would be more accountability for the accuracy of the data. Concerns were also expressed about the locations listed for the equipment set up in the trouble ticket application and the problem codes used to generally describe the problem encountered by the technician. Again, a common theme was data integrity. An improved and more robust process was needed to address this and other less than optimal realities of the "as-found" reactive work order processes.

Analysis of the Preventative Maintenance Work Order Process

Similar to the analysis of the reactive work order process a baseline FMEA was prepared for the preventative maintenance work processes. Feedback was then gathered from the PM planning and scheduling team and from one of the senior PM technicians. The PM planning team provided a number of additional potential failure modes and modifications to some of the failure modes that had already been listed in the baseline assessment. Similar to the analysis of the reactive work order process, the analysis of the PM work order process was potentially biased by those contributing the information desiring to influence future processes or make their job function appear in a better light (despite the fact that FMEA is supposed to be an objective process that focuses on *process* weaknesses, not employee weaknesses). As can be seen in the table below there are significant differences in the top 14 most risky potential failure modes and in the magnitude of the RPNs attached to each of them.

PM Technician FMEA		PM Planner FMEA	
Potential Failure Mode	RPN	Potential Failure Mode	RPN
no parts in stock	700	wrong MIN/MAX	1000
weekend priorities change – PM work gets deprioritized	640	duplicate stock outs don't exist (only order to MAX)	1000
engineering work that doesn't have paperwork done instead of PMs assigned	640	***incomplete PM documentation (no part numbers)	1000

tech cannot find part even though it is physically at CEI (nomenclature problems)	640	***incomplete PM documentation (no hours or other)	1000
critical comments on PMs are not recorded or tracked	640	***no tech name, stock out, time, date, finished checklist, comments, etc. on PM	1000
no procedure available (either from mfg or CEI - nothing with new equipment)	560	using paper (JLR) to distribute and document PMs	1000
no part set up in the inventory for the machine	560	tech cannot find part even though it is physically at CEI (nomenclature problems)	800
wrong MIN/MAX	560	wrong part ordered	800
requested work order from PMs are not created	540	requested work order from PMs are not created	800
incorrect info gets past planner QC check	480	excessive work - overtime, ops mgr, tired	720
Wrong frequency (too little)	448	tech doesn't submit parts request or stock out	700
ECN not entirely implemented	448	techs not available (vacation, absenteeism, etc.)	640
duplicate part numbers	432	no parts in stock	640
Techs are told to do something else by mgmt (other prioritized over PMs)	400	no part set up in the inventory for the machine	560

Table 4-2 PM process FMEA from two perspectives (colors indicate identical items)

It is interesting to note that the spare parts availability and associated processes were seen as more risky/critical by both the technician and the planners (this even though there were fewer than 10 PM tasks that required parts to be replaced). Other similarities include concerns about data integrity – clearly the planners were very concerned about the accuracy (or mere presence or absence) of data coming back with the PM paperwork. It is also interesting to note that both sets of data indicate concern about factory equipment change management (equipment entering or leaving the factory) or lack thereof influencing scheduled PM completion (it was #16 on the RPN pareto for the planners compared to #12 for the technician). Given some of the significant disparity in the responses, the insight of the person who managed the PM planning team was sought. Not surprisingly, she had her own thoughts on what should be focused on as the organization strove to improve the PM processes. She indicated that technician training needed to be done so more people could do more varied jobs (perhaps a more organizational than process related problem), decreasing equipment availability for PMs (requiring greater flexibility in scheduling and executing PMs), and the changing priorities of the organization were the largest concerns that the organization should be dealing with.

Analysis of the Spare Parts Inventory Work Process

The spare parts inventory processes were also investigated as part of the study. Again, a baseline FMEA for the general inventory processes was produced and used to solicit feedback. Feedback was gathered from two sets of technicians and the 3rd party inventory service provider. The FMEA responses were averaged and the failure modes shown to have the highest risk are shown in the table below.

Potential Failure Mode	RPN
distribution of warranteed spares from the store room	900
parts not assigned to a hierarchy of equipment	900
no description or unintelligible description of spare	780
no notification of equipment LEAVING the factory (removing need for some inventory)	594
word doesn't get out that critical spares have arrived	576
parts removed from stock room without a work order or other notification	576
parts lost between receiving and stocking	560
duplicate part numbers created or maintained	512
parts are stocked in the different location than that documented	490

Table 4-3 Highest risk Spare Parts Inventory Failure Modes

While one of the technicians solicited for feedback agreed completely with the baseline FMEA there was some disparity in the responses from the other technicians (one set of technicians covered reactive work and the other covered PMs more often). Perhaps surprisingly there was relatively little disparity in the responses between the technicians and the 3rd party inventory service provider. The largest disparities were differences in assessing the severity of potential failure modes. Not surprisingly each group rated failure modes more important or more annoying to them as having higher severity (the service provider was penalized for stock-outs and the technicians had complained about some of the processes around warranteed and repairable spares). This again raised the question of biases in the data collected.

Similar to the methodology used to validate the findings with respect to the reactive work flow process high risk areas, many technicians were also interviewed and asked about the inventory processes (in the same interview the technician typically was asked about both the reactive and spares inventory processes). The interview responses suggested that there was a lot of dissatisfaction about the way the spare parts were catalogued which is in line generally with a few of the items shown in the table above concerning part numbers, part descriptions, and associating part numbers with equipment. There was significant desire to be able to cross reference different part numbers to try to find the parts that were needed in the stock room (sometimes the technician would only have the OEM part number or the part number in the equipment drawing but would not be able to find the service provider part number to be able to locate the part in the stock room or order it from the equipment maker). Even though it did not show up as the highest risk failure mode there were many comments and concerns with how stock-outs were handled. There was an internally developed application to track stock outs but one technician said, "why should I have to tell [the third party inventory service provider] that they are out of parts?". Second shift stock room coverage by the inventory service provider was also a concern. It was also suggested that separate stocks be maintained for different purposes (reactive fix, PM, project, etc.). This point will be revisited later.

"As-Found" Maintenance Performance Metrics

The performance metrics generation was split up among the different I/T systems supporting the organization just as the maintenance work management was. The metrics for the reactive maintenance work and spares inventory were generated by internally produced applications and the corresponding performance data for the PM work was pulled from the CMMS database. This, of course complicated the data collection. While the relevant data sets could be queried to produce the desired reports, the data was not all stored in the same place and non-standard reports took some time and expertise to build.

Another key problem with the performance metrics as-found was the lack of a link between individual maintenance work orders and the consumption of spare parts. Labor hours were tracked on work orders but spare parts were not individually charged to work orders. The I/T infrastructure that existed at CEI and the 3rd party inventory service provider made potential implementation of a system to charge spare parts consumption to work orders more difficult (as did the tenuous contract between the two parties). Because there was no direct link between work orders and spares consumption and because there were disparate I/T systems covering different types of work on specific pieces of equipment, calculating a total cost of ownership (i.e. total annual maintenance cost divided by replacement value) for a specific machine was difficult. Management recognized this deficiency. It was one of the key drivers behind the effort to unify the I/T infrastructure with a replacement CMMS.

Chapter 5 Future State Work Flow Processes

Given the learnings gained in doing the FMEA and interviews it was clear that, as CEI's management suspected (and as most people in the organization knew), the maintenance work flow processes could be significantly improved. The management wanted to incorporate the process changes into the implementation of a new CMMS. Potential changes and improvements for each of the processes reviewed and analyzed in the previous chapter will be considered in turn as will new performance metrics.

Future State Reactive Work Order Process

As mentioned in the previous chapter's analysis of the reactive work order process there were a number of different ways that information about equipment problems could be inaccurately communicated and/or inaccurately reported. This resulted in lost production and technician time while the technician looked for the trouble spot in the factory (location was inaccurately communicated and/or the problem was not described correctly) and wasted time in correcting inaccurate work order records to be used in determining needs for increased equipment reliability. Both types of problems reduced the effectiveness of the organization. The root of the problem was partly due to the way the process was set up and partly due to the way the software system handled the trouble tickets. Any new process needed to address these problems.

The new proposed process, as contained in the new CMMS configuration/customization specification that was written as part of this study and reviewed with many stakeholders, brought the trouble ticket software application into the CMMS. This change was suggested by the management as the study was beginning. This would help consolidate much of the software infrastructure supporting the maintenance organization. This would also allow the technicians to help set up the trouble ticket equipment information afresh – in other words the inaccurate equipment association hierarchies and location information could be fixed and the trouble codes for each piece of equipment could be simplified and made more relevant to the equipment then existing in the plant.

Additionally, as seen in the flow chart below, the potential new dispatch function would ask specific and consistent questions of the person reporting the maintenance problem. It should also be noted that the CMMS customization/configuration specification was written in such a way that it would accommodate the internalization of the dispatch function into the CMMS. Under this process the operations supervisors or those given access to the system would submit their maintenance work requests directly to the CMMS and hence those individuals would be responsible for the data provided. This suggestion was a controversial one. One group had successfully done something similar at CEI but some felt that the relationship between operations and maintenance would not support such a process.

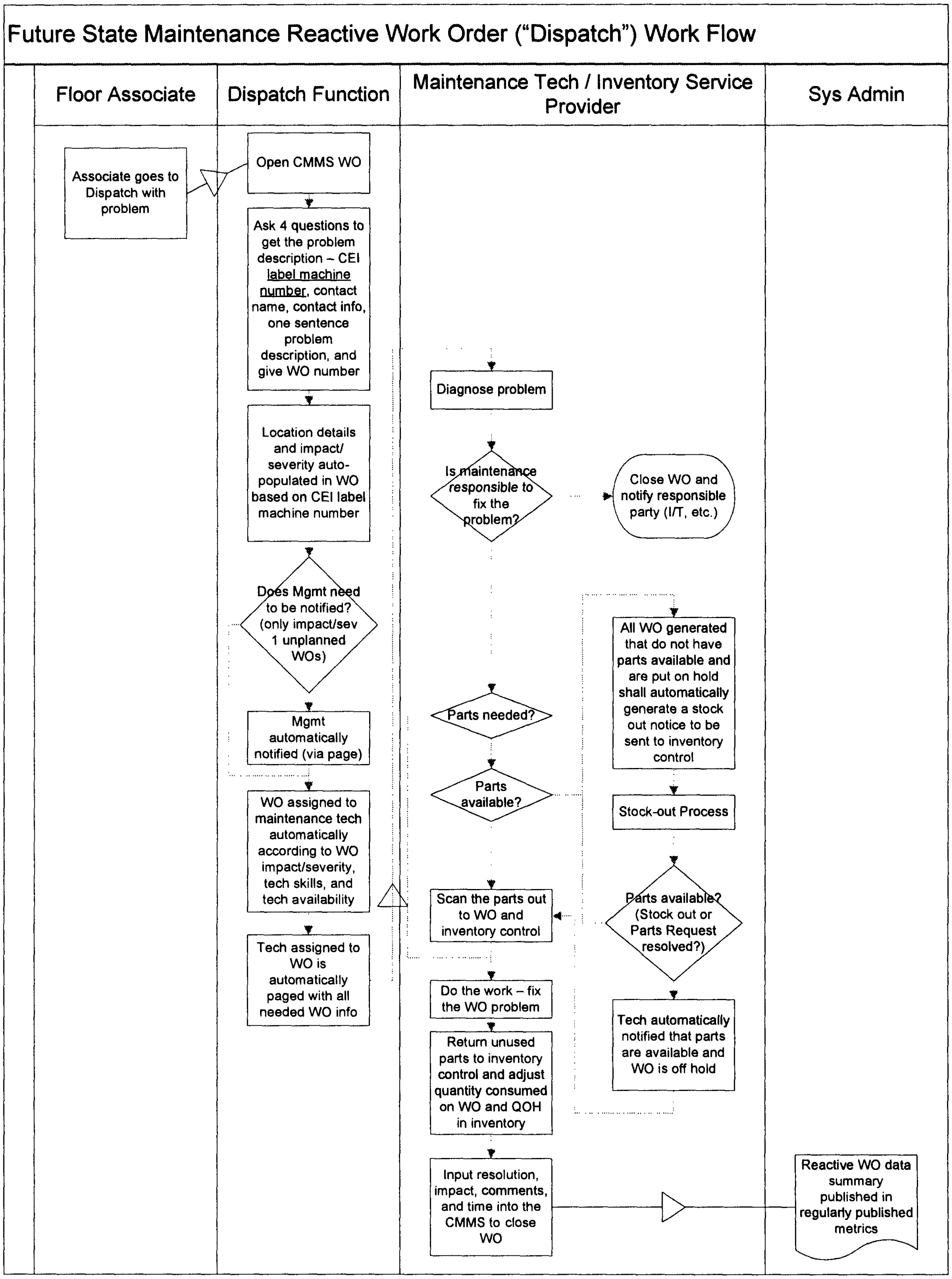

Figure 5-1 Proposed New Reactive Work Process Flow

It should also be noted that the above process shows that spare parts used in reactive fixes to equipment would be charged to work orders ("WO" in the flow chart). As mentioned before, the implementation of this would be non-trivial. Although not all of the highest risk reactive maintenance process failure modes would be addressed by the new process proposed above, the implementation of a new CMMS and the associated incorporation of the reactive maintenance processes into that CMMS would allow the organization to set up the work order data in a manner that would provide more accurate and more useful data to the technicians who need it and allow for better performance metrics as well (i.e., equipment histories and total cost of ownership with spares to be charged to work orders). If careful effort is put into a new CMMS implementation, and the CMMS database is accurately and regularly updated, the proposed new process for reactive work orders could substantially improve the maintenance organization's performance.

Future State Preventative Maintenance Work Order Process

The previous chapter outlined some of the potential process problems associated with the preventative maintenance work flow process. These problems could be categorized as concerns about spare part availability, data integrity, and flexibility in execution of the PM work. (It is perhaps odd to note that the maintenance organization wanted more flexibility so that that they could be more reactive to the ops schedule.) The suggested future process as seen in the flow chart below would try to address these concerns.

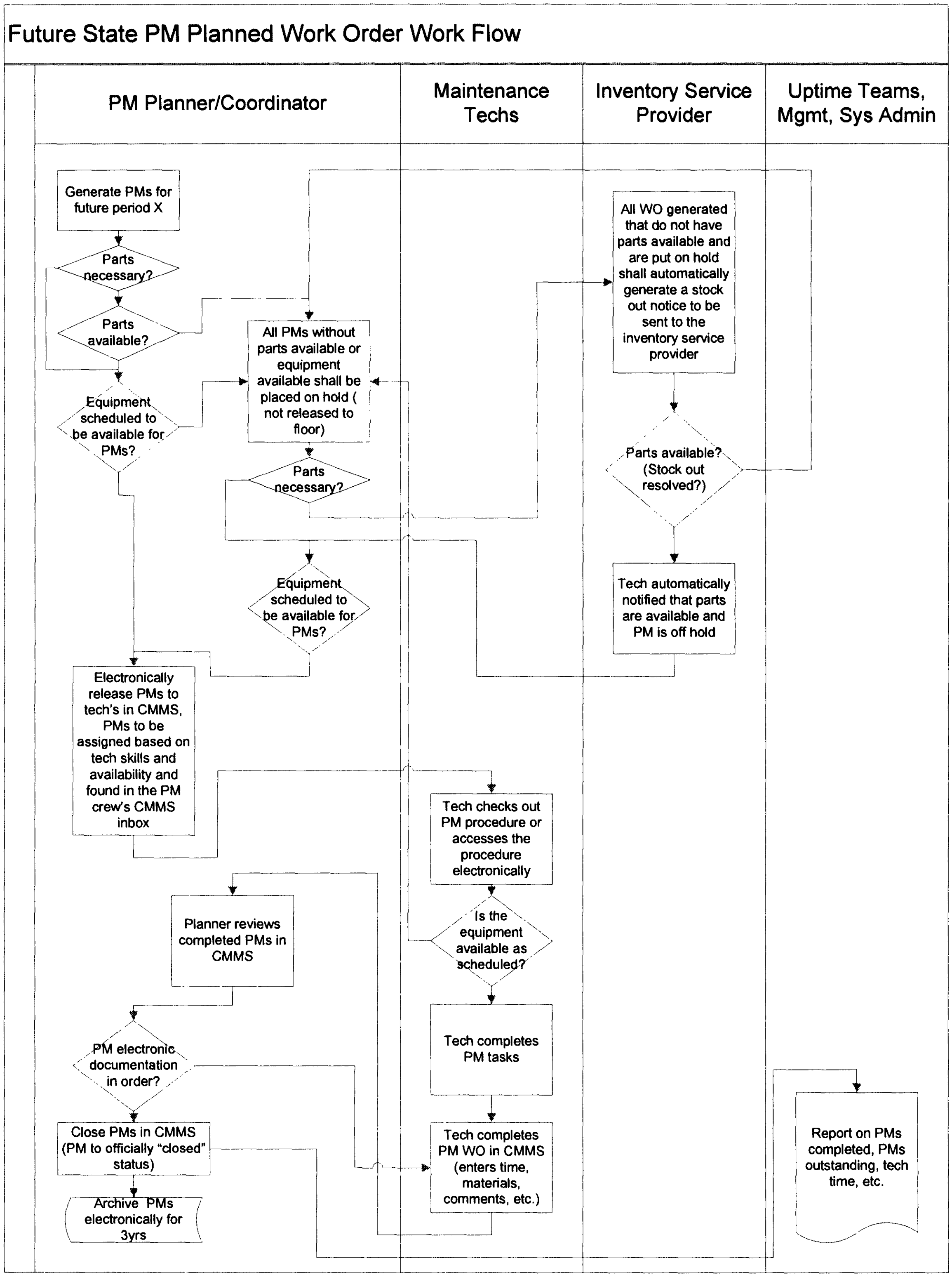

Figure 5-2 Proposed New PM Work Process Flow

While the process above is in many ways very similar to the as-found process, there are some significant differences. The process above provides for electronic distribution of the PM work orders and electronic completion of them by technicians. This would eliminate many of the data integrity and communication concerns the PM planning/scheduling team had with respect to the paper based system used in the as-found process. This electronic distribution of the PM work orders to the technicians and the electronic availability of PM procedures would also allow the PM planning team to be more flexible in working around the highly variable production schedule associated with their work environment. The check for spare parts required before electronic PMs would be distributed for completion was designed to deal with concerns about spare parts availability. Again, if careful effort is put into a new CMMS implementation, and the CMMS database is accurately and consistently maintained, and the proposed new PM process is set up properly, the proposed process could substantially improve the maintenance organization's performance.

Future State Inventory Work Processes

The potential inventory process problems mentioned in the previous chapter included poor part numbering, poor part descriptions as well as parts not being associated with equipment in the CMMS. A number of the technicians also complained about the way that stock-outs were managed. They had to fill out a stock-out notice and go to a computer terminal away from the stock room to do it.

The future state processes described below would address these concerns. As mentioned previously with respect to the reactive work flow processes, the implementation of a replacement CMMS would allow CEI to renumber all the spare parts and/or to associate key spare parts with the factory equipment. Of course, a new CMMS would not be needed to enact this change but it would provide a good opportunity to do so. Also, it was suggested that the 3rd party inventory service provider's system and CEI's CMMS be integrated (even if only superficially) to allow the charging of consumed parts to work orders (whether reactive or PM) at the stock room. Along with that a suggestion was also made that the stock out notification process also be incorporated into the CMMS and be available at the stock room.

The new process would allow a technician to come to the stock room and request a part that would then be charged through a bar code scan to the service provider's inventory tracking system and then subsequently to a work order through a separate scan into CEI's new CMMS. If no part was available (stock out situation) the relevant work order would be put on hold and given the status of "awaiting part". Stock-outs would be tracked by counting the number of work orders with "awaiting part" status. When a work order would be put on hold the CMMS would email the service provider with the notification of the stock-out situation. This limited integration of CEI's CMMS and the time investment necessary to number and associate the parts to equipment to ease the search for parts would do much to mitigate the risk associated with some of the potential process failure modes.

New Performance Metrics

As with the improvements to other processes some of the improvements to the performance metrics would come with integrating the I/T infrastructure supporting the maintenance organization. The incorporation of the reactive work order process into the replacement CMMS along with eliminating almost all other non-CMMS applications used in the organization to manage maintenance work would ease the data collection for metrics generation and quicken the time to information. Enabling the process of charging consumption of spare parts to work orders and setting up the CMMS in such a way (creating a standard report) so as to quickly produce annual maintenance cost vs replacement value data for each type of equipment in the factory would greatly enhance the ability of the management to make better decisions when investigating future equipment purchases. Equipment histories could also be more quickly compiled to assess individual pieces of equipment. This would enable a more data based approach to assessing PM frequencies and allow technicians and engineers to better show management where the problem areas of the factory are. If careful effort is put into a new CMMS implementation, and the CMMS database is carefully and consistently updated, the spare parts and performance information could help substantially improve the maintenance organization's performance.

Replacement CMMS and New Processes

Much has been said about a replacement CMMS contributing to improved work flow processes in the preceding sections. Indeed, a well implemented CMMS can contribute to better organizational processes, but it needs to be remembered that a CMMS is only a tool and it is only as good as the data contained in it and the processes stipulated by it.

Process Improvement Area	Will a CMMS help?
Data flow	possibly
Data structure	if set up correctly and maintained
Data Integrity	possibly
Finding spares	if set up correctly and integrated with the stock room
Spare parts availability	if set up correctly and maintainted
Better Metrics	if data integrity is good and reports are set up correctly

Table 5-1 CMMS Utility

The table above indicates there are many areas where a new CMMS can be helpful in improving maintenance processes but ultimately it is the CMMS-person interactions that will determine if any CMMS implementation will be effective. If the people responsible do not input correct data or choose to follow routines outside of those facilitated by the CMMS it will not be an effective tool, in fact, it may become a source of confusion and misinformation. A CMMS must have its database accurately and regularly updated to remain effective.

Chapter 6 Factory Equipment Spares Inventory Management

As stated previously many of the problems associated with the spare parts processes stemmed from the fact that in many ways the spare parts information was not very well organized. There were at least two and in many cases three different part numbers for each spare part (OEM part number, inventory service provider part number, and CEI part number that indicated what equipment the part belonged to). In most cases the OEM part number was the most critical to ordering a replacement part. This part number was not always easy to obtain. The part descriptions also did not always allow technicians to quickly search the database for possible matches for the parts that they needed. Spare parts were also not always associated with equipment in the CMMS and more importantly most technicians didn't have access to the CMMS to view any associations that did exist to assist in their search for spare parts. Additionally, a significant number of parts (many tens of percent) didn't have lead times available making risk decisions about stocking parts more difficult. Basic Min/Max methodology was used in managing the spare parts inventory but the min levels were not based on the historical demand and were changed only when it was thought necessary. CEI provided the min/max inventory levels to the 3rd party inventory provider for each part. The service provider then ordered parts based on a "below-min" report at least once a day. As already noted some of the realities of this system were the cause of frustration to many technicians. Even though the reported stock-out rate was below 1% (there was some debate over the stock-out metric definition and there were complaints about availability of parts regardless of the reported stock out rate) it seemed that there were many things that could be done to not only improve the processes (those items noted in the previous chapter) but also improve the way the inventory was managed (re-order points, etc.) to make a more financially efficient system.

In order to try to arrive at a more data-based methodology to determine appropriate re-order points for spare parts and to understand if there was a way to potentially reduce the overall inventory position, the previous 21 months of monthly demand data were obtained from the 3rd party inventory service provider for all spare parts. To simplify the initial analysis only the parts associated with one of the buildings served by the inventory service provider were considered. Initial observations of the data revealed many parts that had no demand for the previous 21 months and had no quantity on hand. Other parts had no prices listed for them. All of these parts were eliminated from the data set. This may not have been the best course of action as some of the parts eliminated may have been associated with key equipment but with zero quantity on hand it was thought that this would be reasonable for the purposes of this study. It was also noted that a large number of the parts in the data set had monthly demand data that was not normally distributed. Many of the parts had monthly demand that was heavily skewed – many months of zero demand with sporadic demand occurring from time to time. Because of this it appeared that the Poisson distribution would much better describe the monthly demand for many of these parts. The decision was made to model the inventory of some parts assuming that they had monthly demand that was normally distributed and other parts assuming they had monthly demand that followed a Poisson distribution. If the difference between the mean of the monthly demand and the variance was greater than 5 units the demand for the part was modeled as if it could be accurately described by a normal distribution otherwise it was modeled using a Poisson distribution. (The mean and variance of the Poisson distribution are equal. In this case those parts with variances of monthly demand that were close to the mean of monthly demand were modeled using the Poisson distribution.)

It was also decided that the data should be split up in another way. Not all of the parts were as critical as others to the reliability of the factory. There were a number of pieces of equipment whose failure would affect the performance of the entire factory very quickly. This equipment was known as SPOF (Single Point of Failure) equipment. The spares associated with the SPOF equipment were more critical than the other spares. A stock-out of one of the spare parts for these pieces of equipment would be more costly (on many measures) than for other spare parts. As such it was decided to model the SPOF spare parts inventory separately and differently than the other spare parts. Spare parts with long (>0.5

months) lead times and higher prices (>$500) were also grouped. These parts, while not as critical to the functionality of the factory would take a long time to replace and significantly effect the inventory position. The remaining parts (those not associated with SPOF equipment, with shorter lead times, and less expensive prices) were put in the last group. It would have been desirable to separate the consumable parts (nuts, bolts, fasteners, gloves, safety glasses, etc.) from the groups listed above and handled those parts completely separately but the time associated with doing that was deemed excessive. The methodology followed above is typically referred to as "ABC analysis" with A being the highest priority parts or those parts to be modeled with the most scrutiny. In the current analysis the SPOF spare parts corresponded to the A category, the long lead time and/or expensive parts corresponded to the B category, and the remaining parts constituted the C category.

Ultimately, in order to simplify the analysis, 252 parts were removed from consideration from the B set of parts and 1068 parts were removed from the C set because they had no demand for the previous 21 months even though a non-zero quantity of parts was on hand at CEI in the stock room. This simplification was not made for the A or SPOF parts. Also, in the interests of simplicity and to better correspond to the current process that the inventory provider followed, it was decided to use a continuous review inventory modeling approach. Since the inventory service provider ordered at least once a day based on a "below-min" report, a switch to a new continuous review inventory management policy was not expected to be problematic. One of the basic premises of the approach is to assume that inventory levels are continuously monitored and that parts are ordered when the inventory level falls below a calculated re-order point value. Basic parts of the continuous review inventory management assumptions and methodology are outlined below. (Hopp and Spearman, p75-78 and Graves, lecture slides)

<u>Assumptions:</u>

- regular demand can be assumed to be normally distributed (the Poisson distribution can also be used with this methodology with some modifications)
- demand for different parts can be assumed to be independent (not necessarily true in this case)
- lead times for parts are fixed

<u>Methodology:</u>

Step 1: Determine economic order quantities for each part based on order cost, demand, and holding costs.

Step 2: Determine the critical ratio between part holding costs and stock out costs

Step 3: Calculate the appropriate re-order point inventory level based on the demand over the lead time (demand/time x lead time) and the desired safety stock based on the critical ratio for the part (safety stock = (a multiplier based on the critical ratio) x (the standard deviation of demand over the lead time). The re-order point is the sum of the demand over the lead time and the safety stock.

Step 4: Based on the order quantities and the re-order points calculated above the expected (average) inventory level and the fill rate (fraction of orders filled from stock) can be calculated.

The continuous review inventory management modeling methodology was the background for the basic modeling approach used for the remainder of this chapter which is outlined in Factory Physics (Hopp and Spearman, ("Multiproduct (Q, r) Stock-out Model"), pages 601-610) which contains a section specifically on spare parts inventory management. Some modifications were made to the methodology to better fit the situation under consideration (i.e. the zero demand SPOF equipment spare parts were artificially given EOQ (Economic Order Quantity) values ≥1 so that the expected inventory on hand would be at least 1 unit). The approach is outlined below. The problem for this study was set up as an iterative 2 step optimization to minimize the average inventory position by adjusting the parameters for order cost and cost per stock out subject to constraints on order frequency and fill rate.

Step 1: Pick initial values for order cost and cost per stock out.

Step 2: Use order cost to calculate EOQ values for each part.

Step 3: If the order frequency calculated is equal to the order frequency desired then go to step 4. If not return to step 1 and adjust the order cost (if order frequency is too high increase the order cost).

Step 4: Use the cost per stock out to calculate the re-order points for all parts.

Step 5: Compute the total average fill rate.

Step 6: If the fill rate calculated is equal to the desired fill rate stop. If it is not return to step 4 and adjust the cost per stock out (increase cost per stock out to increase fill rate).

The targeted and realized order frequencies and total average fill rates appear below. Higher fill rates were desired for more critical and longer lead time parts. The target order frequency was meant to minimize the number of orders needed per year (and hence the associated fees that the service provider would charge) and to try to only ever keep ~6 months of part demand on hand. This was not feasible for all situations.

	target order frequency (orders/yr)	target total average fill rate	realized order frequency	realized total average fill rate
A parts (Poisson)	2	99.5%	0.76	99.55%
A parts (normal)	2	99.5%	2	99.56%
B parts (Poisson)	2	98%	0.95	98.41%
B parts (normal)	2	98%	2.04	98.01%
C parts (Poisson)	2	97%	1.47	97.23%
C parts (normal)	2	97%	2.02	97.02%

Table 6-1 Targeted and Realized Order Frequency and Average Fill Rate

It can be seen that the total average fill rates were realized as desired but that the order frequencies were not. There were parts with low monthly demand (modeled with a Poisson distribution) where even when the order costs were adjusted in attempts to increase the average annual order frequency for a given spare part set, an average of two orders per year could not be realized.

The analysis predicted that if the re-order points calculated using the analysis referenced above a >20% reduction (then present spare parts inventory value considered in the analysis minus the expected inventory value) in inventory position was possible. This represented an opportunity to free up multiple hundreds of thousands of dollars in the form of spare parts associated with the building considered. It should be noted that only about two thirds of the anticipated reduction would be directly relevant to CEI as the inventory service provider owned some of the stock room inventory.

It should be noted that there are a number of other considerations that could be included to more completely optimize CEI's spare parts inventory. If some relationship between the number of pieces of process equipment and the demand for specific spares could be understood, this could potentially help better model the part demand as changes in the factory layout occur. There was anecdotal evidence that spare part demand for some pieces of equipment came only in significant blocks. If the distribution for the MTBF (mean time between failures) for a given type of process equipment is very narrow and all the equipment was installed at the same time perhaps this knowledge could be used to better model the spare part demand data (and also PM frequency) for that equipment (periodic delta function). Lastly, one of the technicians (and Hopp and Spearman on p602) suggested that demand and stocks for reactive repairs and PM activities be separated. Demand for PM activities (and other planned work) should be almost deterministic and could be removed from the more variable part demand associated with unplanned maintenance.

Chapter 7 The Role of Technology and Materials in Determining Equipment Reliability

Design for Reliability and Maintainability

One of the most important design decisions when considering reliability or base functionality in any system is the selection of materials to be used. Materials selection methodologies generally consider the loads which various components of the mechanical system are exposed to and the potential geometry of the components. The designer selects materials based on what materials will give the desired properties (mass, etc.) and functionality (strength, stiffness, etc.) with acceptable geometries. This methodology generally addresses the base functionality of the system. In order to address the reliability (and related maintenance) of the system the designer should also consider factors like the dynamic loads and cyclicality of those loads to assess the potential fatigue resistance for the system. The functional environment (temperature, chemical/corrosion, radiation, etc.) should also be considered. Comprehending any fatigue and creep concerns that may exist may also affect the materials ultimately selected for the components.

If fatigue and creep concerns are ameliorated (with sound material, material treatment, and geometrical choices) many of the age-related (wear-out) reliability concerns for the system may be minimal. That still leaves a number of non-age-related reliability concerns to address. As stated previously, many of the non-age-related system failure behaviors are thought to be brought on by non-standard equipment operating conditions. Basically, the equipment is exposed to a non-design stress condition and either fails or is more susceptible to subsequent abnormal stresses or is progressively less resistant to stress. These non-design stress conditions can be the result of operator error (not allowing sufficient warm up time for equipment or due to poor training operating the equipment in a way that it was not intended to operate in). The non-standard conditions can also be the result of problems introduced at equipment installation (shafts misaligned at installation, defective bearings, inadequate lubrication, etc.). Environments not considered by the designer, for example extremely hot, dusty, or humid (or otherwise corrosive) environments, can also cause unanticipated stresses on equipment (Moubray, p140-143). In these cases the best way to deal with the reliability concerns of the equipment may not be in selecting a more robust material or over-designing the system but to provide more training to the potential users of the system about the operating limits of the equipment and the potential ramifications of operating the equipment outside those limits. Indeed, in some cases (as suggested in the RCM methodology) the best way to increase the reliability and maintainability of equipment may be to re-design it to better fit the operating conditions.

Materials selection is an important aspect of the design process and influences the performance and reliability of the system significantly. Materials developments can also help improve the performance and reliability of systems (if the costs are justified). Materials and component geometry, however, are not the only things that affect reliability and maintainability. A number of other design factors influence how equipment is serviced and maintained. These factors include accessibility of key components, accessibility of test points (perhaps for condition-based monitoring for predictive maintenance purposes), and modularity of design. As already mentioned installation, training, operations checklists, and work environment have also been cited as important to the maintainability of equipment (Dhillon, p83).

Materials Based Predictive Maintenance Technology

Design and materials selection can help determine what the expected reliability of equipment should be. Materials characteristics and materials analysis can also play a role in indicating what the on-going reliability or maintainability of a piece of equipment should be when used as part of a consistent and well-thought out predictive maintenance program.

There are many different types of predictive maintenance technologies including vibration, alignment, and electrical parameter analysis as well as thermography. The focus of the remainder of this section will be on the technology or method most closely linked to materials analysis, namely lubrication fluid analysis.

All predictive maintenance methods and technology involve two things – a baseline of a performance or failure indicating parameter with associated trend analysis, and a sampling plan. A practitioner must understand what an acceptable parameter level is and at what intervals to measure the appropriate parameters (Mitchell, sec. 11 and Moubray, p348-349). Lubrication fluid analysis is no different.

The specific type of tests done on the lubrication fluid and intervals the samples are taken at will depend on the equipment under consideration as well as the equipment health history. Moubray outlines guidelines for many different types of equipment in Appendix 4 of his book.

All lubrication fluid testing programs involve 3 types of tests: fluid property tests, fluid contamination tests, and fluid wear debris tests (Mitchell, sec. 11). The results of each type of test can tell the organization about the health of the equipment of concern. Often more general tests are done to understand if more rigorous or specific testing is necessary. Particle counts, viscosity measurement, and moisture content analysis may indicate an abnormal situation that requires further testing to help isolate a potential reliability problem. The follow up testing may indicate that there is some abnormal additive breakdown in the lubricant which may be caused by some contamination or excessive heat. It may also indicate that there is too much water or other contamination getting to where it should not be. The follow up testing (like elemental spectroscopy) may also indicate specifically what kind of particles may be present in abnormal levels and allow the practitioner, if the equipment materials information is available, to isolate areas in the equipment where a failure is more likely to occur.

There are many different kinds of lubrication fluids testing that would be useful for some maintenance organizations as part of their predictive maintenance programs. The specifics of the lubricant testing program would be a function of the equipment associated with the organization and failure modes of interest. The analysis can be somewhat expensive and in many cases requires significant amounts of training and education. If the criticality of the failure of the equipment and the nature of the equipment warrant lubricant analysis on a regular basis the costs can outweigh the benefits. Some companies have reported being able to pay for their oil analysis programs with savings made just by being able to make better decisions about when to replace their lubricants reducing their lubricant consumption (Mitchell, sec. 11).

Clearly, not all equipment warrants lubricant analysis and not all equipment warrants predictive maintenance technology being used with it. However, if a maintenance organization knows what equipment is highly critical to its production systems (typically bottleneck, non-redundant, or key material handling equipment) appropriate predictive maintenance methods can be used to minimize the possibility of a surprise failure. Once a baseline of key parameter performance is established and potential failure conditions are well understood regular sampling of the parameter can help the organization know what the reliability condition of the equipment is and maintenance work can be *planned* around production requirements (various conversations with predictive maintenance consulting firms seeking business with CEI).

Chapter 8 Conclusion

This investigation has shown that there were higher risk areas of the maintenance work flow processes at CEI. Those higher risk areas have been identified and various ways to alleviate some of those risks have been proposed. By modifying the reactive work order, PM work order, and spare parts management processes and methodologies in order to improve data integrity, data structure, and information flow, CEI can reasonably expect more effective and ultimately more efficient work flows. If the new processes contained herein are followed, greater flexibility in maintenance execution and higher availability of spare parts can also be expected. All of these changes should allow for more proactive processes and more proactive technicians who should have more information available to them through a more accessible and more complete CMMS implementation.

Because of financial, time, and management restrictions the future state work processes suggested were not implemented during the internship. It would be of interest to know if the expected benefits of the proposed new processes would be realized and if not, why not. An evaluation of the improvements resulting from the changes proposed herein is left to CEI and/or to another investigator. Other suggestions for further work include: studying what predictive maintenance technologies may be most appropriate and most cost effective for use at CEI, determining what level of contract maintenance labor is desirable given CEI's maintenance to be performed and current maintenance performance level, and determining if a relationship exists between factory/equipment utilization, on-time PM completion rate, and factory/equipment downtime.

References:

Dhillon, B. S., Engineering Maintainability: How to Design for Reliability and Easy Maintenance. Houston, TX: Gulf Publishing Co., 1999

Graves, S. C., *Inventory Basics*. Lecture slides provided as part of courses 15.762 and 15.763, Spring 2004

Hopp, W. J. and Spearman, M. L., Factory Physics. Second Edition, Singapore, Irwin/McGraw-Hill, 2001

Mitchell, J. S. compiler, Operating Equipment Asset Management – Your 21st Century Competitive Necessity. First Edition, State College, PA: Pennsylvania State University, Applied Research Laboratory (made available by a representative of the consulting firm known as Allied Services Group whose ideas influenced parts of chapter 7, previously available on the Pennsylvania State University web site)

Moore, R., Making Common Sense Common Practice, Models for Manufacturing Excellence. Third Edition, Burlington, MA: Elsevier Butterworth-Heinemann, 2004

Moubray, J., Reliability-centered Maintenance. Second Edition, New York, NY: Industrial Press, Inc., 1997

Nakajima, S., Introduction to TPM. Cambridge, MA: Productivity Press, 1988

Nowlan, F. S. and Heap, H. F., *Reliability Centered Maintenance*. Proceedings 1978 Annual Reliability and Maintainability Symposium

Nowlan, F. S. and Heap, H. F., Reliability Centered Maintenance. Los Altos, CA: Dolby Access Press, (for sale by the National Technical Information Service], 1978

Palmer, D. (Palmer, Richard D. goes by Palmer, Doc), Maintenance Planning and Scheduling Handbook. New York, NY: McGraw-Hill, 1999

Shenoy, D. and Bhadury, B., Maintenance Resources Management: adapting MRP. Bristol, PA: Taylor & Francis, 1998

http://www.plant-maintenance.com/maintenance_software_CMMS_A-L.shtml
http://www.plant-maintenance.com/maintenance_software_CMMS_M-Z.shtml

Appendices

Appendix 1 – Nowlan and Heap RCM Question Tree

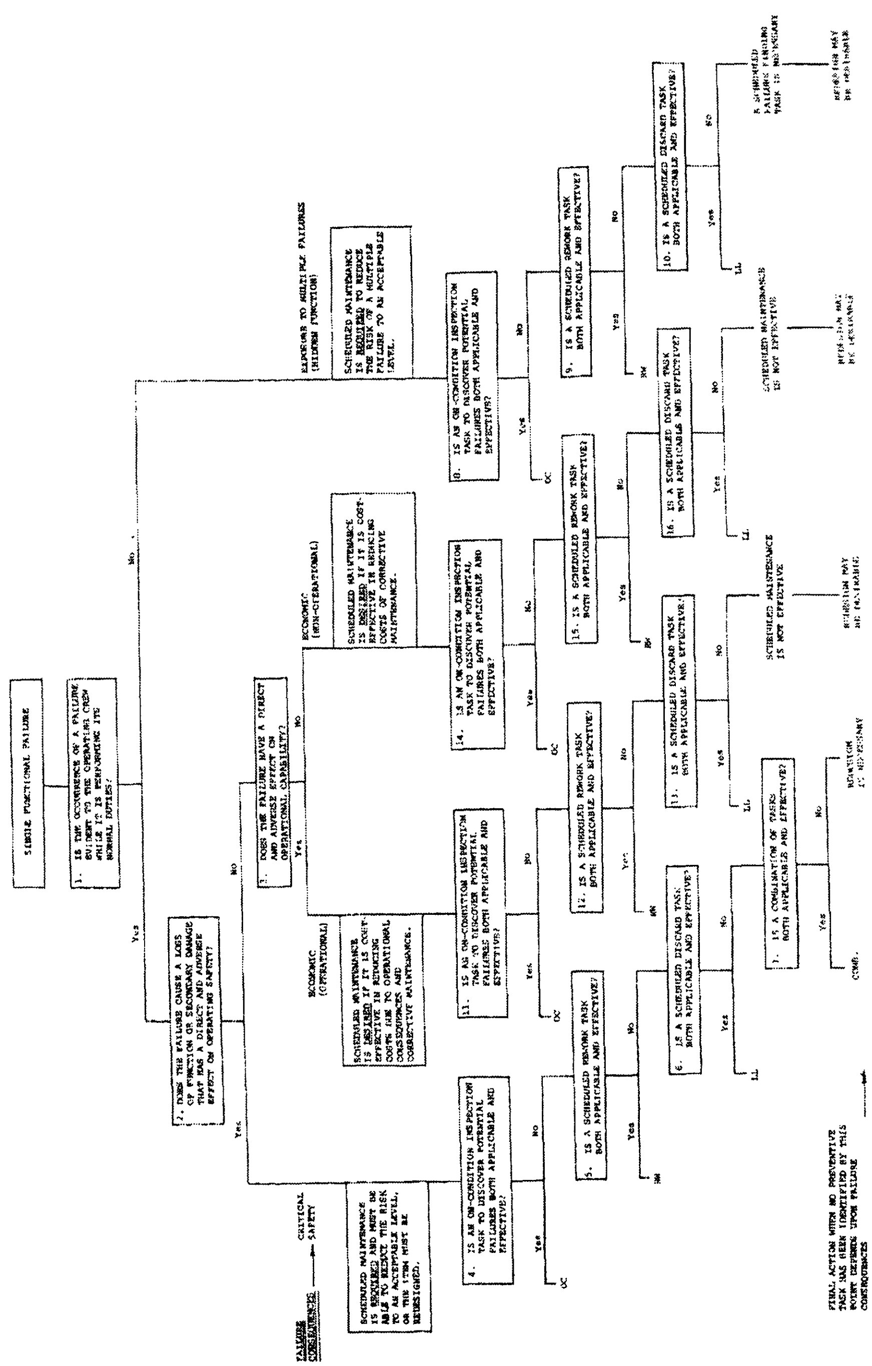

Figure 1. The Reliability-Centered Maintenance Decision Diagram.