

Maintenance In A Contractor Organization

A Practical Approach

by


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(ABSTRACT)

A model for optimizing the assignment of maintenance actions for a piece of equipment is developed in the thesis. The model considers the detectability and the criticality of component failure in order to assign a maintenance instruction. The thesis also develops the framework for an integrated maintenance management system. The system consists of three modules. The first module is work control. It is used to prepare, schedule, and insure the execution of maintenance instructions. The second module is the equipment condition control module which monitors maintenance effectiveness and accordingly updates the maintenance instructions. The third module is cost control. This is the tool used to monitor the economical performance of the maintenance function. An equipment information system is also presented, and two futuristic maintenance proposals are introduced.

The model and the integrated maintenance management system, constitute a strong tool, that equipment managers can use to optimize the maintenance function, and improve the mechanical, operational, and economical performance of equipment.

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Thanks you for the artistic touch, and the computer information you taught me.

Life is tough without friends. For love, care and many other gifts, Thanks for :

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1 Introduction

Since time immemorial, when man used primitive tools to make machines to carry his loads, to draw his water, to till his land and to fabricate his building materials, he has been faced with the prospect of maintaining these assets until such time came as he considered their useful life to be ended. If one takes this theme further, one must accept the fact that most things of a material nature possessed by man, have been made by a machine, and are made used or stored in a building. In the nature of things, virtually nothing man-made is indestructible, but the useful life can be extended by carrying out repairs by an activity known as maintenance (Corder, 1976).

The main asset of a road building contractor is his equipment fleet. The fashion in which the fleet is managed decides its life expectancy, its productivity and the final return to the company from the equipment. As we try to eat healthy food and exercise to keep our bodies in shape, equipment needs to be maintained to stay operable and profitable. The escalating costs of replacement and the increased competition in the economy has lately given a strong thrust to the maintenance aspect of equipment management.

1.1 Objectives

The realization that maintenance is essential for an equipment operation drove many software firms to develop PM programs. The literature is full of "how to" guides, and the market is overwhelmed with software with a wide variety of capabilities and prices. But without a basic approach specifying when, how, and what maintenance actions should be carried out, the software programs remain pieces of technological art, with no practical value. A comprehensive maintenance system should encompass the following modules:

1. A decision model for assigning different maintenance actions to different components of the equipment.
2. A program to schedule and monitor the maintenance applications.
3. A decision support system using the data generated by the maintenance applications to help management make better equipment decisions.

The objective of the thesis is to develop a practical model for assigning maintenance philosophies to equipment components and layout the guidelines for a decision support system for a roadbuilding contractor organization. The system benefits the organization on three levels of operation; mechanical, operational, and economical.

On the mechanical level the expected benefits are:

1. Minimization of the number and severity of breakdowns.

2. Maximization of machine life.
3. Minimization of labor required to maintain equipment.

On the operational level the expected benefits are:

1. Maximization of machine available time.
2. Maximization of production units obtained from machine.
3. Increased probability of meeting schedule deadlines because of increased machine reliability.

On the economical level the expected benefits are:

1. Minimization of running cost.
2. Minimization of capital expenditure on equipment.

1.2 Scope & Limitations

The thesis encompasses four tasks:

Firstly, a maintenance decision model is developed. The model will set the criteria to choose the optimal combination of maintenance philosophies for equipment in a given contractor organization.

Secondly, the thesis will set the specifications to schedule, execute and monitor the maintenance applications.

Finally, the thesis will layout the specifications for an equipment information system and will discuss the benefits and managerial use of the system in optimizing the decision making process.

The thesis limitations are:

1. It will not attempt to develop a computer program. The short amount of time allocated to the thesis does not allow for the development of a comprehensive program that can stand the test of competition from professional software.
2. The thesis will develop guidelines for how maintenance instructions should be produced and implemented. It will not develop these instructions. This task is left to the individual contractor organizations.

1.3 Thesis layout

The thesis will be divided into five chapters:

The first chapter discusses the thesis organization and gives an overview of the maintenance subject.

The second chapter discusses the equipment management parameters that affect maintenance decisions. The chapter will conclude with a functional list of requirements for a comprehensive maintenance system.

The third chapter is the model development. The background, logic and benefits of the model will be developed.

The fourth chapter discusses the functional mechanism for applying and controlling the maintenance functions in the organization. The chapter will layout the equipment information system and will define the managerial parameters that management will use to optimize equipment decisions.

The fifth chapter presents the conclusions and recommendations for further study in the area of maintenance.

1.4 Maintenance: An Overview

1.4.1 The Equipment Cycle

Each piece of equipment goes through three phases during its lifetime. These phases constitute the equipment cycle (Vorster, 1988).

The cycle starts with the realization that equipment is needed. This need can come from 3 sources:

1. Replacement of a piece of equipment that no longer provides the basic function for which it was designed.

2. A technological development that created the need for this piece of equipment in order to increase productivity.
3. Development and growth in the company that dictates expanding the equipment fleet.

Confirmed need initiates the selection phase. In this phase, the capital investment required, the operational capabilities, and mechanical qualities of different competing machines are evaluated and compared with the criteria defined by the company.

After the selection is made, the equipment is acquired. Financing the deal can take different forms. The two most common methods of financing are the direct purchase and the rent with option to buy.

With direct purchase, the full amount of the machine price is paid to the seller. The owner gets the title to the machine and decides on the type of depreciation to employ in order to amortize its cost. The money for the direct purchase can come from the contractor funds, or it can be partially or fully financed with a bank loan.

The rent with option to buy agreement entails a right to the renter to purchase the equipment within a specified period of time. Usually part or the full amount of the rent is applied towards the purchase price of the equipment. If the machine is bought, it is capitalized, otherwise the rent is deducted from taxes as business expenses.

The purchase completed, the allocation of the machine to a project starts the operation phase. The goal then becomes maximizing the efficiency and effectiveness of the machine. The decisions during the operation phase aim at accomplishing the following:

1. Optimizing the combination of the machine with other complimentary machines in order to create the best fleet formation.
2. Optimizing the cycle times of the machine within the fleet operation.
3. Optimizing maintenance application. It is this aspect of the operation phase with which the thesis is concerned.

The retirement phase starts when management realizes that the economic, operational and mechanical performance limits set for the machine are no longer satisfied and therefore the machine should be replaced. The present machine is usually compared to a challenger machine. The replacement is the end result of an evaluation of repair rebuild or replace analysis (RRR). Repair is fixing only the machine component that failed, in order to make the machine functional. Rebuild refers to a machine overhaul that will make it as functional as a new machine. Replace is the retirement of the machine either by selling it or by trading it in for a challenger machine.

1.4.2 Equipment Maintenance

Simply stated equipment maintenance consists of the adjustment, repair, or replacement of a component to insure machine functionality.

On the theoretical front, most of the research was done by academicians in the context of operations research and mathematical modeling, and most of the solutions dealt with specific maintenance problems. The mathematical approach is essentially the combination of a mathematical model describing a particular maintenance problem, the information input required for the solution of the problem, and the factors determining its successful implementation. The mathematical models that were developed suffered from

a large number of limitations which rendered them practically unusable as the practical environment was never able to simulate the perfect settings they assumed. Moreover the models assumed that the problem is well defined and the input is readily available. In practice, the problem itself requires analysis before being defined and many factors are interrelated such as increased cost of maintenance or increased downtime (Christer & Waller, 1984 , Goyal & Kusy, 1985)

The input to the problem is usually failure and economic data related to the machine history. Since these data require rigorous statistical analysis of randomly occurring events that are rarely identical, they are usually not available. The problem presents itself clearly when we are dealing with a highway construction equipment fleet. The equipment are very diversified in size, make and function. The operating environment consisting of weather, soil, and the operator handling of the machine also presents significant variations. Accordingly, defining a set of discrete data for the mathematical model becomes a problem that the equipment decision makers are not willing to commit time and effort. The result was that the gap between theory and practice in maintenance was not bridged. Referring to this problem Turban (1967) notes that: "Plant maintenance management is one area of industrial organization where the gap between theory and practice is extremely wide and while a broad range of mathematical techniques were developed to aid in solving maintenance problems, very few maintenance decision makers use these techniques in practice".

In sorting out the different forms that maintenance can take, Vorster (1988) first defines deterioration of a machine or component as being either overt or covert. Overt deterioration is visible or measurable and remaining life can be predicted by inspection or direct measurement. Covert deterioration is invisible or hidden and hence remaining life

predictions must be based on statistical inference drawn from suitable sample data. He then goes on to define the different forms of maintenance as:

Planned maintenance: Action taken to remedy an overt deterioration in a machine component. In this case maintenance is executed before failure occurs and in accordance with a schedule.

Avoidable failure and repair actions: Action is taken to remedy an overt deterioration which has resulted in failure.

Unscheduled failure repair action: Maintenance action taken to remedy a covert deterioration of a component run to failure.

Preventive maintenance: Maintenance action taken to remedy a covert deterioration before failure according to statistically derived schedules.

Vorster's definitions coincide with three maintenance philosophies adopted by the industry. The avoidable failure and repair actions, and the unscheduled failure repair actions correspond to breakdown maintenance. His definition of planned maintenance is synonymous to condition based maintenance, and preventive maintenance has the same connotations in his definition and that of the industry. The background, advantages, and drawbacks of the three philosophies will be discussed next.

Breakdown Maintenance

In the case of a breakdown maintenance, a deteriorating component in a machine is not repaired or replaced until it fails, causing a loss of functionality of the machine. In this form of maintenance consideration is not taken as to the component deterioration trend or the manufacturer recommendations as to the limits of acceptable operating conditions

of a component. The only controlling factor for the maintenance function is that the machine becomes inoperable. Defending the breakdown philosophy, Zurringen and Shmidt (1979) state that: "The results of a preventive maintenance program might seem like taking a loss of productivity for a benefit which if realized will be down the road. The cost of maintenance programs is calculable, while the payoffs seem out of balance with the known cost. Moreover monitoring and servicing maintenance systems can become bothersome to the point of finding reasons for spacing out these functions allowing slippage to become routine or omitting them all together."

Breakdown maintenance presents significant disadvantages. If component life is not being monitored and the failure occurs, the machine stoppage will be unexpected. This sudden breakdown has a maximum effect on production loss for two reasons:

1. A component reaching the end of its life, has the highest probability of failure under high intensity usage. This usually corresponds to high production level. The machine failing at this point will therefore cause the maximum production loss.
2. Because the failure is unscheduled the ability to have a backup machine is minimized therefore production loss period is maximized. A natural effect for the maximized production loss is a schedule delay that frequently has negative effects on contractual agreements and the contractors cash flow.

Extra costs involved in breakdown maintenance also include cost of standby labor, and increased cost of spare parts. Spare parts cost will increase for two reasons.

1. The machine is a complex assembly of integrated components. Failure in one component, will frequently lead to the malfunction or subsequent failure of other components.
2. Dealers exchange worn parts for new or rebuilt parts. Since the exchange part is a credit to the equipment owner, exchanging it after failure yields a much lower return than before failure. Equipment superintendents state that the replacement cost can more than double when the component is replaced after failure (Shaw, 1988).

Condition Based Maintenance

The second maintenance philosophy is condition based maintenance (CBM). CBM calls for maintenance operations only when machine performance or condition has deteriorated to the point where maintenance is necessary. The system requires that machine operating conditions be continuously monitored against some predetermined limits (Kershaw & Robertson, 1987).

The critical aspect of the system is to define the machine characteristics that should be monitored and the limits of functionality at which the machine should be maintained. Different machines will have different operating characteristics. Manufacturer literature usually explains the different parameters involved in a machine operation and sets limits of acceptance for each parameter. Indeed, after some time and experience in monitoring these parameters, the equipment users can define the limits according to their particular operating environment.

The essence of CBM is a close and detailed inspection. The reward is that in almost all cases advance warning of impending failures can be given if the proper monitoring procedure has been selected. If the maintenance program can establish a quantitative measure of a machine's condition then a graph showing the development of the problem with time can be plotted, and an estimate can be made of the lead time for maintenance limits. The main advantages claimed by CBM advocates are:

1. Most faults can be found on a machine before they lead to failure.
2. CBM allows equipment users to follow fault condition and make accurate estimates of the time remaining for repair.
3. The monitoring process does not require stoppage of the machine to be successful.
4. The increased level of inspection makes the mechanics aware of the machine condition, so that the level of component failure prediction is maximized.

A major British study showed that the potential annual economic benefit from such a program (CBM), can be as high as 50% in increased production and 50% in maintenance related savings (Kershaw & Robertson, 1987).

But these claims cannot all be taken for granted. Two observations can be made concerning the CBM cycle.

1. The high level of inspection required means that the machine has to be stopped and taken out of production more frequently than a regular maintenance function would require.

2. CBM by itself will not optimize the maintenance cost. Inspecting all critical components in a machine repetitively to determine their failure trends mandates an overinvestment in maintenance spending and a substantial loss in production time. A careful economic evaluation of the inspection level that should be implemented is necessary to check the optimal level of inspection as required by CBM vs breakdown or other forms of maintenance.

Preventive Maintenance

The third maintenance philosophy is the preventive maintenance. Preventive maintenance involves those adjustments, repairs, or replacement operations performed on a machine at stated intervals and according to a schedule. The purpose of preventive maintenance is to reduce the wear or failure rate of major parts that would make the machine inoperable.

Functionally, the term preventive maintenance means periodic maintenance, even though the word preventive tends to draw attention to the goal of the activity (prevention) rather than the activity itself (periodic action). For the sake of distinguishing between the different philosophies, the definition of preventive maintenance will exclude all activities that are not carried out on a periodical basis even though they would prevent other defects, accidents and so fourth.

Preventive maintenance is technically applied only to those systems which strive to reduce the likelihood of failure. Such is the case in the operation of aircraft, power stations or critical installations for certain plants such as a steam generator in a laundry, or forced ventilation in a mine. To insure prevention of breakdowns , planned service

is carried out, with the explicit additional objective of detecting weak points and insuring proper functioning by replacing parts that could still be used were it not for the assurance required. Thus, after every service, the machine is functionally as good as new. The intervals for the different repair or replace actions are based either on manufacturer recommendations or on statistical analysis of failing parts.

The advantages of preventive maintenance are many. If production allows maintenance to occur then unscheduled machine downtime will be minimized, and machine availability will be maximized. Moreover the different maintenance intervals being pre-scheduled, the maintenance department can optimize its spare parts inventory by using just in time techniques. Personnel scheduling can follow the same path and the ultimate result is a minimum time for each maintenance shift. Preventive maintenance also has its drawbacks. Two of these drawbacks are as follows:

1. Construction equipment except in rare cases is not constrained by operational or safety factors to work at exceptionally high levels of reliability. In industries such as aircraft and mining, 100% reliability is a must and preventive maintenance is motivated by safety as well as economical considerations. For construction equipment this constraint does not exist, and the main concern is to optimize production cost by balancing cost of downtime with cost of maintenance. Acceptance of breakdown depends on the effect of breakdown on production. In many instances, running a component to failure is more economical than prematurely replacing it to avoid a failure.
2. The strict schedules of preventive maintenance will frequently conflict with tight production schedules. The highway construction industry has not matured enough to sense the advantages of maintenance applications and is usually guided by pro-

duction. The misconception that production always comes first results in delays in maintenance schedules, and frustration between maintenance and production personnel.

1.5 Approaches To Maintenance Analysis

In order to apply these maintenance philosophies, the industry developed some methods of maintenance analysis. The most advanced methodologies are the reliability-centered, and the total productive maintenance approaches.

1.5.1 Reliability Centered Maintenance

Reliability centered maintenance (RCM) was developed by the air transport industry which in recent years has been on the forefront of modern maintenance development. Basically, RCM is a logical decision based approach, used to determine optimal preventive maintenance strategies (Harris, 1985). Some of the important features of RCM approach are:

1. All maintenance decisions are based on a complete analysis of the equipment failure characteristics, failure modes, and the actual causes of failure.
2. The consequence of failure are used to establish the priority of any proposed maintenance action and all failures are divided into either safety, operational, non operational or hidden failure consequence category.

3. Carefully structured decision diagrams and well defined decision rules are used to facilitate the selection of an appropriate maintenance option.
4. The availability of information for decision making is a critical factor in the analysis, and the RCM decision procedure is based explicitly on whatever information is available.

RCM is oriented towards practical decision making yet it retains a strong theoretical bias that is emphasized by the use of statistics to evaluate variations in equipment failure with operating age. The complete RCM decision procedure is normally applied to items of equipment before they enter the service. The RCM process goes through the following stages:

1. Identification of all significant items of equipment.
2. Description of all functions demanded by an item.
3. A clear definition of the condition that constitutes a functional failure in each case.
4. Description of possible failure modes associated with each functional failure.

Based on these criteria, the RCM prioritizes the maintenance functions and defines an optimal maintenance system.

The advantages claimed by the RCM process are (Nowlan & Heap, 1978):

1. It takes into consideration different maintenance philosophies and assigns each one according to a specific set of requirements.
2. It optimizes the maintenance expenditure because it treats each component as a separate element and applies to it the most compatible maintenance policy.

The RCM approach falls in the same trap as that of the mathematical models. Mainly it is limited by two problems:

1. High requirement for data.
2. Its primary objective is to improve the reliability of equipment. The emphasis of the process is therefore on the mechanical performance. The relationship between maintenance and operational and economical performance of equipment is neglected.

1.5.2 Total Productive Maintenance

The second maintenance analysis approach is 'total productive maintenance' (TPM). TPM has become widely known throughout Japanese industry as a term for preventive maintenance with all employees participating through small group activities (Staff, 1986). The unique feature of TPM that is absent from conventional maintenance programs is the autonomous maintenance by operators. TPM aims at improving the company by improving its equipment division effectiveness. This goal is reached by changing attitudes and skills of the people involved with equipment so that they become more competent and considerate in their dealing with equipment. Successful implementation of TPM has five essential outcomes:

1. Improve the effectiveness of each piece of equipment.
2. Establish autonomous maintenance by operators.
3. Establish a preventive or a condition based maintenance system.
4. Establish training programs to improve operation and maintenance skills.
5. Create a system for initial management of equipment.

Excepting the operator involvement the steps previously defined are requirements for any comprehensive maintenance program. However, autonomous maintenance by operator is a key point in TPM. Changing the operators lack of interest in maintenance and developing autonomous maintenance cannot be accomplished overnight. It takes 2 to 3 years from the time TPM is announced until implementation is complete because of the time needed to change the personnel attitude. Japan Institute Of Plant Maintenance (JIPM) one of strongest advocates of TPM has developed a step method for creating an autonomous maintenance system (Staff,1986). Under this method, the actual equipment used by the operator, is used for on the job training. The operator gradually acquires the maintenance knowledge and skills through step by step training and implementation. As he moves through the steps, he gradually builds up a willingness to use TPM.

TPM does present a comprehensive system for maintenance management. Assuming the maintenance function is well designed TPM can achieve maximum equipment effectiveness at the minimum life cycle cost. The application of TPM to the American construction industry will have some drawbacks. These drawbacks are as follows:

1. The transient nature of construction projects does not allow time for operators training. Specifically, highway contractors usually have their projects spread over a large area which dictates that they hire local labor and machine operators for the project and lay them off when the project is finished.
2. Defining what philosophy or blend of philosophies to use remains an important issue in establishing a maintenance system, unless that is given high priority TPM will not reach its optimum level of effectiveness.

1.5 Conclusion

The chapter discussed the objectives, the scope and the organization of the thesis. There is a universal acceptance regarding the need to plan maintenance into construction operations. Very few contractors have however adopted a systematic approach to implement maintenance programs in their operations. A number of maintenance philosophies and approaches were overviewed. Different scholars and practitioners have given different definitions to preventive, condition monitoring and breakdown maintenance. For the sake of clarity and the purpose of the thesis, the different maintenance philosophies will be redefined as follows: (1) Breakdown maintenance consists off all repairs, rebuild and replacement actions performed after the component has failed; (2) Preventive maintenance consists of repair, rebuild, replacement, adjustments, and lubrication actions performed on a periodic basis and according to a prescheduled plan; (3) Condition monitoring consists of all maintenance actions based on a preset threshold of component deterioration, as discovered by inspection or other condition monitoring methods. Preventive and condition monitoring compose the category called planned maintenance. The chapter also defined Reliability-centered, and total productive maintenance as systematic approaches employed to convert the maintenance philosophies into practical applications. The reliability-centered approach consists of identifying significant components, evaluating their failure consequences, and selecting the appropriate maintenance tasks and intervals. TPM stresses autonomous maintenance by operators, as a method to optimize the maintenance function.

2 Maintenance In The Equipment Organization

The organization structure of the company, the cost accounting considerations, and the people involved are some of the factors that affect maintenance decisions. This chapter will define these factors, and describe the general environment in which equipment decisions are made. The chapter will conclude with a functional list of the requirements for a comprehensive maintenance model.

2.1 Role Of Equipment In The Construction Company

Equipment management is not an end in itself. It is an integral part of the construction management process designed to serve one goal; supplying productive equipment to construction projects (Vorster, 1988). Maintenance plays an important role in optimizing the equipment decision. Our understanding of this goal is enhanced by clarifying the concept of the construction company organization system and the equipment life cycle within this system.

The drive for a construction company to exist and grow is to make profits by building successful projects. Generally, to achieve this goal the company is organized in 3 main functions; construction, equipment and executive. The construction function is responsible for the actual physical building of projects. Activities within this sector consist of designing, planning, estimating, building and controlling construction projects. The equipment function is responsible for providing equipment needed for construction activities. The executive function is responsible for strategic planning, budget planning, control and marketing of company services. Figure 1 shows the three functions of the company with their respective responsibilities. The objectives of construction is to make sure the project is built. Equipment provides the support necessary to accomplish construction projects, and the executive monitors both construction and equipment to insure overall company objectives are adhered to.

Strong marketing brings more projects for the company. Good planning and budgeting, keeps it in control of these projects. Profit maximization is mainly a result of optimizing the construction and equipment operations.

With regard to equipment, Construction is concerned with the operational value consisting of such factors as cycle times, production standards and physical ability of the machine to produce units of work. the main concern of the executive function is the return on investment. The equipment function is concerned with satisfying the executive and operational needs of the company. This goal is achieved by optimizing purchasing, maintenance and replacement decisions.

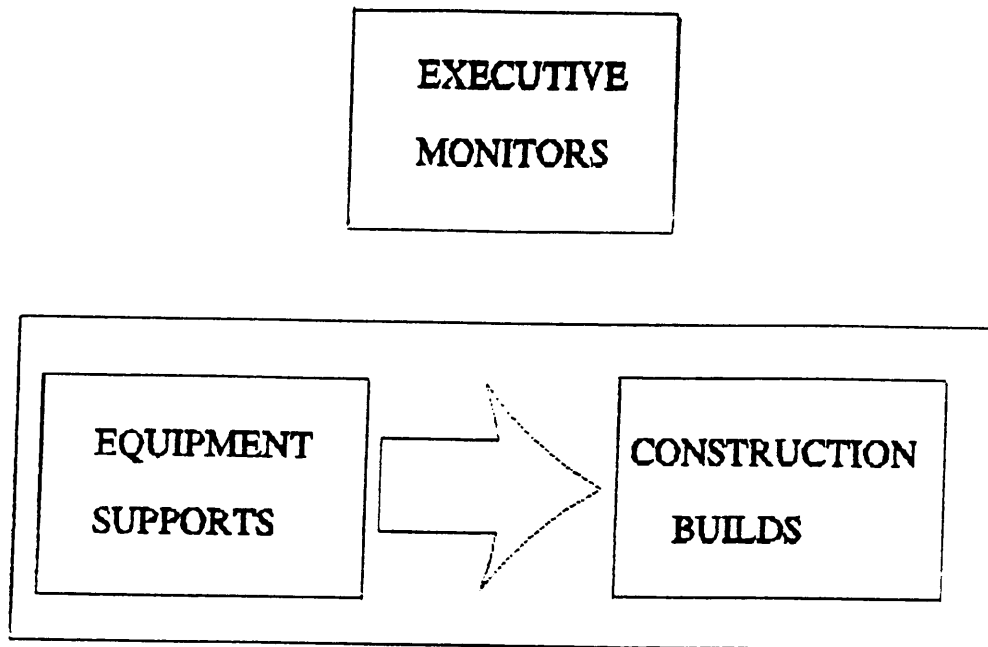


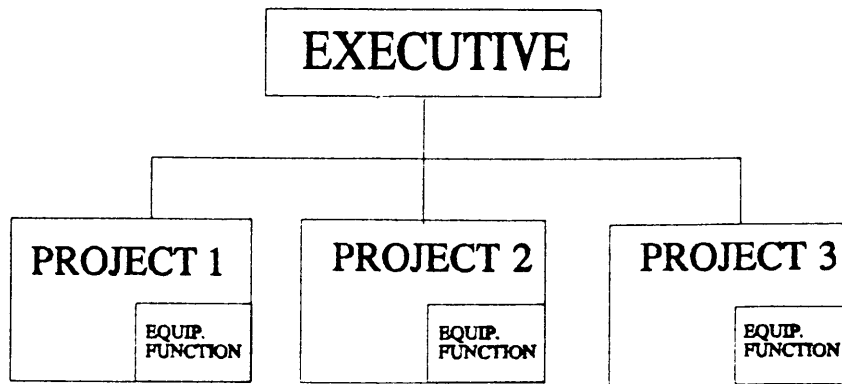
Figure 1. The Three Functions In A Construction Company (Vorster, 1988)

2.2 Equipment In The Organizational Setting Of The Company

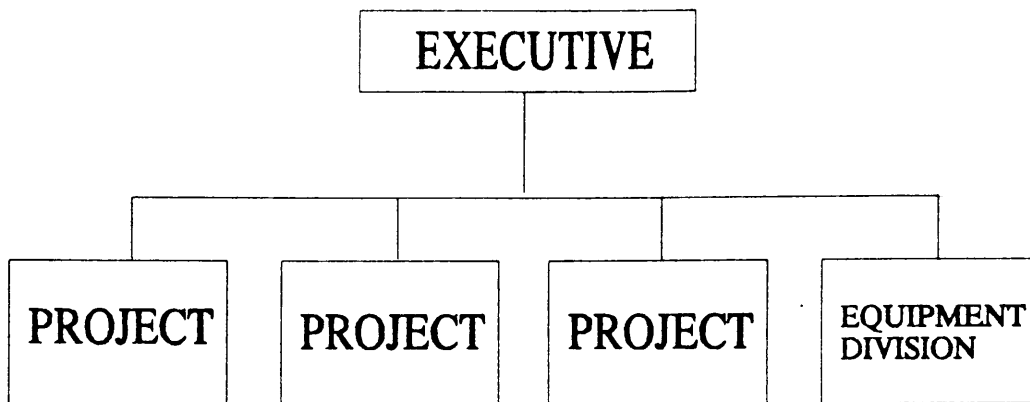
Another factor determining how equipment decisions are taken is the position of the equipment function within the organizational hierarchy of the company. Specifically the equipment function can be located either at the project level, or at the company level.

When the function is located at the project level, equipment decisions are taken fully by the project. This option is only feasible when the size of the project is big enough to justify a whole support function within the project. The equipment support function being fully integrated within the project would require that all purchasing, allocation, maintenance and replacement decisions are considered within the project itself.

The company level equipment function, is the most frequently found form of organization among medium size contractors. In this form, the equipment function is carried out by an equipment division that is independent from other construction divisions and projects. The equipment division plays a support role to all projects in the company, and has complete authority over all equipment decisions including allocation and maintenance. In this organizational format, the equipment manager is at the same level of authority as that of the project manager or project superintendent and any conflicts between the two is resolved at the higher level, executive function. Figure 2 compares a project level layout to a company level layout. The organizational charts provided reflect the difference in lines of authority. Namely in the company level layout the equipment and construction functions are at the same level of importance with regards to the executive function.



PROJECT LEVEL EQUIPMENT DIVISION



COMPANY LEVEL EQUIPMENT DIVISION

Figure 2. Project Vs Company Equipment Function (Vorster, 1988)

2.3 Maintenance In The Organizational Setting Of The Company

When the equipment function is organized at the project level, maintenance responsibilities are undertaken by the project. This is a simple environment for applying maintenance because all activities are centered to one geographic location. When the equipment division is independent from the projects, the maintenance function becomes a more complex process. In a medium size contractors organization the maintenance function can take one of three forms:

1. Maintenance can be dispatched from a central shop that serves all the projects of the company. This option is only feasible when all projects are concentrated in an area economically accessible to maintenance vehicles and personnel.
2. Maintenance activities can be undertaken from different regional shops, with each of these shops responsible for a number of projects in its vicinity.
3. Routine maintenance can be a project function and heavy repair or parts replacement can be undertaken at the main shop.

Since most contractors fleets are diversified, the possibility of having a shop with comprehensive coverage for all fleet repair requirement is very slim. Therefore all above maintenance options are coupled with the dealer or manufacturer repair option. In this case the repair items that are beyond the contractor's mechanical means are sent to the equipment supplier shop.

Centralized Vs Decentralized maintenance

Conceptually two options are presented: Centralized maintenance, with all maintenance activities undertaken through one or a series of central shops. Decentralized maintenance where maintenance activities are undertaken at the project level except for complex maintenance items that need special facilities to be performed.

Centralized maintenance has many advantages. The flexibility of assigning workmen with specific skills to different projects makes it more efficient than decentralized maintenance. Fewer maintenance workmen are needed since specially skilled workmen can be used in all maintenance areas. The same concept applies to special equipment that can be used to a higher degree. The concentration of personnel and tools in one location permits more effective job training, and allows maintenance standards to be formulated, applied and preserved (Niebel, 1985).

Centralized maintenance also presents some disadvantages. In view of the remoteness of some of the maintenance work, more cost and time is spent on mechanics transportation. This cost is augmented by the increase in machine downtime due to the delay of maintenance application. The remoteness of the job makes the supervision of field work more difficult and could eliminate supervision in some cases.

In contrast to centralization, decentralized maintenance eliminates the travel time and cost and the consequential downtime cost due to the maintenance delay. The production and the maintenance workers being on the same project enhances the spirit of cooperation and facilitates both functions tasks. Another advantage of decentralized

maintenance is the acceleration of the learning curve due to the fact that project mechanics work on one set of machines, repetitively and for periods of time.

With a \$20 to \$30 million maximum project size, and an average duration of one year, medium size contractors cannot afford to designate a maintenance shop for each project. At the same time the dispersion of projects away from the main shop, makes it impossible for maintenance to dispatch a mechanics every time a machine breaks down on a job. The solution that most contractors have adopted is to designate a mechanic for each remote job.

The vertical axis in figure 3 describes the required maintenance functions and the horizontal axis describes the facilities needed to perform them. As the maintenance functions become more complex better facilities are needed to perform them. Mobility is a crucial factor in the project mechanics job because the equipment that must be serviced is distributed over a large area of the project. This requirement constrains him to a service truck as a maintenance facility. The truck is usually equipped with an air compressor and an electrical boom. The repairs the project mechanics can handle consists of replacing ground engaging tools, disposable components such as hydraulic hoses, alternator belts, and primary support components such as alternators, starters, and water pumps. Complex maintenance items such as engine, transmission, final drives, track repair or rebuild are transferred to the main shop.

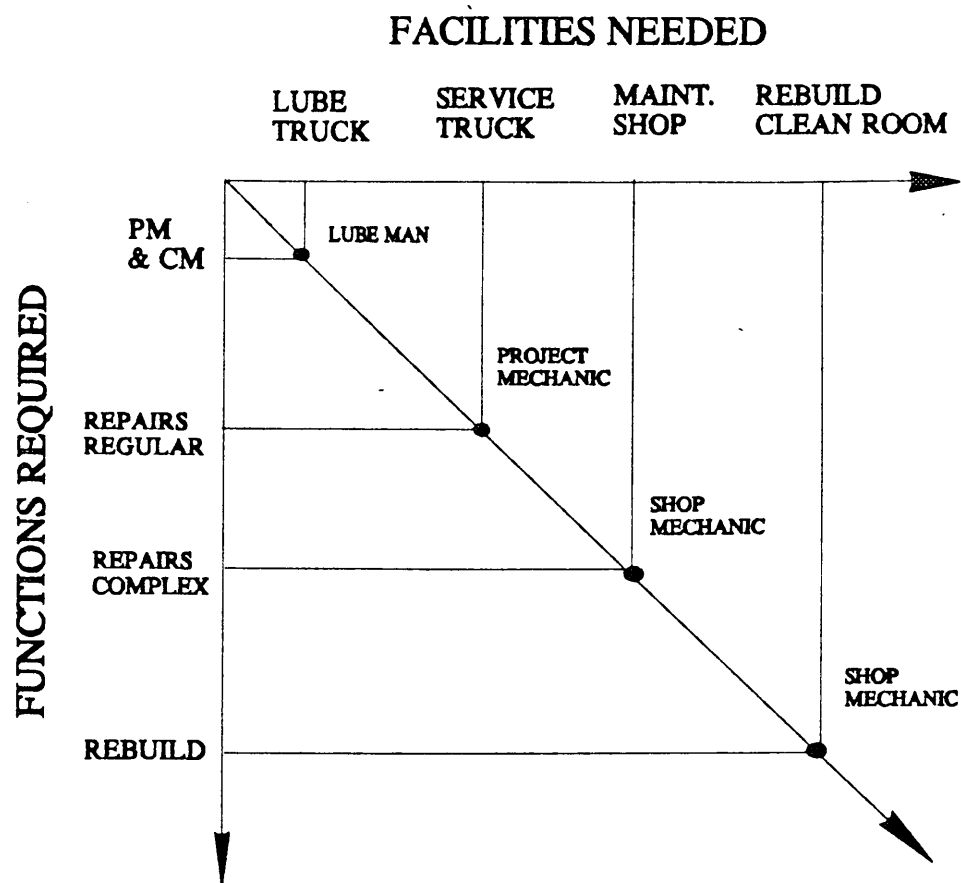


Figure 3. Maintenance Functions And The Corresponding Facilities Required

2.4 The Production Maintenance Conflict

An important consideration in developing any maintenance program is the delay inflicted to production by planned maintenance actions. This problem is intensified in the medium size contractor organization by the lack of backup equipment, and the low availability of mechanics. The result is continuous clashes between project superintendents and equipment managers. Generally the psychological pressures of production schedule requirements give the superintendent a stronger cause. Typically machines are worked until failure. Backup equipment is rented or brought in from other projects. The equipment is unexpectedly sent to the shop which gets clogged with backlog repair items. Delay occurs in the shop, frustration spreads everywhere, low productivity and disorganization governs.

This type of conflict cannot be solved unless top management in the company acknowledges the fact that equipment will fail anyway. Without planned maintenance it will fail earlier and with a higher cost of failure. A maintenance policy should be formulated for the company. The policy should specify a formula for prioritizing maintenance over production and vice versa. The bulk of the problem lays in the stoppage of machines in the middle of a production run. Project superintendents consider planned maintenance time unnecessary lost production. The long term benefits of maintenance actions seem out of balance for them and they cannot tolerate the idling of machines. Maintenance people short on time and personnel and pressed by the preprogrammed schedules need to perform their checks and repairs promptly. Coordination is not available and confrontations result. Three options can be adopted to circumvent the production tie-up problem. These options are as follows:

1. The first option is to plan the maintenance of heavy production items such as heavy dozers during lunch breaks. If time is a problem the maintenance schedule could be broken up in order to be performed in 2 or 3 breaks. Less critical machines such as a scraper in a dozer-scraper operation can be pulled away from the fleet one at a time so that the effect on production is minimal.
2. The second option is the after hours maintenance option. In this case Mechanics would come on a night shift or on week ends to perform the maintenance work. This option is hampered by the fact that extra mechanics might not be available, and the regular mechanics will be exhausted by the end of the regular day to perform effective maintenance.

2.5 Owning & Operating Costs

As in any capital venture, purchasing and running equipment involves many costs. These costs are termed owning and operating costs(O&O). O&O costs play an important role in equipment management. They form the basis for the rate charged for the construction division for its equipment use, and constitute a tool monitoring and controlling the maintenance application.

The owning costs consist of the depreciable capital investment in the machine, the interest incurred on any loans made to purchase the machine and the insurance payments. The owning cost rate of a specific machine is fixed since all elements of the cost are accrued on a regular periodic basis. The most striking fact about owning costs is that they

are always there. Whether the machine is operating or not, it is depreciating, and it is accruing interest and insurance costs. This fact constitutes a strong motivator for equipment managers to maximize the utilization of their equipment.

The operating costs consist of operators, fuel and maintenance costs. Figure 4 describes the operating costs. The variance of the measure of consumption and the cost per unit of consumption are laid out, and an overall predictability for the cost item is deduced. As an example the operator of consumption and cost present very small variations, giving a high predictability to this cost item. In contrast, the interval for a component replacement as well as the cost of this replacement, present a high level of variability, giving this cost item a low predictability. The effects of this predictability will be discussed in the next two sections. The operating costs are affected by the following factors:

1. The operating environment: the physical environment the machine is working in decides the rate of deterioration of its wear items and other components in the machine.
2. The design quality : usually heavy equipment are sturdily built but design or manufacturing standards will define different lives for comparable components of different makes. The variations are noticeable when complex components such as engine, transmission and final drives are considered.
3. Operator's competence: The manner in which a piece of equipment is operated has a strong effect on the life expectancy of many components in the machine. As the equipment become more complex, better skills are required to operate it correctly. Training programs and operator expertise of different companies being different, the

OPERATING COSTS

PREDICTABILITY










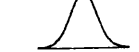

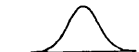

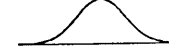

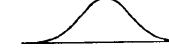

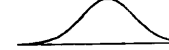
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FUEL	▪	CONSUM/HR	*	COST/HR	HIGH
					
ROUTINE MAINT.	▪	INTERVALS	*	COST/ACTION	HIGH
					
OIL/GREASE	▪	INTERVALS	*	COST/ACTION	HIGH
					
GET	▪	INTERVALS	*	COST/ACTION	MEDIUM
					
TIRES UNDERCAR.	▪	INTERVALS	*	COST/ACTION	MEDIUM
					
REPAIRS	▪	INTERVALS	*	COST/ACTION	LOW
					
REBUILD	▪	INTERVALS	*	COST/ACTION	LOW
					
REPLACE	▪	INTERVALS	*	COST/ACTION	LOW
					

Figure 4. Equipment Operating Costs

effect on equipment condition and therefore maintenance costs will present the same variability.

4. **Maintenance Intensity:** the quantity and quality of maintenance is directly correlated to the operating cost of the machine. More intense maintenance means increased spare parts and labor cost. The trade-off is increased machine availability and productivity. This point will be expanded later in the chapter.

2.6 Accounting For Equipment Cost

Cost Accounting

Direct charge and standard costs are the two main formats used to account for equipment costs in a contractor organization. In the direct charge format the operating costs are calculated periodically and charged to the construction function. The fixed owning costs are charged also on a regular basis. In the standard cost format, a standard hourly cost for each item of equipment is calculated based on an average value of the owning and operating costs. This becomes the rate charged to the function. The standard cost format is the most widely used, and it is motivated by two considerations:

1. It is impossible to calculate accurately the operating cost on a machine for a short period of time. Because machine breakdowns occur randomly, operating cost over short periods of time will present strong fluctuations, and therefore a distorted figure of the real operating cost is produced.

2. There is an optimum level of control in each project. Changing the rate the equipment division charges on its machine creates a lot of complexities in construction costing and budgeting. The simpler the charge format the easier it is for the project manager to know the real cost he is incurring on his equipment usage, and the easier it is to control this cost.

Division Vs Project Cost Accrual

The other complication in cost accounting is the distribution of the charges between the equipment division and the projects. Referring back to figure 4, maintenance costs are divided into lubrication, wear items, and large repair items. Lubrication items consist mainly of filters and lubricants, wear items include ground engaging tools, tires, tracks, and large repair items include transmission, engine blocks, hydraulic cylinders and final drives. Two factors should be considered when deciding on the charge distribution for operating costs.

1. As the predictability of a maintenance item decreases, the project is less inclined to accept the charges for the item.
2. The nature of medium size roadbuilding organizations dictates that the machines be transferred between different projects at short time intervals. It follows that the damage inflicted to the machine by a single project cannot be readily spotted.

Figure 5 shows the operating costs in increasing complexity order on the horizontal axis, and the predictability of these costs on the vertical axis. The figure suggests that as the complexity level of the operating cost item increases, its predictability decreases. The author suggests that, as the predictability level decreases the item should be charged to

the equipment division. This makes the project responsible for operator, fuel, planned maintenance and wear items costs. The equipment division will be responsible for the rest of the items.

It is hard to decide on a cutoff point for charge distribution. The tires, tracks, and some other regular repair items form a grey area where conflict is apt to occur. Management cannot systematically classify an item as a project or a division cost. A required rebuild job on a set of tracks cannot be charged to the project if the equipment has only been on the project for a month. In order to avoid conflict, management should exercise sound judgement when dealing with similar situation.

The cost allocation policy has a direct effect on equipment condition. Since project managers are not responsible for large components repair they might be tempted to neglect those aspects of maintenance affecting the long term condition of the machine. A special clause for equipment abuse should be specified in the cost distribution policy statement. The clause should hold responsible and charge the projects for repair items caused by equipment abuse. This can consist of untrained operators running complex machines, machine use for purposes other than the ones it was designed for, or neglecting preventive and condition monitoring instructions.

2.7 Maintenance Objectives and Requirements

Having defined the setting for the equipment decision process we can clarify the parameters that define a comprehensive maintenance function in a company. It is of great

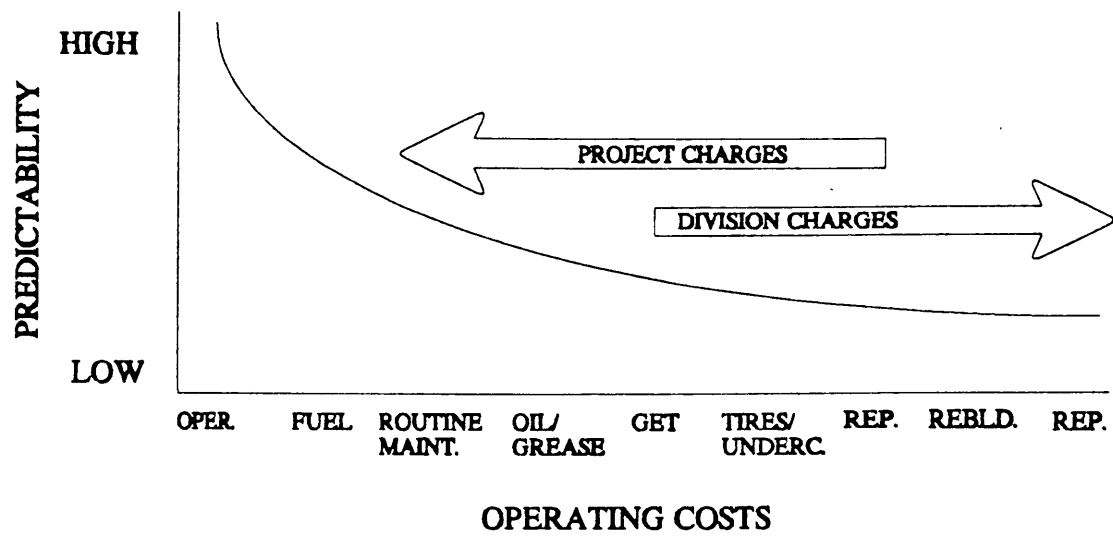


Figure 5. Project Vs Division Cost Allocation

importance to note that the objectives of a maintenance service is dictated by the nature of the enterprise. They vary to a great extent. If for example the enterprise is a hotel, then the objectives of maintenance is maximum customer satisfaction. This may entail both, a high standard of workmanship, and a speedy service. In the case of the airline industry, reliability is the dominant factor. If the enterprise is a mining operation, the objective is to minimize the maintenance cost per ton of ore. In the roadbuilding business, the requirement is a minimum cost per cubic yard of soil moved. So how is this goal reached through maintenance and what are the requirements for a comprehensive maintenance system?

Maintenance should aim at increasing the mechanical and operational performance of equipment. At the same time the maintenance investment should be balanced with the increased production of more efficient and effective equipment. More maintenance does not necessarily mean better maintenance (Niebel, 1985). As an example increasing maintenance spending means an increase in machine reliability and extra machine life. But it also means increased mechanics hours and can take production equipment out of operation to such an extent that cost effective maintenance has been submerged. Figure 6 illustrates this point by showing the relationship between maintenance expenditure and the availability of the machine. A point of diminishing returns exists, whereas increasing maintenance expenditure decreases the availability of the machine rather than improving it.

Maintaining a healthy equipment operation is not only changing oil at 250 hours intervals. It is also employing the right people to operate the equipment, optimizing the maintenance philosophy combination, and providing usable information for management to make good decisions.

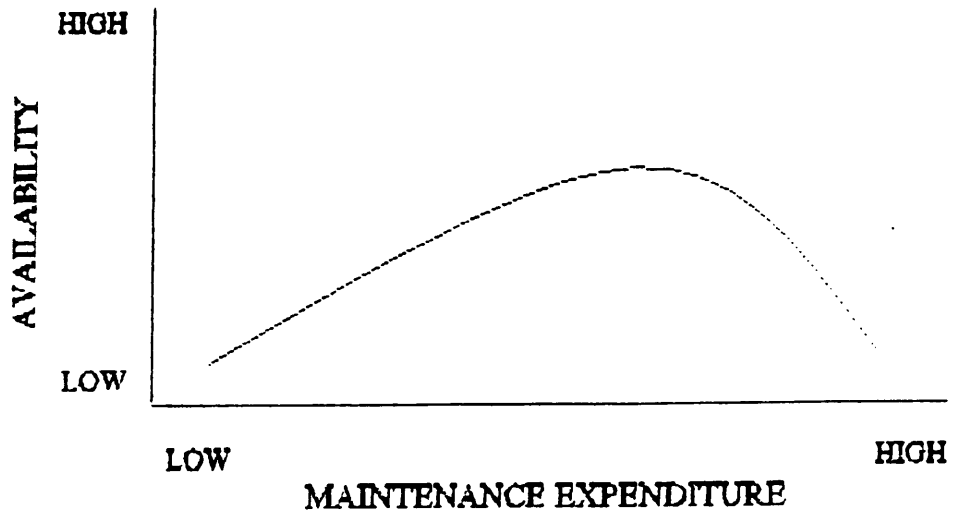


Figure 6. Relation Between Maintenance Expenditure and Availability

A comprehensive maintenance system striving to optimize the equipment function consists of the following components:

1. **An operator's training program:** This program should be an ongoing process within the contractor's organization. Mating untrained operators with complex machines produces failures. Manufacturers are producing more capable, more efficient and at the same time more intricate equipment. A contractor looking to ride the train of growth and development has to keep up with technology. Having competent operators is definitely a prerequisite.
2. **A decision model:** The function of the model is to optimize the maintenance choices (breakdown, preventive, condition monitoring) and extent of application. This is the brain of the maintenance system. It is a combination of economic rules and empirical decision strategies that applies specifically to the operation of a highway contractor.
3. **A decision support system:** This is the tool used to generate, schedule, and track maintenance workorders. The system will build machine history files, cost analysis reports, and produce other financial and operational ratios. These ratios are used by management to monitor and control fleet and maintenance performance.
4. **A policies and procedures manual:** The manual is aimed at reinforcing importance of maintenance for management, reducing conflicts between production and maintenance, creating guidelines for mechanics and other personnel to follow when executing maintenance actions.

The maintenance manual gives maintenance personnel a clear definition of proper practices. It gives step by step explanations of how to perform maintenance activities, instructs mechanics on what forms are to be filled out, and provides an overview of maintenance programs and organizational structure (Derks, 1988). Other benefits from the maintenance manual include improved worker productivity, minimal training time for new employees, increased communication and a systematic approach for administrative management.

2.8 Conclusion

This chapter provided the background against which different equipment decisions are considered. Maintenance is affected by every element of this background. The intent was not to explain all the details of equipment management, rather it was to give the reader a feeling for the complexity of the maintenance decision as it relates to the final goal of maximizing company profits. The training programs, and the policies and procedures manual are out of the scope of this thesis. The next chapter will develop the decision model.

3 The Decision Model

Different failure philosophies have been developed over the last four decades. Be it breakdown, preventive, or condition monitoring, each of these philosophies has its advantages and drawbacks. What concerns the highway contracting industry is maximizing the equipment effectiveness regardless of the maintenance philosophy used.

The concept of a measure of effectiveness implies that a goal is set and that at the end of the period under consideration the extent to which the goal has been achieved is measurable. Thus a necessary prerequisite of employing a measure of maintenance effectiveness is the definition of a goal or objective that is to be achieved. Since safety is not a primary factor in this industry, effectiveness is mostly evaluated in economic terms.

A simple rule of economics for equipment is optimizing the production cost by minimizing equipment operating cost. As defined earlier operating costs consist of fuel, operators and maintenance costs. Fuel and operators costs are dissipated at a constant rate based on machine utilization. Minimizing operating costs consists of optimizing the value of every dollar spent on maintenance.

One factor affecting maintenance expenditure is the maintenance philosophy adopted by the company. One maintenance philosophy might not necessarily be the best for all components of the machine. Based on failure symptoms and criticality, a combination of many maintenance philosophies is necessary to economically maintain all components of the machine.

This chapter will develop a decision model for choosing among different maintenance philosophies. The model evaluates critical components of the machine and assigns to it a maintenance instruction. The practicality of the model is emphasized.

The maintenance application will be a combination of preventive and condition monitoring maintenance. As economic performance is sought, breakdown maintenance might be justified in some instances. Reliability centered and total preventive maintenance as defined in chapter one will be guidelines to set up and apply this combination effectively. The preventive maintenance philosophy will be laid out next. The disadvantages of this approach will lead us to modify it and conclude with the decision model.

3.1 Preventive Maintenance Revisited

Preventive maintenance philosophy states that a maintenance program consisting of extensive inspection lists and periodic maintenance actions is the most effective means to prevent equipment failure. The basic mechanism in a periodic maintenance program is a series of checklists detailing the maintenance functions that should be performed as well as the maintenance frequency. The simplest preventive maintenance policy is known

as the age based policy. According to this policy, equipment is either repaired on failure or, preventive maintenance is undertaken when a specified operating age is reached. A deviation from this policy is the block based policy which states that preventive maintenance should occur at specified schedules whether failure occurred between these schedules or not (Harris, 1985). Figure 7 illustrates the age based and the block based policies. Block based PM is easier to administer. However, it is inefficient in that it does not take advantage of idle time spent repairing the equipment when a failure occurs.

The preventive maintenance program formulation is based on the manufacturer recommendations through the maintenance and service manuals produced for each machine. Another factor in developing these recommendations is the maintenance personnel input. This input is very important because it adapts the standardized manufacturers recommendations to the specific contractor organization. This is especially valid when maintenance intervals are concerned. The manufacturers specified intervals may prove too conservative or might lead the machine to be undermaintained when applied to the contractor's environment of operation.

3.2 Critical Evaluation Of Preventive Maintenance

Research conducted by Pottinger and Sutton (1983) in a wide range of industries concluded that conventional maintenance management systems, even the most sophisticated ones do not work. That is they fail in enabling the maintenance manager to control problems rather than having problems in control. Pottinger and Sutton site the following as limitations to the periodic maintenance programs:

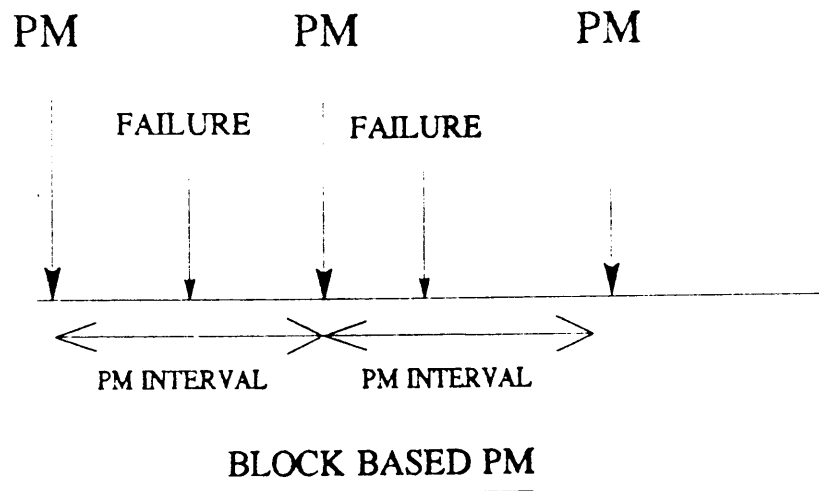
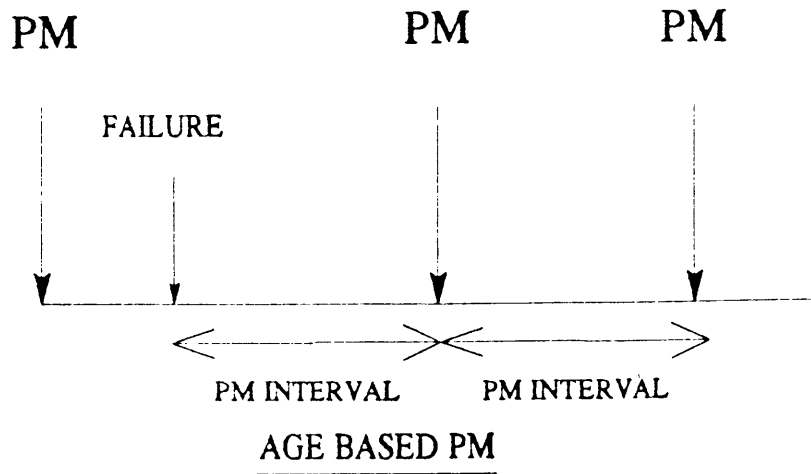


Figure 7. Age Based Vs Block Based Preventive Maintenance

1. Nearly all current planned maintenance systems prescribe work which is unnecessary and which often achieves little for the organization in terms of improved reliability and performance of equipment.
2. Maintenance planners err on the side of conservatism and go for safety in task frequency. This results in an impractical load for the maintenance department. At the same time production suffers because of an excessive stoppage from maintenance actions.

Excessive maintenance is seldom a problem in highway construction. In fact, the majority of medium size contractors undermaintain their equipment. Fear of change and the lack of statistical information do not give a base for the maintenance planner to manipulate the maintenance checklists and intervals in an efficient manner. But the dominating method of preventive maintenance is still the regular periodic maintenance schedules. These schedules will always be the central part in any maintenance program. It is the content, the intervals at which they are applied and the seriousness of their application that decides their effectiveness.

For some components a PM check or adjustment is effective. Changing the oil and checking coolant level are essential for preserving engine life. The intervals at which these measures should be taken will vary depending on manufacturers recommendations, machine age and operating conditions. But, changing the engine or transmission oil will not indicate when this engine will fail. Manufacturer recommendations regarding component life fall short of being exact, again because of the difference in operating environment for different contractors.

Only close inspection and condition monitoring will give some indication of a failure trend. In this case, the maintenance division will have enough time to plan backup equipment and prepare the maintenance personnel and replacement parts for the job. This problem can be clearly illustrated by an evaluation of a dozer tracks. A PM schedule might specify regular cleaning and lubrication of tracks but only a detailed track component measurement will reveal the true condition of tracks.

Successive measurements can be taken to build a wear trend and forecast useful life. Whether they must be overhauled, replaced or adjusted is then decided. Tire condition and oil sampling are two other examples of condition monitoring. We therefore conclude that even with a comprehensive preventive maintenance program, some components condition must be monitored in order to determine the optimal time for maintaining them.

The condition monitoring must be planned and consistent. Spontaneous oil sampling might show indications of increased lead or aluminum level in engine oil, but only a trend of the different metals and other substances level will show the rate of deterioration in the engine and give an indication of a failure potential. Consistent and well documented condition monitoring is an important input in building failure history records for different components of equipment. These records will form dependable information for defining effective maintenance checklists and intervals. One of the big advantages of such information is that it is peculiar to the contractor operation and therefore it is more reliable.

3.3 Background For Developing The Model

The decision model to be developed takes into consideration the different maintenance philosophies previously introduced. Equipment management in a highway construction company dictates two facts that lead the model to emphasize practicality:

1. Statistical data required to feed intricate decision models is not available.
2. The personnel administering the maintenance function is application oriented, and mostly use their gut feeling to make decisions. This gut feeling is frequently more valuable than many complex economic models. Because these people lived with the equipment, they know how it is operated, how it is maintained, and in what physical environment it functions. For them to accept any decision tool it has to be practical.

3.4 Methodology For Model Development

The model will be layed out in the form of a flow chart . The prerequisites for the decision process will be supplied first and the explanation of the model components will follow. The procedure for developing the model is based on the reliability centered maintenance procedure developed for the airline industry and introduced earlier in the thesis (Nowlan & Heap, 1978).

The first step in the procedure is to identify all significant items of equipment. A significant item is any item or component of an item whose failure could affect operating

safety or have major economic consequences. This stage of the procedure involves reducing the scope of the investigation to a manageable size by identifying significant equipment items. Partitioning the equipment into systems is a good method to isolate the significant items. Figure 8 provides an example of a dozer partition. The dozer is divided into a structure, an engine, a transmission, and the final drives. Each major division has a number of supporting systems such as the lubrication, the cooling and the fuel system for the engine. Finally, each system is divided into its major parts. The radiator, the water pump, and the hoses are the major parts in the case of the cooling system. Using this hierarchical analysis, the effect of each component on the system, and consequently on the functionality of the whole machine can be clearly identified.

The second step of the procedure is to evaluate the consequences of failure for each significant component. Different components will show different signs of failure. Failure is defined as a partial or total loss of functionality of the component that would affect the effectiveness of the whole machine. As an example a failure in the track shoes of a dozer reflects excessive wear in the grousers that affected the function of providing traction for the machine. This step should include the following measures:

1. Description of all the functions demanded of an item.
2. A clear definition of the conditions that constitute a functional failure in each case.
3. The possible failure modes associated with each functional failure.

The third step in the procedure is the selection of the appropriate maintenance measures. This is the bulk of the decision model. It consists of taking each component failure mode and applying to it the appropriate maintenance task. For some components simple preventive maintenance is all that can be done to preserve their life. For other compo-

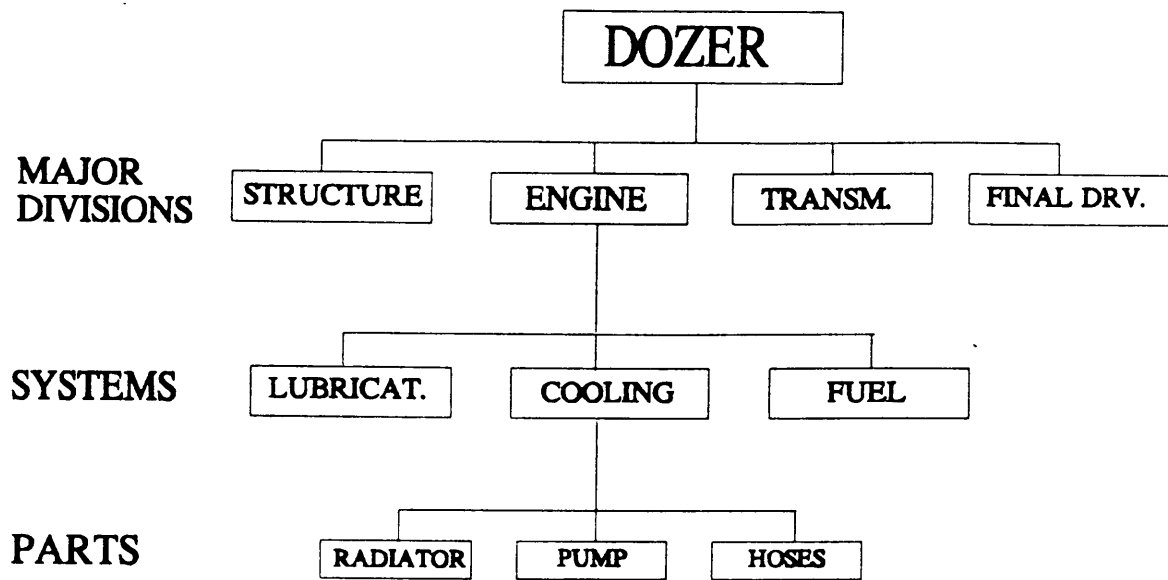


Figure 8. Equipment systems division

nents, condition monitoring and close inspection would be a benefit in forecasting failure and determining the optimal replacement time. Still other components should be totally consumed and allowed to fail before replacing them.

The last step of the procedure is to develop the optimal maintenance frequencies. The decisions for this step should rely basically on manufacturers recommendations and the maintenance mechanics experience.

3.5 The Decision Process

The model focal point is whether the failure trend is observable or not. The detectability of the failure trend decides on the failure tolerance and the prevention method that should be utilized. Figure 9 lays out the decision diagram. It is important to note that some sort of regular preventive maintenance can be performed on every component of the machine. Examples of possible decision pathes are described below:

Path 1-3 is basically the simplest decision rule. If the failure trend of a machine component is observable, two measures can be taken to maximize component life and optimize the repair function. Perform regular PM, Closely inspect component and repair or replace it when it reaches a certain failure limit. Considering the dozer tracks again, the wear extent on the track shoes, rollers and sprockets can be observed. An excessive wear on any of these components would lead to increased after failure repair cost. Since wear is observable the best policy to follow is to periodically clean the tracks, lubricate the rollers and check the sprockets and replace the components when they reach their failure

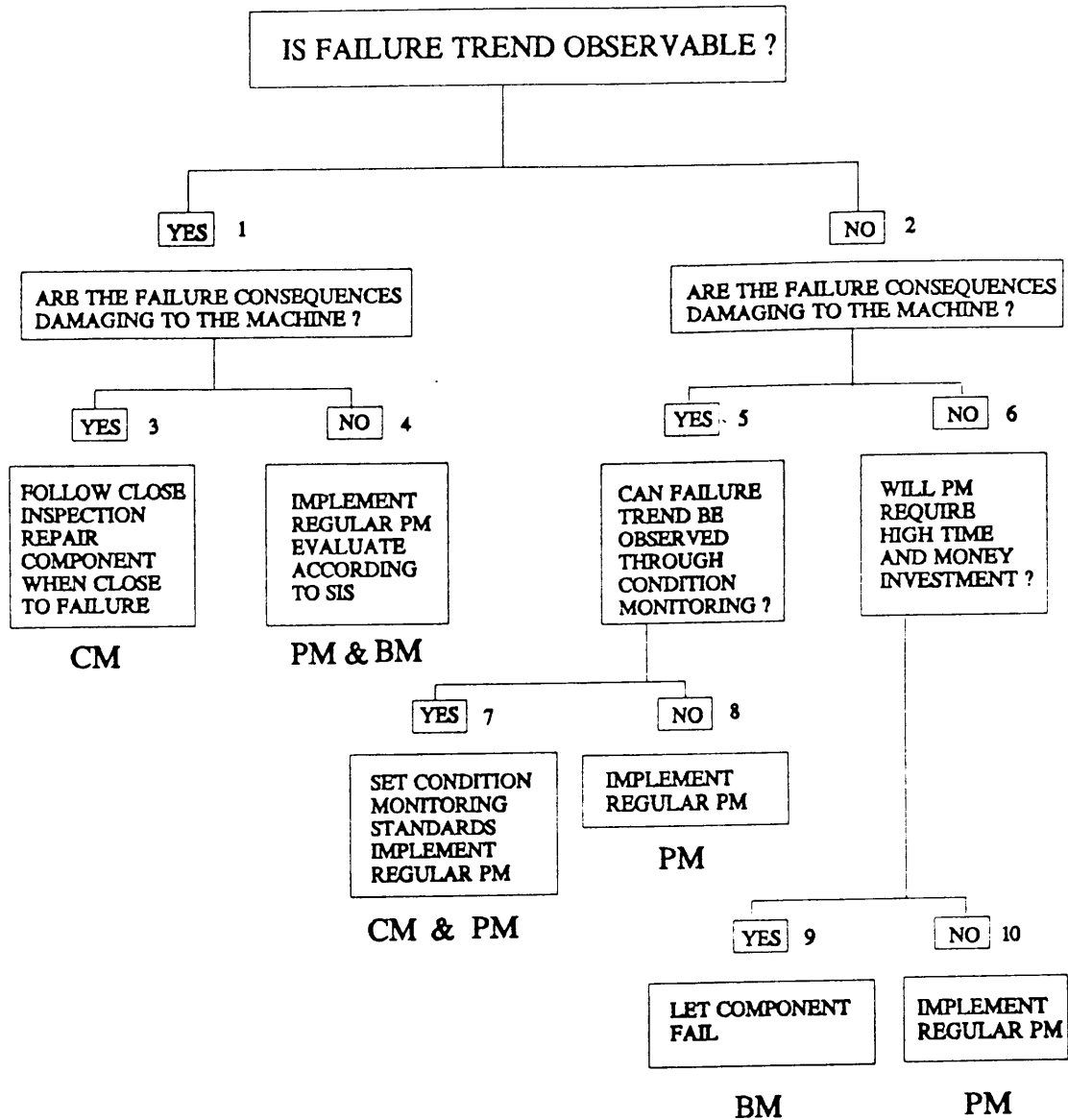


Figure 9. The Decision Diagram

limit. The track bushings present a striking example in this case. Monitoring the condition of the bushings leads to the detection of a certain optimal state where turning the bushings around extends their life by about 40 % .

Path 1-4 illustrates the situation where the failure trend is observable but were the failure consequences are not damaging to the machine. In this case, it might not be economical to change the component after a certain limit. The best alternative would then be to let the component fail or adopt SIS. SIS is an abbreviation for the term since in shop. SIS states that if a machine is brought in the maintenance shop for repairing a specific item, other components that reached a certain operating life would also be changed. This would save the mobilization and tear down time later when these components fail. An example to illustrate this case is the exhaust system. Failure trend in the exhaust system is observable. The consequences of exhaust failure are not really damaging to the machine. This component will either be operated until failure or will be replaced when machine is stopped for a more serious repair. In general when the maintenance trend is observable the maintenance application is an easier decision than when it is not observable. With a good inspection system and operator awareness of where and when to look for problems it is a relatively easy task to optimize the utilization of these components.

Path 2-5-7 is the case were the failure trend is not observable and where the consequences of failure are very damaging to the machine. In this case investigating the possibility of condition monitoring to follow the failure trend of the component is necessary. If condition monitoring is a viable solution, the standards and limits for the performance of the component are set. The regular PM items will still be performed but the repair or replacement of the component is based solely on the failure trend developed by the condition monitoring system.

An example in this case would be the engine. Failure trend is not readily observable, and the consequences of failure are very damaging ranging from reduction in machine efficiency to a total breakdown. The solution would be to monitor the condition of the engine using oil sampling, fuel and lube consumption logs, and performance time studies to determine the failure trend of the engine. These condition monitoring methods are not costly nor time consuming. Added to the regular PM schedules they would give an optimal cover for preempting failures and maximizing component life.

Path 2-5-8 follows the same logic as path 2-5-7 except that condition monitoring methods cannot be used, or will not be effective as a warning device for failure. In this case the only possible remedy is to perform a regular preventive maintenance according to manufacturers recommendations.

Path 2-6 in the model presents the case of a component where the failure trend is not observable through inspection, but where the consequences of the failure are not very damaging to the machine. In this case the component might be secondary. Applying PM to it becomes debatable. The time and money invested in PM should be measured against the benefits obtained from it. If PM means more loss in production than saving in component life preservation, option 9 should be adopted. The component should be left to fail. If PM investment is balanced by the saving in component life, then PM applications should be performed. This is option 10.

3.6 Conclusion

This chapter developed the decision model for applying consistent maintenance philosophies to machine components. The model constitutes a simple and practical decision tool that planners can use to attack the maintenance problem in a structured manner. Each of the maintenance philosophies adopted has its advantages and disadvantages. It is an optimal combination of the philosophies that maximizes the effectiveness of maintenance on a certain machine. This is what the model aimed at accomplishing.

Improvements to the system depends on influencing the two main activities of preventive maintenance and condition monitoring. With regards to preventive maintenance, including the critical components and optimizing the interval of execution is the condition for effectiveness. The basis for condition monitoring is that through inspection of wear behavior the more important components are continuously monitored. On purely economic grounds, there is nothing to be gained from including items which have no significant effect on availability. This is the justification for allowing such items to fail.

The policy development is only part of the maintenance function application. It is complimented by an administrative process to organize, monitor and administer the maintenance application and by a managerial process to interpret the control figures and use them to optimize equipment decisions. The next chapter will develop the maintenance administration and control system.

4 Maintenance Administration And Management Control

The model presented in chapter 3 defined the best maintenance alternative for different equipment components. The next step is the application of the maintenance function. The conversion of maintenance philosophies into practical systems requires a well organized administrative process. This process will define what maintenance actions should be taken and when they should be performed. These actions must also be monitored and their costs should be controlled. Management should be able to use the information generated by the administrative process to measure the effectiveness of the maintenance application, and to improve equipment decisions. This chapter will layout the administrative aspect of equipment management as it relates to maintenance, will define the management information system as the driving engine of the process, and will discuss the managerial parameters used to assess the maintenance function.

4.1 The Management Control System

The management control system consists of three modules. The first module is the work control system used to plan, schedule and monitor the maintenance actions. The second module is the equipment condition control system employed to create and update the equipment maintenance history. The third module is the cost control system used to monitor the effectiveness of maintenance and assist in making optimum repair, rebuild and replace decisions. These modules are interdependent in terms of data sources and their integration forms the basis for a strong maintenance management system. Figure 10 shows the three modules and their functions.

4.1.1 Work Control

The first module of figure 10 is the work control system. It consists of selecting machine maintenance requirements, preparing the maintenance workorders, scheduling the dispatch of the maintenance workorders to the different projects, and insuring the execution of these workorders. Figure 11 illustrates the work control process.

Maintenance Requirements Selection

The information compilation is directly related to the decision process discussed in chapter 3. Figure 12 describes the process whereby the components are evaluated and

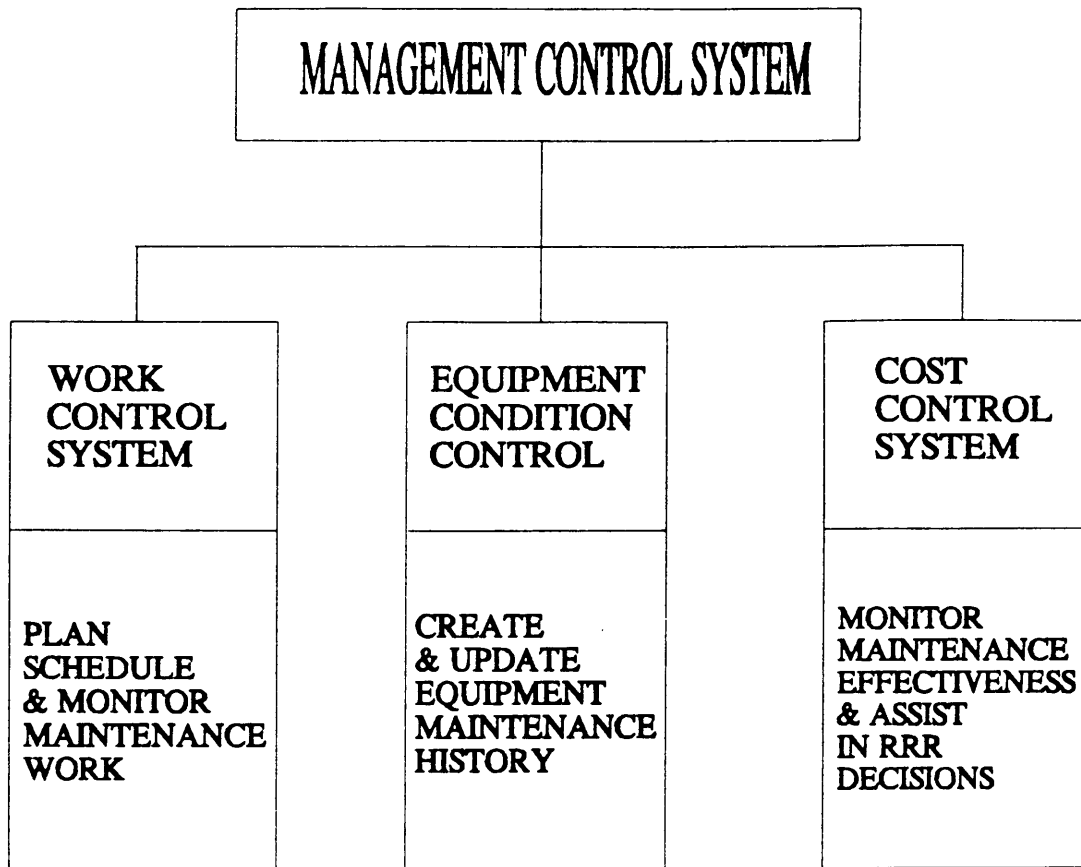


Figure 10. The Management Control System

WORK CONTROL

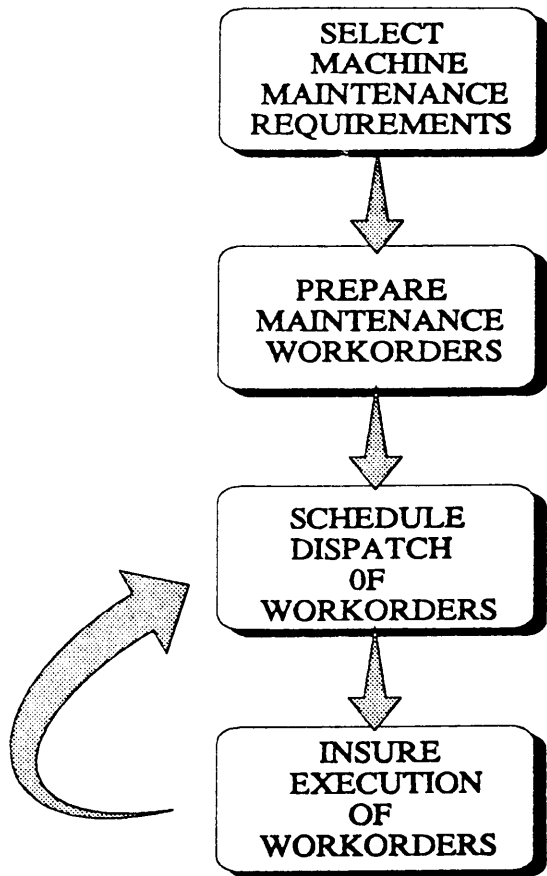
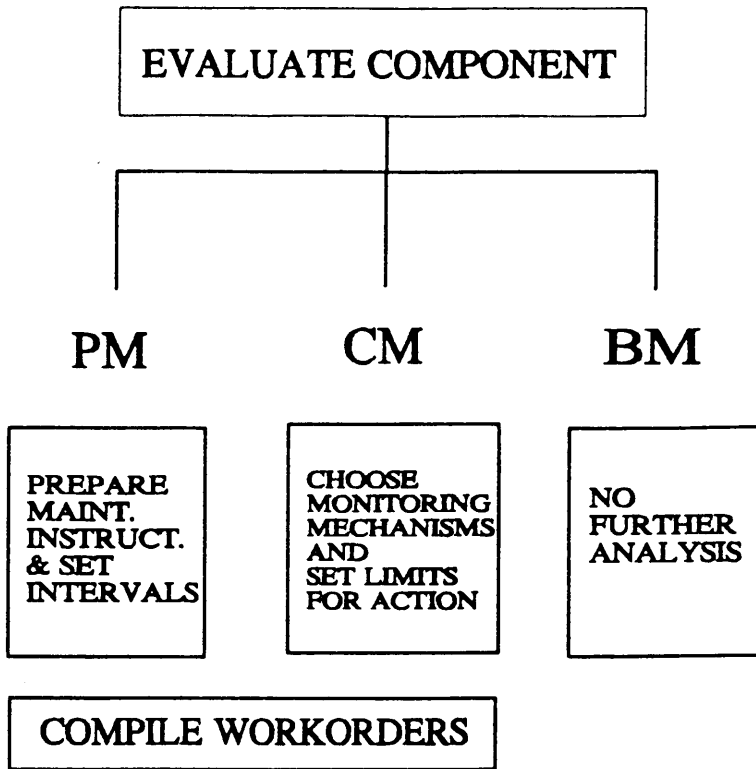


Figure 11. The Work Control System



PM - PREVENTIVE MAINTENANCE
 CM - CONDITION MONITORING
 BM - BREAKDOWN MAINTENANCE

Figure 12. Maintenance Requirements Selection

either preventive maintenance, condition monitoring, or breakdown maintenance is selected as the proper maintenance action. If PM is the choice, the maintenance instructions are formulated and the intervals specified. In the case of condition monitoring, the monitoring mechanisms and the intervals are chosen and the controlling limits for taking action are set. Transmission oil sampling at 500 hours with a requirement to change gears when the iron and lead accumulation rate exceeds 90 parts/million is an example. When breakdown maintenance is to be applied no further analysis is required.

Maintenance Workorder

The second module of the work control system as defined in figure 11 relates to the preparation of the maintenance workorder. This is the document that relays to the workforce the maintenance actions required on a piece of equipment. The workorder is a control tool that the maintenance planner can use to organize the operation. Without a well structured and carefully adhered to workorder system, the equipment division is likely to find the work coming in controlling the organization rather than the organization controlling the work (Niebel, 1985).

The workorder must fulfill the following functions:

1. Communicate to the maintenance personnel the details of the work required. Even in very centralized maintenance facilities, misunderstanding occurs. A mechanic forgetting to check an item or replacing a part, is a common occurrence in maintenance shops.

2. Indicate to maintenance personnel the parts and materials to be used in their operation. Lubricants, filters and other spare parts required in maintenance operations should be specified.
3. Provide a control system on maintenance labor spending. This is accomplished by taking feedback from the actual labor hours spent on equipment and comparing it to the estimated time for each repair. In order for these comparisons to be made, it is necessary to have a database of the average time it takes to repair different components of the machine. If the database is not already available, it should be built up as repairs are made.
4. Provide a feedback to maintenance management personnel on the actual adjustments or repairs vs those requested. Due to a lack of time, materials or personnel, not all maintenance items will be accomplished. Such items should be reported to the maintenance planning department to be rescheduled or reassigned.
5. Provide a feedback on any noticeable failure or malfunction in components not specified in the workorder. This can be accomplished by designing a comments section in the workorder. This process reinforces the close inspection process as a way to discover malfunction and deterioration in order to preempt failure.
6. Provide a feedback to maintenance management on the cause of the failure. The mechanic handling the workorder will specify what he thinks caused the failure. His assessment will then be used to control the failure cause and prevent similar occurrences.

Scheduling Maintenance Work

The third module of the work control system as defined in figure 11 is scheduling. Scheduling is one of the the advantages to doing preventive maintenance and condition monitoring over waiting until equipment fails and then doing emergency repairs. The key to scheduling is planning ahead. Scheduling for preventive maintenance and condition monitoring can be done weeks even months in advance. This will insure that production interruption is minimal, maintenance parts and materials are available, and the workload is relatively uniform.

Scheduling is primarily concerned with balancing demand and supply. Demand comes from the equipment's need for maintenance. Supply is the availability of the equipment, crafts people and materials necessary to do the work.

The scheduling process starts with defining the maintenance workorders and specifying the intervals at which they should be performed. The intervals will be standardized at 50, 100, 250, 500, 1000 and 2000 hours and all workorders over 50 hours contain subschedules. For instance the 100 hours workorder will include the items checked in the 50 hours workorder and 500 hours workorders will contain as subschedules the 50, 100, and 250 hours workorders items. It is recommended that the workorders specify all the details of their subschedules rather than just listing that their execution is required. The reason underlying this recommendation is that maintenance craftsmen will not be able to remember all the items of previous schedules. The best way to assist them is to actually list the items for them.

In order to simplify scheduling, the different maintenance workorders are designated with letters with each letter encompassing one or more workorder. As an example, the 50 hours workorder is designated by the letter A; the 100 hours workorder is designated by the letter B.

Figure 13 shows a sample schedule formulation. The code designates the maintenance levels in alphabetical, and the corresponding hours are listed next. The rightmost number under the hours heading corresponds to the cumulative operating hours needed to perform the maintenance workorders.

Two mechanisms are used to control the dispatch of maintenance workorders. The first is an operational mechanism, and the second is a calendar control. The operational mechanism uses the operating hours elapsed on a machine to dispatch the workorders at the proper intervals. The calendar controlled scheduling system dispatches PM instructions at prespecified time intervals. The advantage of time control is that scheduling the dispatch of PM workorders becomes as easy as reading a calendar. The disadvantage of this method is that it assumes a constant rate of equipment utilization and bases the scheduling intervals on this rate. In industrial operations, this assumption is valid because machines are worked for constant shifts. In a contractor operation, one work week for a piece of equipment can include 30 to 60 hours of operation. Therefore equipment runs the risk of being under or over maintained. The advantage of using hours elapsed as a control mechanism for scheduling is that maintenance is scheduled regularly. The drawback is the need to accurately report operating hours.

After the PM schedules are compiled and the intervals determined, the master schedule is prepared. The master schedule is a listing of all PM workorders by type and by period of dispatch. When the control mechanism is time, the master schedule takes the form

PM SCHEDULES ANALYSIS

=====	=====						
CODE	HOURS						
=====	=====						
A	50						
B	50	100					
A	50						
B	50	100					
C	50		250				
B	50	100					
A	50						
B	50	100					
A	50						
D	50	100	250	500			
A	50						
B	50	100					
A	50						
B	50	100					
C	50		250				
B	50	100					
A	50						
B	50	100					
A	50						
E	50	100	250	500	1000		
A	50						
B	50	100					
A	50						
B	50	100					
C	50		250				
B	50	100					
A	50						
B	50	100					
A	50						
D	50	100	250	500			
A	50						
B	50	100					
A	50						
B	50	100					
C	50		250				
B	50	100					
A	50						
B	50	100					
A	50						
F	50	100	250	500	1000	2000	

Figure 13. Schedule Formulation Sample

of a biaxial chart where the PM workorders form coordinate points relative to time in weeks, and equipment number. Figure 14 shows a sample master schedule. Two documents are produced from the master schedule:

1. The equipment schedule checklist: This is the document that lists all the schedules for a specific equipment. It serves as a check mechanism to insure that maintenance workorders are being performed.
2. The weekly job program: This is the document that lists all the equipment that should be maintained on a certain job for a certain week. This document helps the planning department dispatch the schedules for the different jobs at the right time. Figure 15 provides a sample of an equipment schedule checklist and a weekly job program.

Using the hours elapsed as the controlling mechanism is more accurate than calendar dependant scheduling, and will more precisely determine when maintenance workorders should be dispatched. This is where computerization would be effective. A computer database uses weekly operating hours reports to automatically generate a planning sheet that includes all equipment that reached a maintenance interval. This is equivalent to the weekly job program in the calendar controlled system.

When using the hours elapsed as the controlling mechanism the hour meter reading should be reported off each machine weekly. The problem with hour meters is that they have a high rate of failure. If not noticed and repaired when failure occurs, disrupt of the preventive maintenance scheduling process can occur. When the hour meters fail the operating hours reported are less than the actual operating hours on the machine. The

TIME EQUIP #	JAN	FEB	MAR	APR
	3 10 17 24	1 8 15 22	29 5 12 19	26 3 10 17 24 31 7 14
323	A B A B C B A B D B A B C B A B E A B A C			
453	A B C B A B D B A B C B A B E A B A C A B			
234	A B C B A B D B A B C B A B E A B A C A B			
155	A B A B C B A B D B A B C B A B E A B A C			

Figure 14. Master Schedule Based On Time Control

EQUIPMENT # 326

PM LEVEL DATE PERFORMED

A	4/03/89
B	4/10/89
A	4/18/89
B	4/24/89
C	
A	
B	
D	

EQUIPMENT SCHEDULE CHECKLIST

WEEK OF : 12/02/88

EQUIP #	PM LEVEL REQ'D
326	B
348	D
356	F
256	B
715	B
618	A

WEEKLY JOB PROGRAM

Figure 15. An Equipment Schedule Checklist & A Weekly Job Program.

direct result is a delay in the dispatch of the workorders that causes the equipment to be undermaintained. One way of monitoring the hour meters performance, is to request the fuel man or the operator to report the hour meter reading on a daily basis. Readings for consecutive days can then be screened and identical readings would give an indication of failure in the hour meter. The project mechanics can then be notified to repair or replace the meter.

4.1.2 Equipment Condition Control

The second module in the management control system illustrated in figure 10 is the equipment condition control. The preparation of maintenance schedules is not a once and for all exercise in establishing a planned maintenance scheme, As experience is gained, and equipment operational and historical data are built up through preventive maintenance and condition monitoring the schedules must be revised. The object of the revision is to ensure that an optimum level of maintenance is not exceeded to the point where uneconomic over-maintenance occurs and by the same token to insure that under-maintenance does not persist. What is important is to maximize the effectiveness of maintenance on the long run with respect to the actual availability and reliability of equipment. Whether it is preventive or breakdown, the maintenance function must be monitored. The equipment condition control forms the basics for the monitoring system. The equipment condition control operates by aggregating and analyzing the history of the equipment. This database consists of a chronological listing of events such as repairs, rebuilds, preventive maintenance, inspection and condition monitoring actions pertaining to the equipment. Parts, materials, and labor spending is also tabulated. This information is accumulated using the workorder system.

Another document used to accumulate equipment condition data is the inspection list. This is a checklist enumerating the critical items that should be checked when a machine is transferred among different projects. The concept and benefits of the inspection list will be discussed more in section 4.3.3.

Equipment condition control aims at identifying recurrent or major failures. These failures initiate an investigation into the real cause of the problem. In order to maximize the use of the system, the failures are classified by components and by cause of failure. A statistical analysis can then be performed to spot the components that reflect a high rate of failure and the cause of these failures. Figure 16 shows a sample equipment history data sheet. An index of the failure area and the reason for failure is provided in order to help make the coding scheme consistent. The results of the investigation initiate many corrective actions and can include the following:

1. Improvement of the preventive maintenance program either by adding a new action or by changing the frequency of an old action.
2. Improvements to the condition monitoring guidelines. These improvements can be made by adding better trouble shooting and fault finding methods or by raising the standards of corrective maintenance work.
3. Decentralizing the maintenance workforce or contracting out maintenance if it found ineffective in coping with the maintenance load.
4. Some failures can be traced back to incorrect operating procedures. If this is the case concentrated training programs can be implemented.

EQUIPMENT HISTORY DATA SHEET

EQUIP #:

DATE	REPAIR	PARTS \$	LABOR (HRS)	FAIL. CODE	FAIL REASON
<u>FAILURE CODE</u> 1 ENGINE 2 TRANSMISSION 3 TRACKS/TIRES 4 FINAL DRIVES 5 HYDRAULICS			<u>FAILURE REASON</u> A NORMAL WEAR B ABUSE C ACCIDENTS D UNDER-MAINTENANCE E OPERATING TECHNIQUE F ENVIRONMENT		

Figure 16. Equipment History Data Sheet

4.1.3 Cost Control

The third module of the management control system as defined in figure 10 is cost control. The necessity for controls in maintenance arises with the growth of an enterprise and its increasing complexity. Control is the process of monitoring a certain activity by keeping track of its parameters. Maintenance control is expressed both in terms of money and in operation figures. The later reflects the performance of the maintenance team and that of the equipment being serviced. Although money is considered a common denominator, it cannot quantify all the variables of the operation and therefore other units of measurement must be used.

Developing a control system has a number of prerequisites, the most essential are:

1. The right data must be collected using prescribed procedures so that they will remain consistent between periods, and in order to reflect similar activities in a uniform way.
2. The method of compiling data must be uniform so as to allow systematized presentation.
3. The information collected must be relevant to the objectives and policies of the company. The maintenance manager should determine why each statistic is collected and how it should be used. The information to be collected should serve a specific purpose otherwise it is a waste of time and money.

The control function in maintenance covers both cost and operational parameters. Cost control Aims at monitoring the cost of labor, parts and material and the overhead cost. The operation control aims at monitoring the application of manpower, the work com-

pleted and outstanding, and the performance of equipment. The control mechanism is based on four functions: Reporting, coding, budgeting, and variance analysis.

Reporting

Reporting is the process of information gathering and relaying to the maintenance planning. Commenting on maintenance reporting, Priel (1972) states that management's frequent lack of understanding of maintenance frequently, stems from the fact that good maintenance reporting systems are hard to find. Reporting is the first level tool for maintenance control. A good reporting system has the following ingredients:

1. An agreement on what is needed and what can be provided on a regular basis.
2. A reliable and consistent recording procedure to obtain data.
3. A competent staff to do the job.
4. A simple format for the report providing concise and relevant information.
5. A commitment to read and react to the report content.
6. A full support from top management to the reporting system.

Maintenance cost reporting consists of recording the actual expenditures in terms of labor time, materials and spare parts.

Labor time is reported using the time sheet or the workorder to register the actual hours worked on a piece of equipment. When the maintenance operation is well organized and sufficiently staffed, the workorders will identify all the hours spent in the shop. The average medium size contractor is understaffed, and the normal practice in his operation is to pull mechanics off their assigned workorders to deal with emergencies that occur

frequently. Consequently the workorders might not reflect all the hours worked and therefore time sheets should still be used. This problem becomes clear when we consider the field mechanics. Even when an excellent preventive maintenance program is in place field mechanics are always running around after small emergency repairs. Accounting for all their time requires an unrealistic number of workorders per day. The solution would be a daily log of their activities that they fill out and that is processed by the job clerk in order to post the activities to their respective accounts.

Time reporting can be used as an incentive program, in addition to accounting for labor hours. If the contractor can build a database of the average time for repairing or replacing different components, these estimated times can be specified on the workorders and the mechanics can work against them. Some sophisticated time recording systems such as bar code wands do a good job at controlling the mechanics time to the closest minute. These systems will be discussed in the next chapter.

Maintenance materials consist of lubrication fluids and grease. These should be reported by the fuel and lube man on a daily lube and oil sheet. Normally the fuel man takes care of the oil and lube too. So the reporting sheet will contain fuel, oil and lube for the different equipment on the job. Figure 17 shows a typical fuel lube oil form.

Spare parts are reported on the workorders as they are installed in equipment. They are accounted for using purchase orders and invoices. The posting of purchase orders and invoice information to the equipment database is an important factor in building machine history files and aggregating cost information.

FUEL/LUBE/HOUR METER REPORT

DATE: ___/___/___

PROJECT # : _____

EQUIP #	FUEL GAS	FUEL DIESEL	ENGINE OIL	TRANS. OIL	HYDR. OIL	HOURS

Figure 17. Typical Fuel/Lube/Hour Report Form

Coding

Coding is the labeling of the different cost information with the purpose of posting it to different accounts. Coding is the tool used to aggregate a mass of information into meaningful figures that management can use. Maintenance cost coding should consider the following accounts:

1. An equipment general ledger code: This is the general account for equipment, to be used for assessing total equipment operating cost and calculating profit figures.
2. A workorder code: Since all maintenance actions will be performed according to workorders, this code is useful to sort maintenance information based on workorders. The number of workorders processed, the cost and labor time spent on executing a workorder are examples of information that can be extracted from such a sort.
3. An equipment code: This is the initial equipment record where the history of the equipment is built. This code is used to post cost and labor time data to the specific equipment.
4. A subassembly code: This code relates to the different functional systems previously proposed to decide on the maintenance policy for each component. The example of dividing the track dozer into engine, tracks, transmission, and attachment was noted. This code helps maintenance analyze the cost distribution between the different parts of the machine. The benefit is that extra spending is pinpointed on a

component level rather than at the machine level. In this case control and remedial action become an easier job for the maintenance supervisor.

5. Reason for repair code: In addition to subassembly code, specifying the reason for repair gives the maintenance planning an edge in analyzing the equipment history, and allows for more preventive measures to be taken in reviewing current maintenance practices. Fatigue, heat, normal wear, or inadequate lubrication are examples of reasons for repair that can be coded.

Figure 18 illustrates an example of a coding scheme.

Budgeting

Budgets are integral parts of any control system, since they represent the standards against which actual performance is compared. Maintenance budgets represent management best estimate of expenditure for a defined period usually not exceeding one year. The level of equipment availability required, the historical maintenance workload, labor, materials, and spare parts requirements form the framework against which maintenance expenditures are forecasted (Schonert & Unger, 1980). Figure 19 shows a proposed budget formulation outline. The equipment fleet is broken down by equipment. The different functions the maintenance division is expected to perform are tabulated. For each function, the labor, overhead and materials requirements are estimated. The overhead is a more stable cost and can be more readily forecasted. The labor, overhead, and materials cost are the budget figures that form the yardstick for measuring the cost performance of maintenance operations.

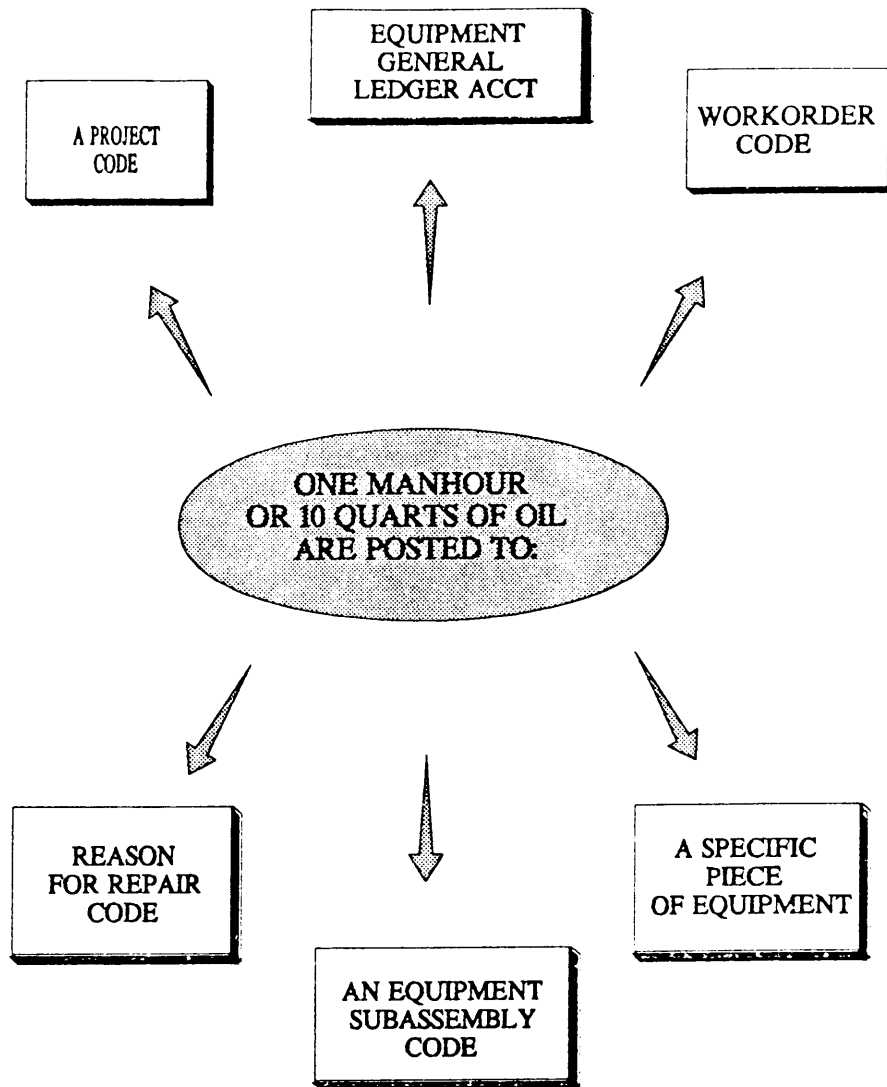


Figure 18. Equipment Coding Scheme

WHAT IS
MONEY
SPENT ON

EQUIPMENT

HOW IT
IS SPENT

TYPES OF MAINTENANCE SERVICES

REPAIR & ADJUSTMENTS	PLANNED MAINTENANCE	REBUILD	TRAINING
-------------------------	------------------------	---------	----------

WHAT IS PAID FOR
(BUDGET ITEM)

EXPENDITURE INCURRED ON

LABOR	OVERHEAD	MATERIALS
<ul style="list-style-type: none">• CRAFTSMEN• SUPERVISORS• OUTCONTRACTED LABOR	<ul style="list-style-type: none">• SHOP FLOOR SPACE• MAINTENANCE EQUIP.• CLERICAL PROCEDURES• MANAGEMENT STAFF	<ul style="list-style-type: none">• SUPPLIES• SPARE PARTS

Figure 19. Budget Formulation Scheme

A well prepared budget is an invaluable tool for improving management control. However, it doesn't by itself insure that costs are contained within acceptable limits. This is monitored by means of variance analysis reports which show actual vs budgeted expenditures and highlight undesirable trends.

Variance Analysis

Reporting and coding are the tools for aggregating and organizing the maintenance expenditure data into meaningful figures. Management can look at operating cost organized by class of equipment, by individual equipment, components, reason for repair, or projects. Taken as they are, these figures will give management an idea of how money is spent on equipment maintenance; however their analytical value is limited. A thermometer indicating 107 degrees as a patient temperature means that this patient is on the verge of dying, but measured off a water container it indicates a lukewarm water. Figures are only meaningful when they relate to certain standards. Operating cost figures should be compared with standard or budgeted figures in order to conclude effective information. Budgeted figures can be obtained from equipment manufacturer's handbooks, or they can be built from contractors experience. Other contractors and expert's opinions can also be used.

Variance analysis characterizes in a quantitative way the things that should happen during a budget period with the things that actually happened. It is the difference between the actual and the forecasted maintenance expenditures. Variance analysis helps the maintenance manager gain control of the operation by allowing him to ask questions such as:

1. Which variances or differences should be investigated ?
2. Who is responsible for the variances ?
3. What is the cause of each difference that is to be investigated ?
4. What corrective actions need to be taken ?

This managerial approach is called management by exception (Smith, Keith & Stephens, 1986). The term refers to only identifying and investigating significant variances. The emphasis is placed on the word significant. If the variances are insignificant in amount; not only might the causes never be determined, but the benefits of eliminating the variances might not outweigh the cost of investigation and corrective action. Variance analysis coupled with the managerial ratios to be discussed in section 4.3.2 constitute strong maintenance control tools. The prerequisite to use these tools is a well organized reporting and coding system. Another prerequisite is a good information system that will aggregate the mass of information collected, and organize it into usable figures.

4.2 Equipment Information Systems

Management information systems is defined as a communicative process in which data are accumulated, stored, processed and transmitted to appropriate organizational personnel for the purpose of providing information on which to base management decisions (Hodge, Fleck & Honess, 1984). This concept of MIS applies to any business enterprise including that of an equipment intensive contractor organization.

Many factors should be considered In designing an equipment information system. Technically speaking, it is easy to collect mechanical, operational, and economical data. Component failure, cycle times, and cost of component replacement are examples of readily available data. But, if this data does not produce information that influences the decision making process, collecting it, is a pure loss of time and effort. Another factor involved in MIS design is that the information produced should be targeted at the level of organization that will make use of it.

4.2.1 Decision Making Levels

Decision making can be classified on three levels:(1) strategic, (2) tactical, (3) technical (Burch, Strater & Grudnitski, 1983). Figure 20 illustrates the three decision levels and defines their time frame and the organizational sector responsible for their application.

1. Strategic level decisions are future oriented and characterized by a great deal of uncertainty. They establish long range plans coherent with the objectives of the organization. In an equipment setting, expanding or reducing fleet size, maintenance facilities additions, and brand diversification are examples of strategic decisions. These are taken at the executive level of the company.
2. Tactical level decisions pertain to short term activities and the allocation of resources to reach company objectives. Equipment division budget formulation, variance analysis, shop layout, productivity improvements and training are viable examples in equipment management. These decisions are usually handled by an equipment manager level position and because of their short term nature, present less uncertainty than strategic decisions.

DECISION LEVEL	TIME FRAME	RESPONSIBILITY
STRATEGIC	LONG RANGE	PRESIDENT & VICE
TACTICAL	SHORT RANGE	EQUIPMENT MANAGER
TECHNICAL	IMMEDIATE	FOREMAN & MECHANICS

Figure 20. The Three Levels Of Decision Requirements

3. Technical level decisions follow more rigid standards. Managerial decisions at this level focus on control with planning performed on a rather limited scale. Mechanics supervision, components repair or replacement decisions, scheduling and performance of preventive maintenance fall in this category. These decision are taken at the mechanics and foreman level.

It is important to differentiate between the decision making levels discussed in this section, and lines of authority or responsibility in the organization. Depending on the size and organizational structure of the contractor's organization, a president might occasionally make technical decisions. Moreover, the information produced will be used at more than one level. the equipment history file can be used at the technical level to investigate the recurrence of a certain component failure. At the tactical level, the equipment manager will also use it as a help tool in making a replacement decision.

4.2.2 Database Concepts

The foundation of information systems is the ability to store data, manipulate it, and analyze it to conclude usable information. A database is a repository of interrelated data of use to the users of the system (Burch, Strater & Grdnitski, 1983). The physical storage can be a file cabinet, journals, ledgers, punched cards, a hard disk or the neural cells in the human brain. Where volume and complexity, timing and computational demand are low, the human mind represents the ultimate database. Within these limits its associative abilities and computational speed are yet to be surpassed by the most advanced of computers. But even in small organizational settings, the volume of data is too massive for the human mind to process. Moreover, the users requirements greatly vary.

It takes a few minutes for a secretary to find demographic information on a piece of equipment, but it might take hours of file searching and manipulating to compile a yearly cost report on the machine. This problem was resolved with the introduction of computerized databases. These consist of data elements organized into records and files. The data represents an entity by giving it three descriptors: (1) a data attribute, (2) a data attribute value, (3) a data representation. The combined capabilities of the database program, and the computational and storage ability of computers make it possible to manipulate, change, and combine data to produce different information required by the user. Figure 21 gives an example of how data descriptors are applied to three equipment demographic data items.

4.3.3 The Equipment Information System

The equipment management information system consists of a set of data input feeding a data base that sorts out the data and produces a set of usable reports. The components of the system are explained next and are illustrated in figure 22.

The input to the data base consists of the following:

Repair workorders: Repair workorders are the instructions for maintenance actions different than planned maintenance. They specify what type of work will be done, who will do it, who requested the work, the estimated and the actual hours for the job. The workorder will have a code consisting of the different coding specifications defined earlier. The workorder conveys to the database mainly three types of information: (1) A description of the actual work done; (2) An account of labor time; (3) an account of spare parts.

DESCRIPTOR ENTITY	DATA ATTRIBUTE	DATA ATTRIB. VALUE	DATA REPRESENTATION
EQUIPMENT	EQUIPMENT #	326	3 DIGITS
	NAME	1979, D8K	20 ALPHANUMERICS
	PURCHASE PRICE	78,560.00	9 DIGITS, 2 DECIMALS

Figure 21. Data Descriptors Sample

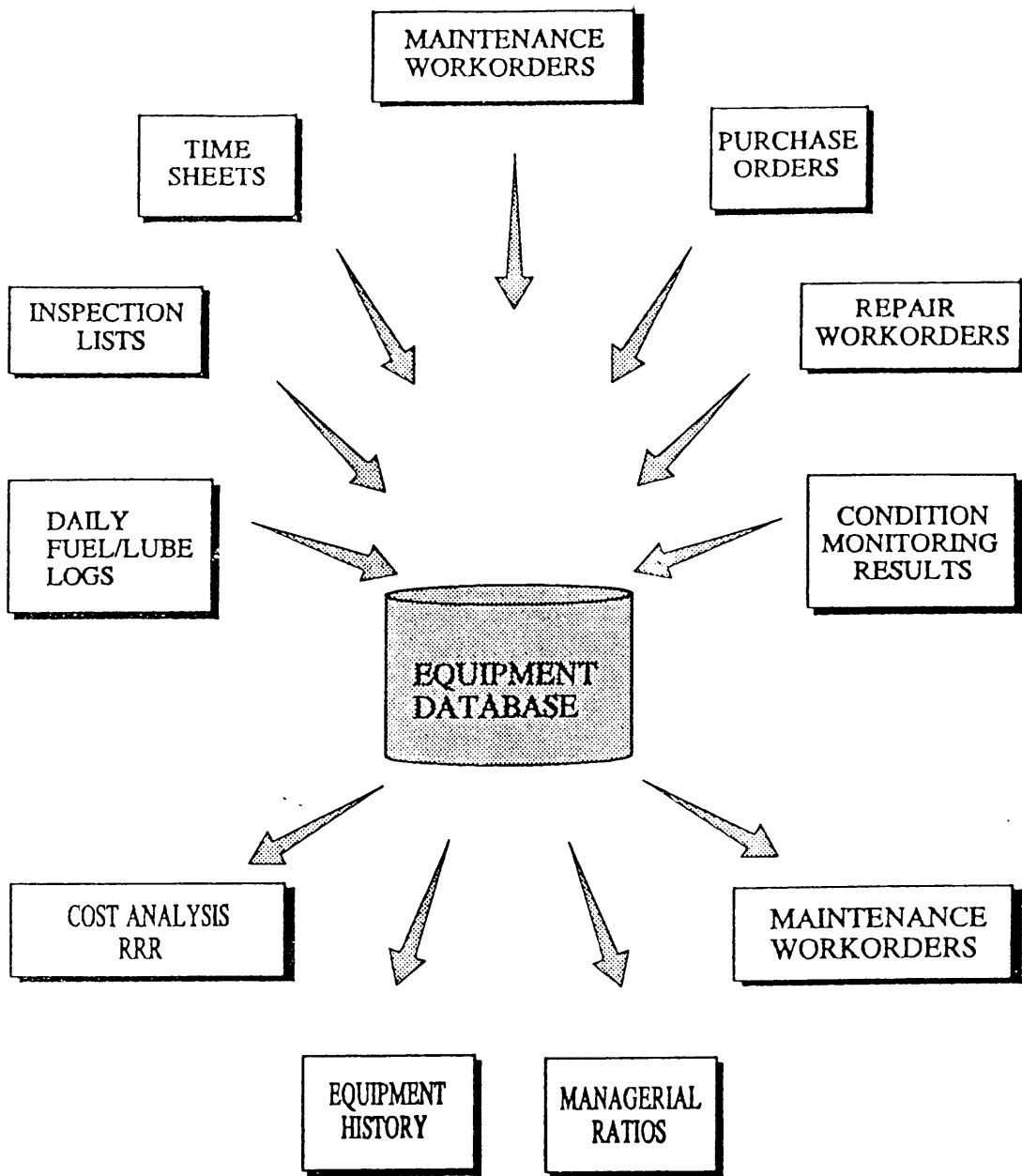


Figure 22. The Equipment Information System

Time sheets: Where workorders do not constitute an accurate method of accounting for labor time, time sheets should be employed. In smaller operations, time sheets will be more reliable in accounting for labor time because mechanics in these operations do not usually finish a workorder without a number of interruptions. Since the workorder is machine specific, it would be hard to issue a workorder for every emergency job that occurs in the shop and that requires some of the mechanics time.

Purchase orders: Purchase orders constitute a tool for keeping track of company purchases. Construction companies usually have open accounts with many local parts and materials suppliers. Any purchase is usually initiated by providing the supplier with a purchase order number. When the PO is coded by workorder, the parts description and cost information is automatically posted to the different modules of the equipment data base. Invoices will be used to check the validity of purchase orders, and substitute for these when not available.

Inspection list: A typical occurrence in a medium size contractor organization is the transfer of equipment between different projects. One of the drawbacks of such transfers is that the receiving job is unaware of any hidden problems in the machine. The inspection list enumerates the critical functional components that are not noticeable by immediate inspection, such as engine or transmission overheating. The list is completed by the mechanic on the job the equipment is leaving. The inspection list also applies when the equipment is leaving the job to the maintenance shop. The coding scheme is also applied to the inspection list. Two functions are accomplished by using the inspection list concept:

1. The first function is that of communication accomplished by conveying information to the receiving job and the equipment data base about the condition of the equipment.
2. It is utilized to keep a tag on the treatment the equipment gets from the different jobs. The coding system will allow the equipment manager to browse the data base either by equipment to check how each job treated a specific piece of equipment, or by job to check the condition of the equipment that left the specific job.

Maintenance workorders: In order to keep track of planned maintenance actions, completed maintenance workorders should be inputted into the database. Timeliness of PM and condition monitoring instructions execution, and noticeable malfunction or needed repairs are information that can be extracted from inputted data.

Condition monitoring results: Oil sampling, track inspection, compression test and any other condition monitoring results must be inputted in the database. These inputs will be used to build historical trends that will help forecast future failure occurrences and take preventive measures.

Daily lube and fuel consumption: The purpose of inputting this data is two fold: (1) the data is used to build contractor specific fuel, lube, consumption records. (2) the data is used as a condition monitoring mechanism. This is accomplished by pinpointing significant deviation from regular consumption rates and investigating their causes. A transmission consuming 2 quarts of oil per day or a sudden 50 % increase in fuel consumption are symptoms that could initiate closer preventive investigation.

The output to the data base consists of the following:

Maintenance Workorders: These are the preprogrammed PM and condition monitoring instructions generated by the database at different intervals. The timing mechanism is either a weekly calendar or an hour meter report inputted to the database or a combination of both time and hours. The combination proves its effectiveness when the machine is idle for an extended period of time. Even though the oil was not used for enough hours to warrant its change, it loses its lubrication properties. To account for this problem, a time limit is set at which PM instructions are generated even if machine did not accumulate enough hours.

The equipment history: This file contains the equipment demographic information. Make, model, year of manufacture, engine model, and serial numbers are examples of items included in this file. The more crucial information contained in this module is a chronological listing of repairs with the corresponding spare parts and manhours spent on each repair.

Another module in the equipment history file is a statistical analysis of the type, frequency and cause of each failure. This information is used at the technical level of decision making to trace failure causes and spot recurrent failures and rework. Two transmissions failing in a three scrapers fleet on a job with steep haul road gives an indication of incorrect operating procedure such as downshifting at high speed.

A statistical analysis of labor hrs spent on component repair or replacement is also part of the equipment history file. This is used to build a contractor specific labor consumption database. Improving the productivity of the mechanics by making

them work against standard hours, and cost comparison between in-house and contracted-out repair are some of the uses of this database.

The contractor labor consumption rates present much more realistic figures than those supplied by the manufacturer. When the manufacturer suggests an average of 8 hours to change a transmission on a dozer, a new dozer and custom trained mechanics are considered. The dozer which the contractor mechanics are working on will most likely have at least 5000 hours with broken bolts and rusted connections. Moreover the mechanics might not have the same level of experience as those of the manufacturer.

Cost analysis reports: The cost analysis output consists of detailed cashflow for each machine. The cash flow is a listing of the owning and operating cost over the life of the machine. Based on the past cashflow trend, a forecast of future cashflow is generated. The cashflows take into consideration the income from machine production. An integrated repair, rebuild, or replacement analysis uses the information produced by the cost analysis to produce the optimal alternative for each machine.

Another important output of the equipment data base is the managerial ratios that form a yard stick for measuring maintenance performance. The next section will discuss in details this aspect of the database.

4.3 Advanced Management Decision Tools

4.3.1 Performance Measurement

Performance measurement follows the same lines of control but is very different in concept. It relates to the expression of results in figures that evaluate a certain activity in relation to targets. Where control tells us what is happening, performance measurement shows how well or how badly it is being done. Control is an indicative tool of management and provides short term view, while measurement is an assessment and being more cumbersome can be effective only on a long term basis (Priel, 1974).

The performance of maintenance activities cannot be measured in simple figures. In production, units of output and cost per unit are enough to assess how well or how badly the results are achieved. In production we try to produce as much as possible as economically as possible. In maintenance this simple relation cannot be used to assess performance.

Rules must be defined to arrive at a figure that would prove maintenance performance to be good or poor. What is expected? Is it Prompter service, more work done, less over all cost? Some of these costs affect each other in an inverse relationship. If we want prompter service and faster response to calls, we may need more people, either at the central maintenance shop or at the projects. More service trucks and better communication methods between projects and shop might also be needed. This could improve service and could raise the utilization ratio of mechanics, but it has to be paid for.

The overall operation as a result might be less economical, because the cost of the average maintenance hour may rise. Many other examples can be given to prove that the appraisal cannot rely on any single measure. In this context Priel developed a qualitative multivariate chart (Fig. 23). The chart evaluates the plant or equipment condition, the work completion rate, the manpower utilization, the change in the cost of the maintenance hour, the change in the ratio of the maintenance to production hours, the maintenance expenditure, and the quantity of equipment serviced (operating hours), in order to assess the maintenance performance. The chart adopts a sequential approach by considering that if certain conditions are met the final assessment will be favorable. However, one unfavorable answer might spoil the whole picture. Commenting on the complexity of the performance process Priel (1974) states: "Performance measurement is expected to indicate in two words both cause and effect and a comparison between past and present. Worst of all, it is expected to express in figures a constantly changing situation. Evidently, when we survey figures of the past and present, we expect to draw from it inferences for the future. Looking at the results, we also try to understand their implication in light of probable future events."

4.3.2 Performance Ratios

On the positive side of the picture, many companies have developed performance indexes to be yardsticks for the different performance parameters. The difficulty remains in developing standard or optimum values for these indexes. Some indexes take years of experience and a lengthy process of trial and error to obtain a value that the company can use as a standard for comparison.

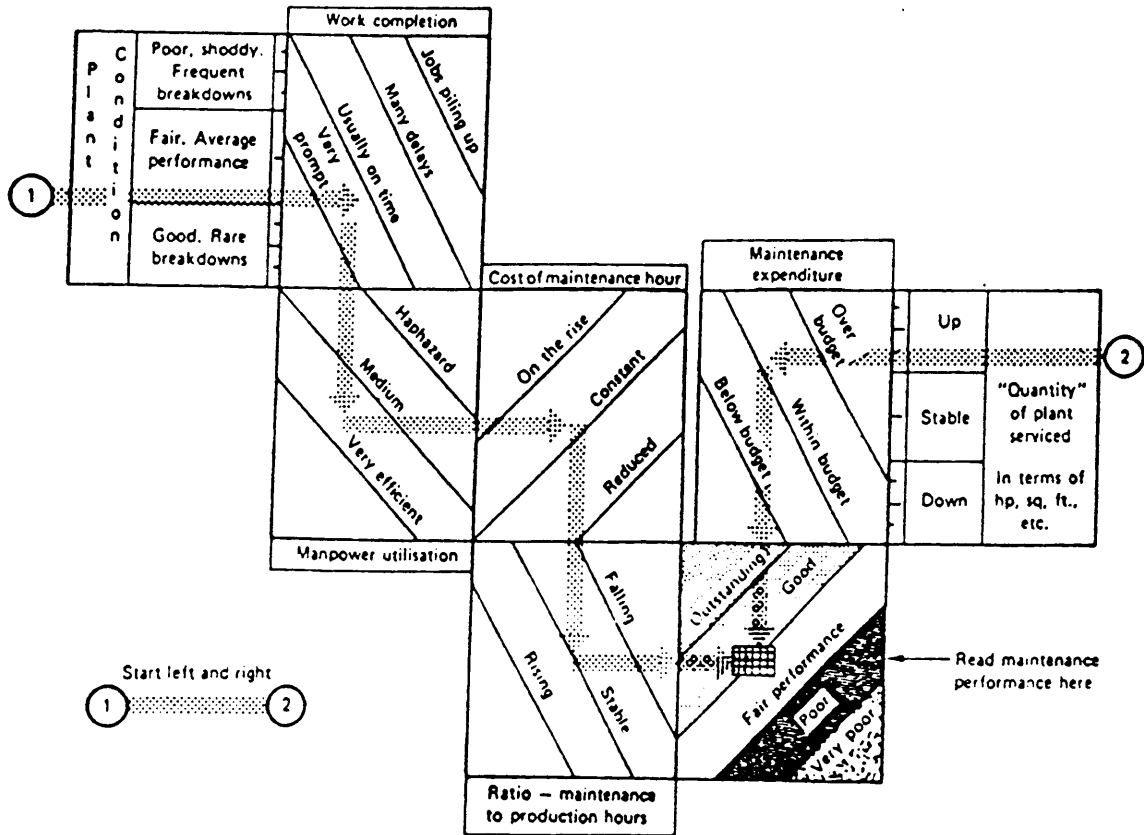


Figure 23. Qualitative Performance Measurement Chart (Priel, 1974)

Vorster approached the problem of measuring maintenance performance by defining machine quality as an outcome of maintenance effectiveness. The following three indexes were proposed:

E = extent to which machine fails

G = frequency of mechanical failure

H = average duration of failure

Where,

$$E = (D/W) * 100$$

$$G = (V/W) * 100$$

$$H = D/V$$

And where,

D = Hours the machine is incapable of working due to failure in the period.

W = Hours the machine has worked in the period.

V = Number of unplanned mechanically sourced failure in the period.

Vorster then combines the three indexes by applying specific weighting factors to each of them in order to reach a single index for mechanical quality.

Other indexes designed to measure the performance of the maintenance shop, the assessment of the service and the expenses justification have also been developed by other maintenance scholars (Priel, 1974, Harris, 1985, Niebel, 1985). The most important are described next and summarized in figure 24.

PERFORMANCE RATIOS

1 - WORKORDER TURNOVER =	$\frac{\text{NUMBER OF JOBS COMPLETED}}{\text{TOTAL NUMBER OF JOBS HANDLED}}$
2 - COST OF MAINT. HOUR =	$\frac{\text{TOTAL MAINTENANCE COST}}{\text{TOTAL DIRECT MAINT. HOURS}}$
3 - DOWNTIME DUE TO MAINTENANCE =	$\frac{\text{TOTAL DOWNTIME FOR SERVICE}}{\text{TOTAL SHIFT HOURS WORKED}}$
4 - BREAKDOWN WORKLOAD =	$\frac{\text{HOURS SPENT ON BREAKDOWN REPAIR}}{\text{TOTAL MAINTENANCE HOURS}}$
5 - MAINTENANCE TO PRODUCTION HRS=	$\frac{\text{TOTAL MAINT. DIRECT HOURS}}{\text{TOTAL DIRECT PRODUCT. HOURS}}$
6 - OVERTIME RATIO =	$\frac{\text{MAINTENANCE OVERTIME HOURS}}{\text{TOTAL MAINTENANCE HOURS}}$
7 - MAINTENANCE COST COMPONENT =	$\frac{\text{TOTAL MAINTENANCE EXPENDITURE}}{\text{TOTAL REVENUES}}$
8 - COST OF SCHEDULED SERVICE =	$\frac{\text{COST OF PM, CM, INSPECTION}}{\text{TOTAL PRODUCTION COST}}$

Figure 24. Performance Indexes Listing

The workorder turnover: It is the ratio of the total number of jobs completed over the total number of jobs handled by the maintenance shop. This ratio can only relate to workorders that represent individual requests of repair rebuild or replacement of components of equipment, and not for planned maintenance workorders. The denominator is made up of all the workorders on hand at the start of the period. A widening figure between this and the workorders completed will indicate that a backlog of work is piling up. A rising number of incoming jobs hints to the low effectiveness of the maintenance function, but will not necessarily reflect badly upon the shop performance. A low turnover will show that the team is not being able to cope with the work load.

Cost of maintenance hour: It is the ratio of the total maintenance costs over the total maintenance hours applied. This figure can be used for estimating purposes and for deciding whether to subcontract a maintenance job or do it in the contractors shop. Because the labor, materials, and overhead composition of maintenance jobs differ greatly, caution must be exerted in using this figure as a guide in cost estimating. Time consuming jobs like lubrication or fault finding, may be grossly overestimated, while jobs like component rebuilds may be underestimated. Weather condition, experience level and supervision effectiveness are all factors affecting mechanics productivity. The cost of the maintenance hour should be modified to account for these factors. The job superintendent record of treating equipment and supervising mechanics, and the environment in which the equipment will work are basic considerations in adjusting the the cost of the maintenance hour. The decision to subcontract the work or do it internally is based on a comparison between this index and the rate the dealers charge for their services. A significant improvement in the value of this index should occur when the amount of planned maintenance increases.

Downtime due to maintenance: It is the ratio of the total downtime hours for service over the total shift hours worked. The total amount of downtime is the result of unexpected stoppages, waiting for service, waiting for faults to be discovered and corrected. It reflects the effect of thorough servicing or the lack of it, and also the promptness of the response to calls of service. There is of course a difference between a figure resulting from a large number of small waiting periods or a sum of two stoppages in which the spare parts are shipped across the country. To reach any conclusion the downtime composition in terms of length and failure nature should be examined. This ratio reflects the effectiveness of the communication process, the speed of the diagnosis process and the availability of spare parts with emergency repairs or in finding better ways to do preventive maintenance and condition monitoring.

Breakdown workload: It is the ratio of the total hours spent on breakdown repairs over the total clocked maintenance hours. It is significant to realize how much of the total hours paid for are spent on the repair of breakdowns. This will serve as a broad indicator showing a penalty figure that the company has to pay for some shortcomings. Identifying the cause will serve as a guide whether inadequate maintenance policy, poor skills of operation, age and condition of plant and accidents are to be blamed. All jobs which appear unexpectedly and are deemed urgent fall in this category. Owing to the disruptive nature of these jobs they should be separated from regular jobs and their figure regularly scrutinized.

Maintenance to production hours: This is the ratio of the total maintenance hours over the total production hours. A rising value can indicate that more maintenance is available or that the company has a smaller number of contracts. A decreasing

value indicates that the maintenance services are inadequate for the level of production the company is undertaking.

Overtime ratio: This is the ratio of the overtime hours of maintenance over the total hours of maintenance . Rising figures for this ratio show that the amount of breakdown maintenance is increasing or that the maintenance shop is understaffed. Efforts should be exerted to keep this ratio to a minimum. Besides the fact that it costs more to work on overtime, the quality of work and productivity level of mechanics is much inferior than that of regular hours work.

Maintenance cost component: It is the ratio of the total maintenance expenditure over the total company revenues. This ratio helps managers that are sensitive to the cost of maintenance and think they can't afford it. When the maintenance component in an earthmoving operation is \$.02/CY a needed maintenance budget increase of 25 % will raise this figure to \$.025. Considered separately this figure will negatively affect company profits. But the benefits will outweigh the profit losses if the budget increase improves the effectiveness of the maintenance function. A sensitivity analysis considering the maintenance component change, the direct effect on profit and the expected benefits from an increase or decrease in maintenance spending should be performed to obtain the optimal maintenance cost component.

Cost of scheduled service: It is the ratio of the cost of preventive, condition monitoring and inspection services over the total production cost. This ratio should demonstrate the value of scheduled services. With a very modest rate of expenditure on regular services, a sharp reduction in breakdowns can be achieved. When a saturation point has been reached, further expenditure on this type of service may not yield a reduction of breakdowns and may not lead to reduction in other costs. This

is the level that has to be watched. A certain amount of equipment can take only a limited amount of scheduled services. Services beyond that figure should be carefully controlled as it may represent over-maintenance.

4.4 Conclusion

This chapter defined the administrative system as the driving engine of the maintenance function. The performance of the system depends on the successful integration of many modules. The most important are: (1) A work control module to to produce, schedule, and monitor maintenance instructions. (2) An equipment condition module to monitor the effectiveness of maintenance in conserving the equipment at an acceptable functional level. (3) A cost control module to track maintenance expenditures. At the heart of the administrative process is an equipment information system that aggregates the different data and sorts it into usable information. This constitutes a strong decision support tool that management can use to optimize equipment decisions.

5 Conclusion

5.1 Thesis Accomplishments

The thesis provided a model for choosing the optimum maintenance philosophy combination for a piece of equipment. The model considers each significant component in the machine, evaluates its failure mode and consequences, and assigns to it the corresponding maintenance philosophy.

The thesis also developed the framework for a maintenance control system. Management control is based on an administrative process consisting of three modules: (1) a work control system to generate, schedule, dispatch and insure the execution of maintenance instructions; (2) an equipment condition control system to monitor the condition of the machine and the effectiveness of the maintenance actions performed on it. This is a chronological listing of all repairs, rebuilds and replacement of machine components with the corresponding spare parts and labor hours consumed; (3) a cost control system to monitor and control the economic performance of the maintenance function. The

cost control process is based on reporting and coding maintenance data, and planning maintenance expenditure through systematic development of maintenance budgets. Variance analysis is then employed to spot deviations from standard budgeted figures and investigate their cause. This concept is labeled management by exception.

The driving engine of the administrative process is the equipment information system. The system emphasizes that only data that is needed to produce usable information should be collected, and defines the decision making information requirement at the different levels of the organization. Concepts of database operations are introduced as the tool to accumulate, sort, and manipulate data to produce the required information. The equipment history file, the maintenance workorders, and the cost analysis reports are some of the information produced. Another set of information generated by the system is the managerial ratios. They constitute another tool to measure quantitatively, and qualitatively the effectiveness of the maintenance function.

The proposed administrative system forms the basis for systematic equipment management. The maintenance function effectiveness does not only depend on optimizing the maintenance philosophies and control systems. The success of a comprehensive maintenance management system is based on a active contribution from the following parties:

1. **Top management:** Setting policies aiming at avoiding equipment-production conflicts, providing incentives to insure that maintenance instructions are applied (basing yearly bonuses of job superintendents on quality of machines on their job is one option), and allocating fair budgets to the equipment division are some of the contributions expected from top management.

2. **Equipment division:** This party's contribution consists of insuring that the equipment purchased fits the company environment of operation, maximizing the productivity of mechanics, controlling PM and condition monitoring instructions, and insuring the most effective replacement policies.
3. **Production:** The contribution from this sector includes insuring that only qualified operators are employed, using the machines only for their intended purpose (a grader should not be used to clear mud), and insuring timely performance of maintenance instructions.
4. **Operators:** Operators responsibilities include adhering to good operating techniques, and reporting any malfunctions such as leaks, and unusual noises to supervisors. A daily walk-around inspection to check critical components of the machine will prove beneficial in this regard. The project fuel and lube specialists can also perform the same function on a daily basis. This would be an extra safeguard against potential failures.

The active contribution of all parties, the decision support system and the control tools introduced in the thesis constitute a practical and effective maintenance management system. Implementing it requires a process of education and training, competent personnel, and an inspiring leadership to disseminate the importance of maintenance at all levels of the company.

5.2 State Of The Art

Advancements in maintenance technology are focusing on improving two areas: data gathering and transmittal, and decision support effectiveness. In the first area, bar coding technology is proving to be increasingly effective. Expert systems are the wave of the future for optimizing the decision making process.

5.2.1 Bar Coding

A bar code system is a data gathering tool that uses a stationary or a hand held scanner to read information encoded in the width and interspaces of bars (Bell & McCulloch, 1988). The information gathered is automatically stored in the computer memory, or in the case of portable scanners is later downloaded to the computer. Bar codes permit rapid and almost error free data entry into any type of computer system. Bar code technology is making a strong thrust in the data gathering, reporting and transmittal of maintenance management. Applications extend from time and spare parts control, to productivity measurement.

Preprinted time cards can be bar coded with any combination of descriptors to indicate employee number, crew designation, cost account codes, work area and so on. After the time cards have been manually completed (work hours, work accomplishments, and other data entered) the data can be rapidly entered into a computer system by scanning the bar codes on a menu tablet that corresponds to the data that were manually entered. This process can be taken a step further in minimizing paper work: Using a portable

programmable scanner, the mechanics enter their designation (name or number) and scan all other information off preprinted bar code listings. Figure 25 provides an example of a bar code listing for an equipment maintenance shop. The menu contains codes relating to type of work performed, repair priority, reasons for work interruption, and management decisions concerning a repair item. The information stored in the scanner can be downloaded later to the computer. The benefits from using bar coding in gathering and reporting maintenance data include:

1. Elimination of paperwork processing time: Since the information is directly inputted by the mechanics and downloaded to the computer, the clerical function of manually entering the information is eliminated.
2. Improved labor time control: The portable programmable wand has a built in clock which basically transforms it into an electronic time sheet. The mechanics also use a bar code menu with different activity options. Workorder execution, consulting with management, diagnosing other equipment, and break time are some of the options. This facilitates the process of recording and monitoring mechanics time. The amount of time and the work area on which it was consumed serves the role of a payroll sheet and a labor productivity monitor.
3. Accurate accounting for spare parts: All spare parts used in a maintenance shop can have preprinted affixed bar codes. A library of parts bar codes can be built up with time. Mechanics working on a repair item can directly account for the spare parts used for this repair by scanning corresponding bar codes off a menu or off whatever container was used for the part.

MAINTENANCE		MANAGEMENT DECISION		CLASS		SITE	
	1 Breakdown		21 Capital Improvement	Scheduled 	Facility 		
	2 Fuel Consumption		22 Conversion	Non-Scheduled 	Service Call 		
	3 Oil Consumption		23 Modification	Emergency 	Terminal 		
	4 Driver's Report		24 Special Study		Vendor 		
	5 Inspection Routine		29 Campaign				
	6 Lubrication	OUTSIDE INFLUENCE		DOWNTIME PRIORITY			
	7 Pre-Delivery		31 Accident Non-Reported		1 Urgent		
	8 P.M.		32 Accident Reported		2 ASAP		
	9 Rework		33 Manufacturer's Recall		3 When Possible		
	10 Road Call		34 Statutory Inspection	DOWNTIME STATUS			
	11 Routine		35 Statutory Modification	Parts 	Special Equipment 		
<div style="border: 1px solid black; padding: 5px; width: fit-content;"> REPAIR ORDER COMPLETE </div>			36 Theft	Personnel 	Funds 		
			37 Vandalism	Space 	Management Approval 		
			38 Policy Adjustment				
			39 Natural Causes				

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Figure 25. Preprinted Bar Code Menu (J P Systems Inc., Greensboro, NC, 1987)

The bar coding system initiates a complete cost tracking process at the mechanics level. For each repair, a workorder is initiated by scanning a specific bar code. Consider as an example changing the water pump on a piece of equipment. The mechanic uses the programmable wand to enter his name, and the equipment number. He uses the pre-printed bar code menu to scan the bar code corresponding to changing a water pump. The scanner automatically starts recording the time spent on the workorder. Any parts used are also read in by scanning their bar code designation. When the work is done, the mechanic scans a bar code corresponding to workorder accomplished. Any interruptions during the work order execution period are also accounted for by the bar code menu. Example of interruptions include emergency work on other equipment, management interruption, lunch brake and so forth. This cycle automatically reported the work description, the labor time, and the spare parts used. The nature and frequency of interruptions also gives management a clue on the factors affecting productivity in the shop.

Bar coding technology presents a strong potential for savings in maintenance management. A department of defense study has documented costs and benefits associated with bar code implementation projects at various DOD installations (Bell & McCulloch, 1988). As an example an equipment management system that tracks scheduled maintenance, location, warranty information for a \$ 500 million equipment fleet will produce \$ 4 million in savings over the life of the equipment. These savings are the results of reduced manpower, potential for reduced fraud and waste, and improved tracking of loaned equipment.

5.2.2 Expert systems

Expert systems are interactive computer programs incorporating judgement, experience, rule of thumb, intuition, and other expertise to provide knowledgeable advice about a variety of tasks. Expert systems differ from conventional programs in that they represent and use knowledge instead of data, and heuristics rather than algorithmic processes to solve problems. Symbolic processing orientation as opposed to numerical processing orientation is another distinguishing factor of expert systems. One of the big advantages of expert systems is their ability to emulate the human way of thinking. Their main function is to transfer the expert's knowledge to less experienced people.

Expert systems are developed by knowledge engineers (the computer experts) interacting with domain experts. The domain experts identify the problem, and provide the rules to solve it. The knowledge engineers program the diagnosis and solution rules in an interactive software format. Expert systems have a potential to solve a large number of problems, but at this stage they are limited by software and hardware capabilities. These limitations define the following criteria for solving a problem using an expert system:

1. The problem should focus on a narrow specialty area, and should not involve a lot of common sense knowledge.
2. The problem should not be too difficult or too easy for human experts to solve.
3. The knowledge describing the problem should be clearly defined. In this context it should be noted that an expert system cannot solve a problem that the experts cannot solve.
4. Commitment from an articulate expert or group of experts is necessary.

In the thesis context, expert systems can be used in two areas:

1. In formulating the maintenance philosophy combination, the decision model can be replaced by an expert system employing the same rules specified in the model.
2. Field and shop mechanics are faced with the problem of diagnosing a failure, identifying its cause, and finding ways to eliminate it. The experience level of the mechanics performing the diagnosis has a great effect on its accuracy and on the efficiency of the remedial action undertaken. Expert systems can be used to emulate the experts in diagnosing equipment failures and suggesting remedial actions. These systems will compensate for the shortage of experienced mechanics the highway contracting industry is facing.

Many programs have already been developed in the maintenance area. PumpPro, a centrifugal pump failure diagnosis developed by Stone and Webster, Field diagnosis of welding defects, and a maintenance advisor for old elevators are some examples (levitt, 1988).

5.3 *The Future*

5.3.1 A Maintenance System For The 90's

Figure 26 describes what the author foresees the maintenance process will develop into during the next 10 years. The system uses bar coding technology to collect data from the field. The operator inputs the daily walk around results by scanning bar codes corresponding to the faults noticed on the machines. The fuel and lube man enters consumption information, by scanning bar codes corresponding to items added to the machine and entering the quantities. The mechanic, whether in the field or in the shop, uses the bar codes for two purposes: (1) imputing failure symptoms; (2) inputting information about materials and spare parts he used on repairs. Time is automatically accounted for by the programmable wand. The wand information is later downloaded to the project computer which transmits it via phone lines to the main maintenance facility. In the case of shop mechanics the wands are downloaded directly to the main computer. The computer stores the data and transfers it to a resident expert system. The expert system analyses the information by relating it to maintenance history, age, past repair, rebuild or replacement actions. The expert system then makes recommendations concerning potential failures and repair options for mechanics. The computer also generates cost analysis, performance analysis (ratios), and PM and condition monitoring instructions.

For the system to become feasible, two prerequisites have to be satisfied:

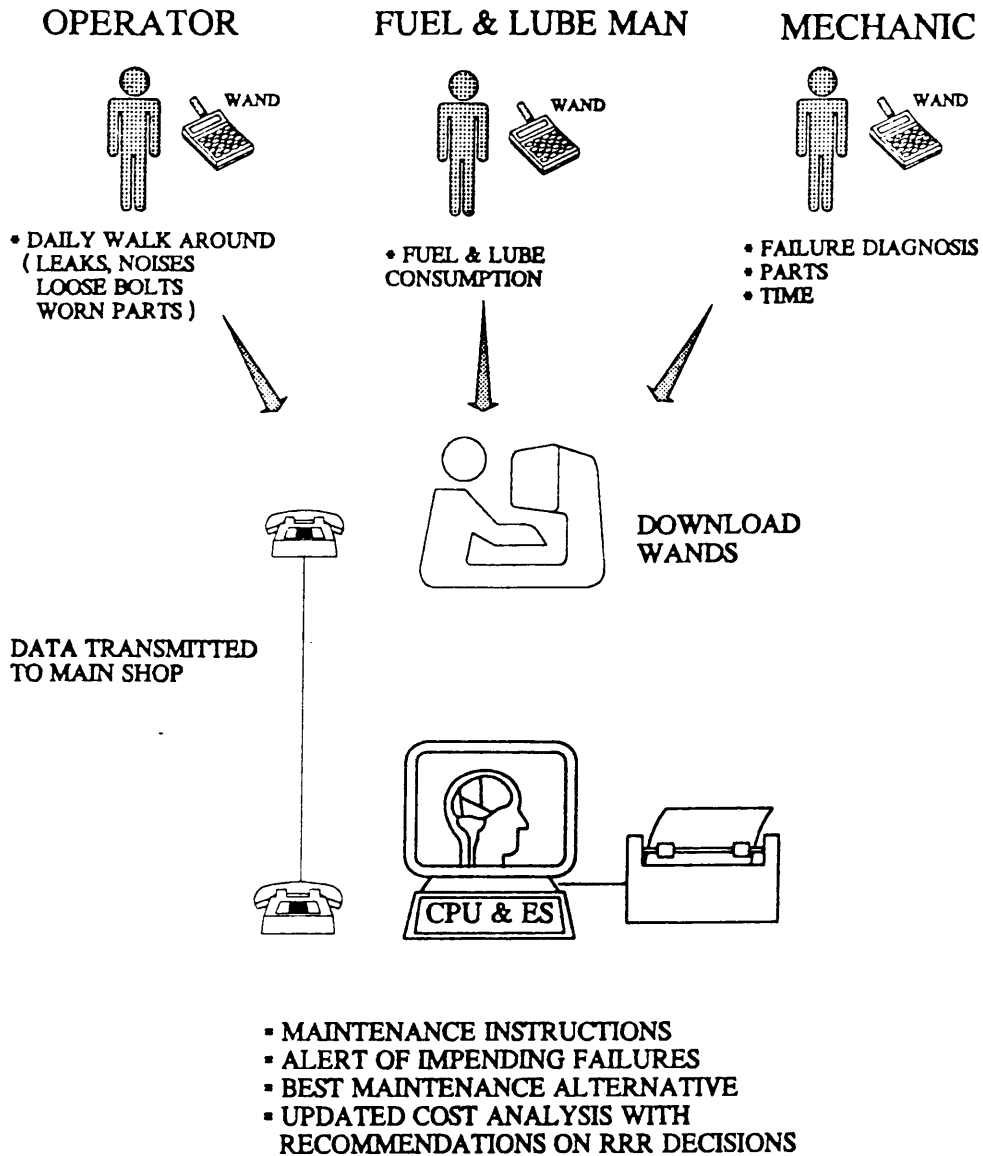


Figure 26. Proposed Maintenance System For The Next Decade

1. The bar coding technology has to become affordable: Technically current bar coding systems are capable of performing the actions called for in the model. But at \$1600 - \$2000 for a portable programmable wand, the contracting industry cannot afford to generalize the use of bar coding. Making the analogy with portable calculators, once the real potential of bar coding has been spread, its mass production and therefore cheaper prices will be expected.
2. Expert systems technology has to gain more flexibility and power before it can successfully tackle the diversity of maintenance problems facing the industry.

5.3.2 A Maintenance System For The Year 2001

The future maintenance system will be based on performance and fault sensing technology and on expert systems as decision support tools.

On-board sensors generate signals relating to oil and exhaust gas condition ,fuel system performance, and noise and vibrations. See figure 27. The signals are stored in a central memory unit and transmitted on a real time basis to the central maintenance facility. The on board sensors function as condition monitoring devices that will free mechanics from this responsibility. This real time feedback system permits accurate warning of failures, and transforms the lubricants and filters change from a prescheduled periodical function to an as needed function. Interfacing with an expert system, this monitoring process allows for optimum component replacement time to become a reality.

Production control and performance sensors are currently being researched . The goal in this case is to optimize cycle times and cost control in heavy equipment operations (Paulson, 1987 , Hagenbuch, 1988). Systems performance sensors are yet to come. Oil

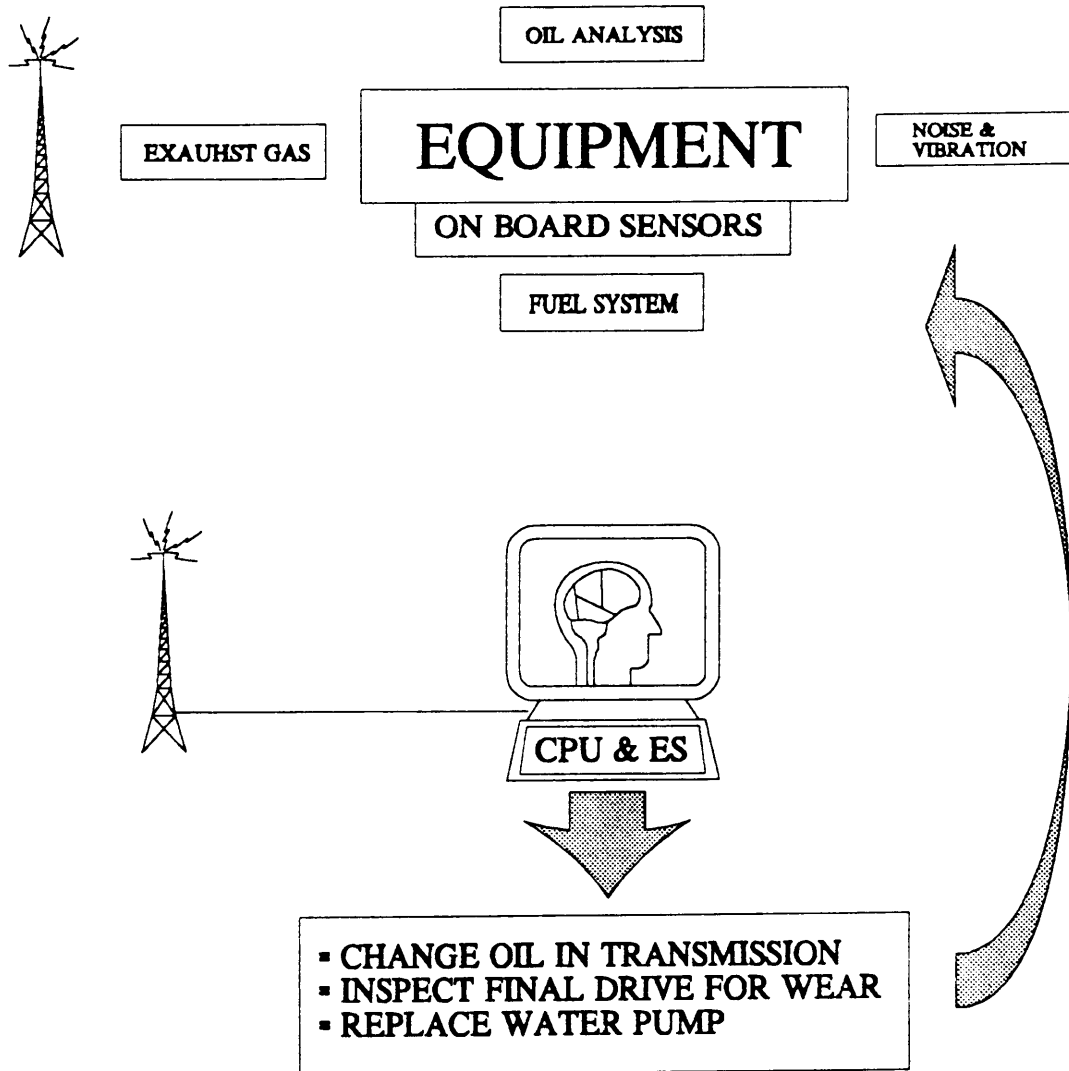


Figure 27. Maintenance For The Year 2001

analysis, exhaust gas analysis, and other monitoring systems have to reach a high level of sophistication in order to install them on board the machine. Another problem facing this system is the expert systems development previously discussed. Research in this area will have a significant impact on the way maintenance is currently analyzed and implemented.

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