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MAINTENANCE STRATEGIES: A SYSTEMATIC APPROACH FOR SELECTION OF THE RIGHT STRATEGIES

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In this paper we use Computerised Maintenance Management Systems (CMMSs) to propose a method of selecting best maintenance strategies. There are fundamental questions that need to be asked with regard to existing CMMSs, such as: What do users really want from a CMMS? Does it support what is happening in the shop-floor? Or, Is it a rather expensive calendar to remind one of when to perform a maintenance schedule? Is it really worth spending so much effort, time, and money in buying a system for just being an electronic calendar or a monitoring device? Do existing CMMSs really contribute to the bottom line benefits of the company and support in the reduction of breakdowns or are they just a beast to be served by an army of IT specialists? Companies seem to spend a vast amount of resources in acquiring systems to perform data collection (clever databases) and data analysis (clever charts), and the added value to the business is often questionable. They then hope that somehow someone will make sense of the data and eventually things would get better. The key message here is that the aspect of decision support is missing in these systems. In this paper we propose a cohesive model that uses data in a CMMS to help in the selection of best maintenance strategies. It is an attempt to develop an intelligent system that can support decisions in maintenance.

1 INTRODUCTION

Computerised Maintenance Management Systems (CMMSs) are vital for the co-ordination of all activities related to the availability, productivity and maintainability of complex systems. Modern computational facilities have offered a dramatic scope for improved effectiveness and efficiency in, for example, maintenance. Computerised maintenance management systems (CMMSs) have existed, in one form or another, for several decades. The software has evolved from relatively simple mainframe planning of maintenance activity to Windows-based, multi-user systems that cover a multitude of maintenance functions. The capacity of CMMSs to handle vast quantities of data purposefully and rapidly has opened new opportunities for maintenance, facilitating a more deliberate andconsidered approach to managing assets. Some of the benefits that can result from the application of a CMMS are:

a) resource control – tighter control of resources ;
a) cost management – better cost management and audibility;
b) scheduling – ability to schedule complex, fast-moving workloads;
c) integration – integration with other business systems; and
a) reduction of breakdowns – improved reliability of physical assets through the application of an effective maintenance programme.

The most important factor may be reduction of breakdowns. This is the aim of the maintenance function and the rest are ‘nice’ objectives (or by-products).

This is a fundamental issue as some system developers and vendors as well as some users lose focus and compromise reduction of breakdowns in order to maintain standardisation and integration objectives, thus confusing aim with objectives. This has led to the fact that the majority of CMMSs in the market suffer from serious drawbacks, as will be shown in the following section.

The term maintenance has many definitions. One comprehensive definition is provided by the UK Department of Trade and Industry (DTI):

> "the management, control, execution and quality of those activities which will ensure that optimum levels of availability and overall performance of plant are achieved, in order to meet business objectives".

It is worth noting that the definition implies that maintenance is a managerial and strategic activity; today, the term 'asset management' is often used instead. It is also worth noting that the word 'optimum' was used rather than 'maximum' which implies that maintenance is an optimisation case, where both over-maintenance and under-maintenance should be avoided.

In this paper an investigation of the characteristics of Computerised Maintenance Management Systems (CMMSs) is carried out in order to highlight the need for them in industry and identify their current deficiencies. This is achieved through the assessment of the state-of-the-art of existing CMMSs.

A proposed model is then presented to provide a decision analysis capability that is often missing in existing CMMSs. The effect of such model is to contribute towards the optimisation of the functionality and scope of CMMSs for enhanced decision analysis support. The system is highly adaptive and has been successfully applied in industry. The proposed model employs a hybrid of intelligent approaches. In this paper, we also demonstrate the use of AI techniques in CMMS's. The paper is organized as follows. Section 2 provides evidence of existence of 'black holes' in the CMMS market. An alternative is provided in Section 3 where a model for decision analysis called the Decision Making Grid (DMG) is introduced. Section 4 describes maintenance policies that are covered by the DMG. This is then followed by demonstration of incorporating the DMG into a CMMS through a case study in Section 5 with a discussion of the results. The final two sections (Sections 5 and 6) deal with the unmet needs in CMMSs and a discussion of future directions for research.

2 EVIDENCE OF 'BLACK HOLES '

Most existing off-the-shelf software packages, especially CMMSs and enterprise resource planning (ERP) systems, tend to be 'black holes'. This term has been coined by the author as a description of systems that are greedy for data input but that seldom provide any output in terms of decision support. In astronomical terms, 'black holes' used to be stars at some time in the past and now possess such a high gravitational force that they absorb everything that comes across their fields and do not emit anything at all, including light. This is analogous to systems that, at worst, are hungry for data and resources and, at best, provide the decision-maker with information that he/she already knows. Companies consume a significant amount of management and supervisory time compiling, interpreting and analysing the data captured within the CMMS. Companies then encounter difficulties analysing equipment performance trends and their causes as a result of inconsistency in the form of the data captured and the historical nature of certain elements of it. In short, companies tend to spend a vast amount of capital in acquisition of off-the-shelf systems for data collection, but their added value to the business is questionable. Few books have been published about the subject of CMMSs (Bagadia, 2006), (Mather, 2002), (Cato and Mobley, 2001), and (Wireman, 1994). However, they tend to highlight its advantages rather than its drawbacks.

All CMMSs offer data collection facilities; more expensive systems offer formalised modules for the analysis of maintenance data, and the market leaders allow real time data logging and networked data sharing (see Table 1). Yet, despite the observations made above regarding the need for information to aid maintenance management, a 'black hole' exists in the row titled 'Decision analysis' in Table 1, because virtually no CMMS offers decision support.1 This is a definite problem, because the key to systematic and effective maintenance is managerial decision-making that is appropriate to the particular circumstances of the machine, plant or organisation. This decision-making process is made all the more difficult if the CMMS package can only offer an analysis of recorded data. As an example, when a certain preventive maintenance (PM) schedule is input into a CMMS, for example to change the oil filter every month, the system will simply produce a monthly instruction to change the oil filter and is thus no more than a diary.

Table1: Facilities Offered by Commercially Available CMMS Packages

Price Range	*£1,000 +*	*£10,000 +*	*£30,000 +*	*£40,000+*
Data collection	✓	✓	✓	✓
Data analysis		✓	✓	✓
Realtime			✓	✓
Network				✓
Decision analysis		*A 'black hole'*		

A step towards decision support is to vary the frequency of PM depending on the combination of failure frequency and severity. A more intelligent feature would be to generate and prioritise PM according to modes of failure in a dynamic real-time environment. A PM is usually static and theoretical in that it does not reflect shop floor realities. In addition, the PM that is copied from machine manuals is usually inapplicable because:

b) all machine work in different environments and would therefore need different PMs;
d) machine designers often have a different experience of machine failures and means of prevention from those who operate and maintain them; and
b) machine vendors may have a hidden agenda of maximising spare parts replacements through frequent PMs.

The use of CMMSs for decision support lags significantly behind the more traditional applications of data acquisition, scheduling and work order issuing.

While many packages offer inventory tracking and some form of stock level monitoring, the reordering and inventory holding policies remain relatively simplistic and inefficient. See the work of Exton and Labib (2002) and Labib and Exton (2001). Also, there is no mechanism to support managerial decision-making with regard to inventory policy, diagnostics or setting of adaptive and appropriate preventive maintenance schedules.

A noticeable problem with current CMMS packages regards provision of decision support. Figure1 illustrates how the use of CMMS for decision support lags significantly behind the more traditional applications of data acquisition, scheduling and work-order issuing.

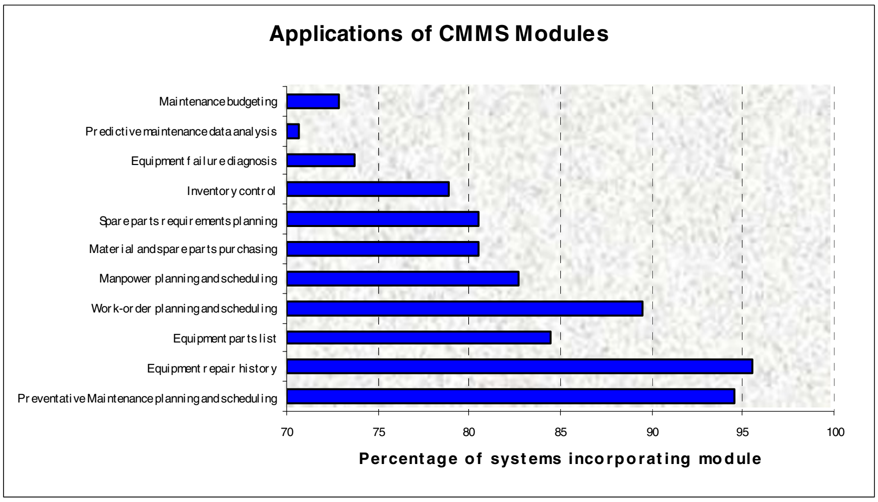

Figure 1 Extent of CMMS module usage (from Swanson, 1997)

According to Boznos (1998):

> "The primary uses of CMMS appear to be as a storehouse for equipment information, as well as a planned maintenance and a work maintenance planning tool."

The same author suggests that CMMS appears to be used less often as a device for analysis and co-ordination and that

> *"*existing CMMS in manufacturing plants are still far from being regarded as successful in providing team based functions*"*.

He has surveyed CMMS as well as total productive maintenance (TPM) and reliability-centred management (RCM) concepts and the extent to which the two concepts are embedded in existing marketed CMMSs. He has concluded that:

> "It is worrying the fact that almost half of the companies are either in some degree dissatisfied or neutral with their CMMS and that the responses indicated that manufacturing plants demand more user-friendly systems."

This is a further proof of the existence of a 'black hole'. To make matters worse, it appears that there is a new breed of CMMSs that are complicated and lack basic aspects of user-friendliness. Although they emphasise integration and logistics capabilities, they tend to ignore the fact that the fundamental reason for implementing CMMSs is to reduce breakdowns. These systems are difficult to handle for both production operators and maintenance engineers; they are accounting- and/or IT-orientated rather than engineering-orientated. Results of an investigation (EPSRC – GM/M35291) show that managers' lack of commitment to maintenance models has been attributed to a number of reasons:

c) Managers are unaware of the various types of maintenance models.
e) A full understanding of the various models and the appropriateness of these systems to companies is not available.
c) Managers do not have confidence in mathematical models due to their complexities and the number of unrealistic assumptions they contain.

This correlates with surveys of existing maintenance models and optimisation techniques. Ben-Daya *et al*. (2001) and Sherwin (2000) have also noticed that models presented in their work have not been widely used in industry for several reasons, such as:

d) unavailability of data;
f) lack of awareness about these models; and
d) restrictive assumptions of some of these models.

Finally, here is an extract from Professor Nigel Slack (Warwick University) textbook on operations management regarding critical commentary of ERP implementations (which may as well apply to CMMSs as many of them tend to be nowadays classified as specialised ERP systems):

> "Far from being the magic ingredient which allows operations to fully integrate all their information, ERP is regarded by some as one of the most expensive ways of getting zero or even negative return on investment. For example, the American chemicals giants, Dow Chemical, spent almost half-a-billion dollars and seven years implementing an ERP system which became outdated almost as it was implemented. One company, FoxMeyer Drug, claimed that the expense and problems which it encountered in implementing ERP eventually drove it to bankruptcy. One problem is that ERP implementation is expensive. This is partly because of the need to customise the system, understand its implications for the organisation, and train staff to use it. Spending on what some call the ERP ecosystem (consulting, hardware, networking and complimentary applications) has been estimated as being twice the spending on the software itself. But it is not only the expense which has disillusioned many companies, it is also the returns they have had for their investment. Some studies show that the vast majority of companies implementing ERP are disappointed with the effect it has had on their businesses. Certainly many companies find that they have to (sometimes fundamentally) change the way they organise their operations in order to fit in with ERP systems. This organisational impact of ERP (which has been described as the corporate equivalent of dental root canal work) can have a significantly disruptive effect on the organisation's operations."

Hence, theory and implementation of existing maintenance models are, to a large extent, disconnected. It is concluded that there is a need to bridge the gap between theory and practice through intelligent optimisation systems (e.g. rule-based systems). It is also argued that the success of this type of research should be measured by its relevance to practical situations and its impact on the solution of real maintenance problems. The developed theory must be made accessible to practitioners through IT tools. Efforts need to be made in the data capturing area to provide necessary data for such models. Obtaining useful reliability information from collected maintenance data requires effort. In the past, this has been referred to as 'data mining' as if data can be extracted in its desired form if only it can be found.

In the next section we introduce a decision analysis model. We then show how such a model has been implemented for decision support in maintenance systems.

3 APPLICATION OF DECISION ANALYSIS IN MAINTENANCE

The proposed maintenance model is based on the concept of effectiveness and adaptability. Mathematical models have been formulated for many typical situations. These models can be useful in answering questions such as "how much maintenance should be done on this machine? How frequently should this part be replaced? How many spare should be kept in stock? How should the shutdown be scheduled? It generally accepted that the vast majority of maintenance models are aimed at answering efficiency questions, that is questions of the form "how can this particular machine be operated more efficiently?" and not at effectiveness questions, like "which machine should we improve and how?". The latter question is often the one in which practitioners are interested. From this perspective it is not surprising that practitioners are often dissatisfied if a model is directly applied to an isolated problem. This is precisely why in the integrated approach efficiency analysis as proposed by the author (do the things right) is preceded by effectiveness analysis (do the right thing). Hence, two techniques were employed to illustrate the above-mentioned concepts mainly the Fuzzy Logic Rule based Decision Making Grid (DMG) and the Analytic Hierarchy Process (AHP) as proposed by Labib etal (1998). The proposed model is illustrated in Figure 2.

The Decision-Making Grid (DMG) acts as a map where the performances of the worst machines are placed based on multiple criteria. The objective is to implement appropriate actions that will lead to the movement of machines towards an improved state with respect to multiple criteria. These criteria are determined through prioritisation based on the Analytic Hierarchy Process (AHP) approach. The AHP is also used to prioritise failure modes and fault details of components of critical machines within the scope of the actions recommended by the DMG. The model is based on identification of criteria of importance such as downtime and frequency of failures. The DMG then proposes different maintenance policies based on the state in the grid. Each system in the grid is further analyzed in terms of prioritisations and characterisation of different failure types and main contributing components.

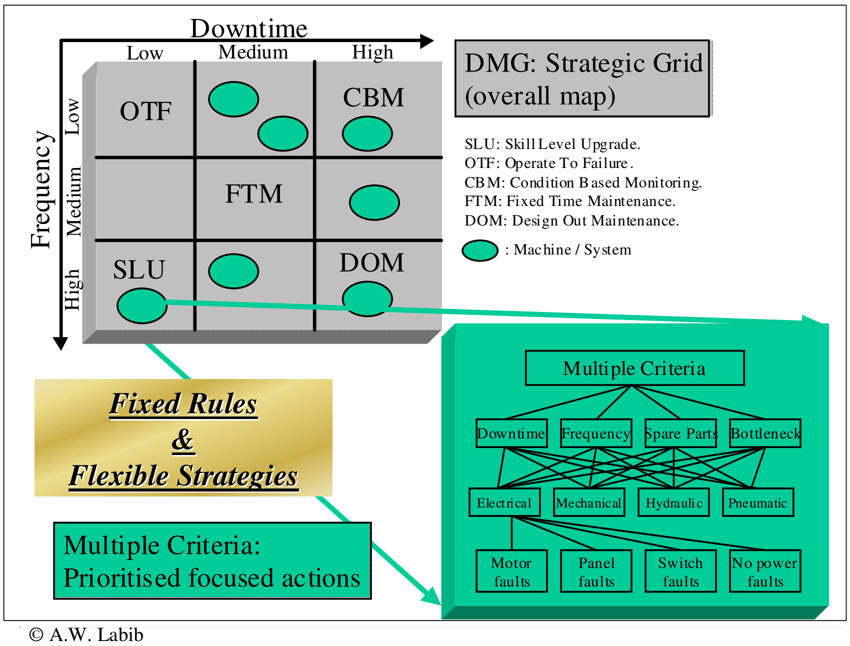

Figure. 2 Decision Analysis Maintenance System

4 MAINTENANCE POLICIES

Maintenance policies can be broadly categorised into the technology or systems oriented (systems, or engineering), management of human factors oriented and monitoring and inspection oriented.

RCM is a technological based concept where reliability of machines is emphasised. RCM is a method for defining the maintenance strategy in a coherent, systematic and logical manner. It is a structured methodology for determining the maintenance requirements of any physical asset in its operation context. The primary objective of RCM is to preserve system function. The RCM process consists of looking at the way equipment fails, assessing the consequences of each failure (for production, safety, etc), and choosing the correct maintenance action to ensure that the desired overall level of plant performance (i.e. availability, reliability) is met. The term RCM was originally coined by Nolan and Heap (1979). For more details on RCM see Moubray (1991, 2001), and Netherton (2000).

TPM is human based technique in which maintainability is emphasised. TPM is a tried and tested way of cutting waste, saving money, and making factories better places to work. TPM gives operators the knowledge and confidence to manage their own machines. Instead of waiting for a breakdown, then calling the maintenance engineer, they deal directly with small problems, before they become big ones. Operators investigate and then eliminate the root causes of machine errors. Also, they work in small teams to achieve continuous improvements to the production lines. For mordetails on TPM see Nakajima (1988), Hartmann (1992), and Willmott (1994).

Condition Based Maintenance (CBM) – not Condition Based Monitoring – is a sensing technique in which availability based on inspection and follow-up is emphasised. In the British Standards, CBM is defined ast *the preventive maintenance initiated as a result of knowledge of the condition of an item from routine or continuous monitoring."* (BS 3811, 1984). It is the means whereby sensors, sampling of lubricant products, and visual inspection are utilised to permit continued operation of critical machinery and avoid catastrophic damage to vital components The integral components for the successful application of condition monitoring of machinery are: *reliable detection, correct diagnosis, and dependable decision-making*. For more details on CBM, see Brashaw (1998), and Holroyd (2000).

The proposed approach in this paper is different from the above mentioned ones in that it offers a decision map adaptive to the collected data where it suggest the appropriate use of RCM, TPM, and CBM.

5 THE DMG THROUGH AN INDUSTRIAL CASE STUDY

This case study demonstrates the application of the proposed model and its effect on asset management performance. The application of the model is shown through the experience of a company seeking to achieve World-Class status in asset management. The company has implemented the proposed model which has had the effect of reducing total downtime from an average of 800 hours per month to less than 100 hours per month as shown in Figure 3.

5.1 COMPANY BACKGROUND AND METHODOLOGY

In this particular company there are 130 machines, varying from robots, and machine centres, to manually operated assembly tables. Notice that in this case study, only two criteria are used (frequency, and downtime). However, if more criteria are included such as spare parts cost and scrap rate, the model becomes multi dimensional, with low, medium, and high ranges for each identified criterion. The methodology implemented in this case was to follow three steps. These steps are i. Criteria Analysis, ii. Decision Mapping, and iii. Decision Support.

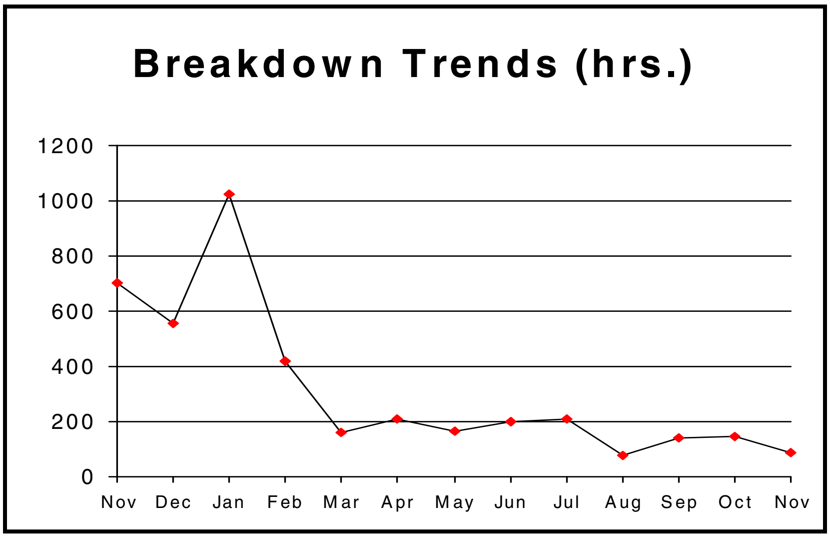

Figure 3 Total breakdown trends per month

5.2 STEP 1: CRITERIA ANALYSIS

As indicated earlier the aim of this phase is to establish a Pareto analysis of two important criteria Downtime; the main concern of production, and Frequency of Calls; the main concern of asset management. The objective of this phase is to assess how bad are the worst performing machines for a certain period of time, say one month. The worst performers in both criteria are sorted and grouped into High, Medium, and Low sub-groups. These ranges are selected so that machines are distributed evenly among every criterion. This is presented in Figure 4. In this particular case, the total number of machines is 120. Machines include CNCs, robots, and machine centres.

Criteria:	Downtime		Frequency		
	Name	Downtime (hrs)	Name	Frequency (No. off)	
HIGH	Machine [A]	30	Machine [G]	27	HIGH
	Machine [B]	20	Machine [C]	16	
	Machine [C]	20	Machine [D]	12	
MEDIUM	Machine [D]	17	Machine [A]	9	MEDIUM
	Machine [E]	16	Machine [I]	8	
	Machine [F]	12	Machine [E]	8	
LOW	Machine [G]	7	Machine [k]	8	
	Machine [H]	6	Machine [F]	4	LOW
	Machine [I]	6	Machine [B]	3	
	Machine [j]	4	Machine [H]	2	
	Sum of Top 10	**138**	**Sum of Top 10**	**97**	
	Sum of All	**155**	**Sum of All**	**120**	
	Percentage	**89%**	**Percentage**	**81 %**	

Criteria Evaluation

Figure 4 Step1: Criteria Analysis

5.3 STEP 2: DECISION MAPPING

The aim of this step is twofold; it scales High, Medium, and Low groups and hence genuine worst machines in both criteria can be monitored on this grid. It also monitors the performance of different machines and suggests appropriate actions. The next step is to place the machines in the "Decision Making Grid" shown in Figure 5, and accordingly, to recommend asset management decisions to management. This grid acts as a map where the performances of the worst machines are placed based on multiple criteria. The objective is to implement appropriate actions that will lead to the movement of machines towards the north - west section of low downtime, and low frequency. In the top-left region, the action to implement, or the rule that applies, is OTF (operate to failure). The rule that applies for the bottom-left region is SLU (skill level upgrade) because data collected from breakdowns - attended by maintenance engineers - indicates that machine [G] has been visited many times (high frequency) for limited periods (low downtime). In other words maintaining this machine is a relatively easy task that can be passed to operators after upgrading their skill levels. Machines that are located in the top-right region, such as machine [B], is a problematic machine, in maintenance words "a killer". It does not breakdown frequently (low frequency), but when it stops it is usually a big problem that lasts for a long time (high downtime). In this case the appropriate action to take is to analyse the breakdown events and closely monitor its condition, i.e. condition base monitoring (CBM). A machine that enters the bottom-right region is considered to be one of the worst performing machines based on both criteria. It is a machine that maintenance engineers are used to seeing it not working rather than performing normal operating duty. A machine of this category, such as machine [C], will need to be structurally modified and major design out projects need to be considered, and hence the appropriate rule to implement will be design out maintenance (DOM). If one of the antecedents is a medium downtime or a medium frequency, then the rule to apply is to carry on with the preventive maintenance schedules. However, not all of the mediums are the same. There are some regions that are near to the top left corner where it is "easy" FTM (Fixed Time Maintenance) because it is near to the OTF region and it requires re-addressing issues regarding who will perform the instruction or when will the instruction be implemented. For example, in case of machines [I] and [J], they are situated in region between OTF and SLU and the question is about who will do the instruction - operator, maintenance engineer, or sub-contractor. Also, a machine such as machine [F] has been shifted from the OTF region due to its relatively higher downtime and hence the timing of instructions needs to be addressed.

Other preventive maintenance schedules need to be addressed in a different manner. The "difficult" FTM issues are the ones related to the contents of the instruction itself. It might be the case that the wrong problem is being solved or the right one is not being solved adequately. In this case machines such as [A] and [D] need to be investigated in terms of the contents of their preventive instructions and an expert advice is needed.

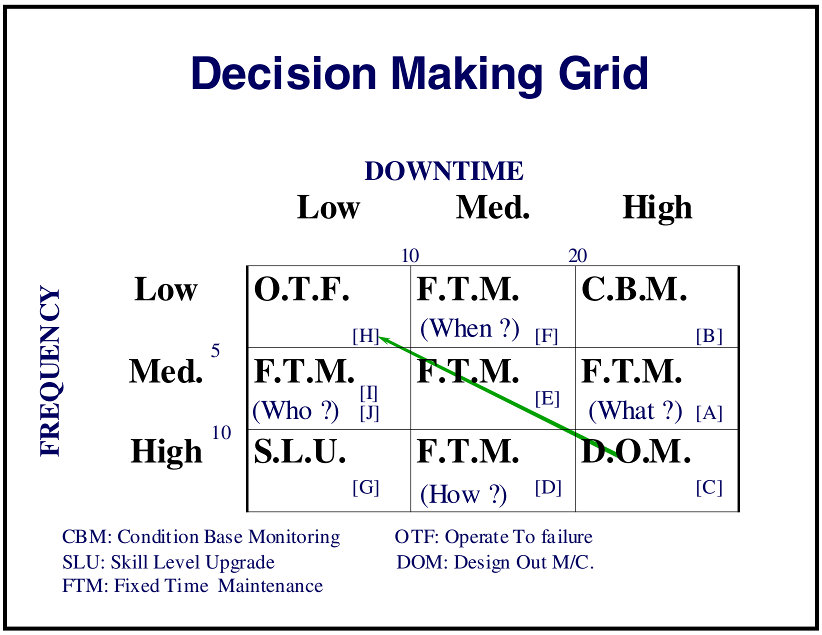

Figure. 5 Step2: Decision Mapping

5.4 STEP 3: MULTILEVELED DECISION SUPPORT

Once the worst performing machines are identified and the appropriate action is suggested, it is now a case of identifying a focused action to be implemented. In other words, we need to move from the strategic systems level to the operational component level. Using the Analytic Hierarchy Process (AHP), one can model a hierarchy of levels related to objectives, criteria, failure categories, failure details and failed components. For more details on the AHP readers can consult Saaty (1988). This step is shown in Figure 6.

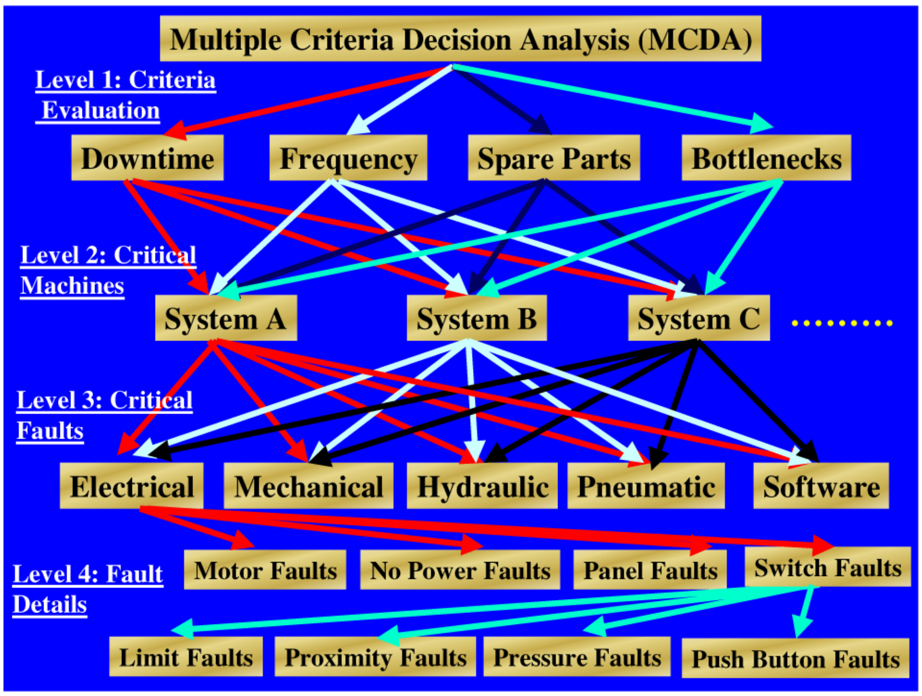

Figure. 6 Step3: Decision Support

The AHP is a mathematical model developed by Saaty (1980) that prioritises every element in the hierarchy relative to other elements in the same level. The prioritization of each element is achieved with respect to all elements in the above level. Therefore, we obtain a global prioritized value for every element in the lowest level. In doing that we can then compare the prioritized Fault Details (Level 4 in Figure 6), with PM signatures (keywords) related to the same machine. PMs can then be varied accordingly in an adaptive manner to shop floor realities.

The proposed decision analysis maintenance model as shown previously in Figure 2 combines both fixed rules and flexible strategies since machines are compared on a relative scale. The scale itself is adaptive to machine performance with respect to identified criteria of importance. Hence flexibility concept is embedded in the proposed model.

Fuzzy Logic Rule based Decision Making Grid

In practice, however, there can exist two cases where one needs to refine the model. The first case is when two machines are located near to each other across different sides of a boundary between two policies. In this case we apply two different policies despite a minor performance difference between the two machines. The second case is when two machines are on the extreme sides of a quadrant of a certain policy. In this case we apply the same policy despite the fact they are not near each other. Both cases are illustrated in Figure 7. For both cases we can apply the concept of fuzzy logic where boundaries are smoothed and rules are applied simultaneously with varying weights.

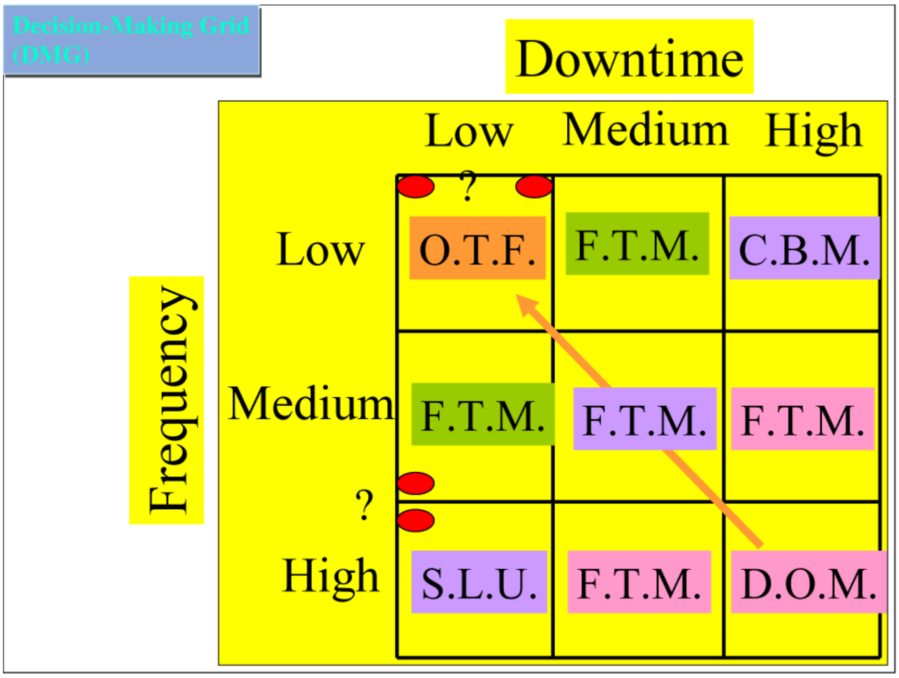

Figure 7 Special cases for the DMG model

In fuzzy logic, one needs to identify membership functions for each controlling factor, in this case: frequency and downtime as shown in Figures 8 (a) and (b). A membership function defines a fuzzy set by mapping crisp inputs from its domain to degrees of membership (0,1). The scope/domain of the membership function is the range over which a membership function is mapped. Here the domain of the fuzzy set Medium Frequency is from 10 to 40 and its scope is 30 (40-10), whereas the domain of the fuzzy set High Downtime is from 300 to 500 and its scope is 200 (500-300) and so on.

The output strategies have a membership function and we have assumed a cost (or benefit) function that is linear and follows the following relationship (DOM > CBM >SLU > FTM > OTF) as shown in Figure 9 (a).

The rules are then constructed based on the DMG grid where there will be 9 rules. An example of the rules is as follows:

Rules:-

e) If Frequency is High and Downtime is Low Then Maintenance Strategy is SLU (Skill Level Upgrade).
e) If Frequency is Low and Downtime is High Then Maintenance Strategy is CBM (Condition Based Maintenance).

Rules are shown in Figure 9 (b).

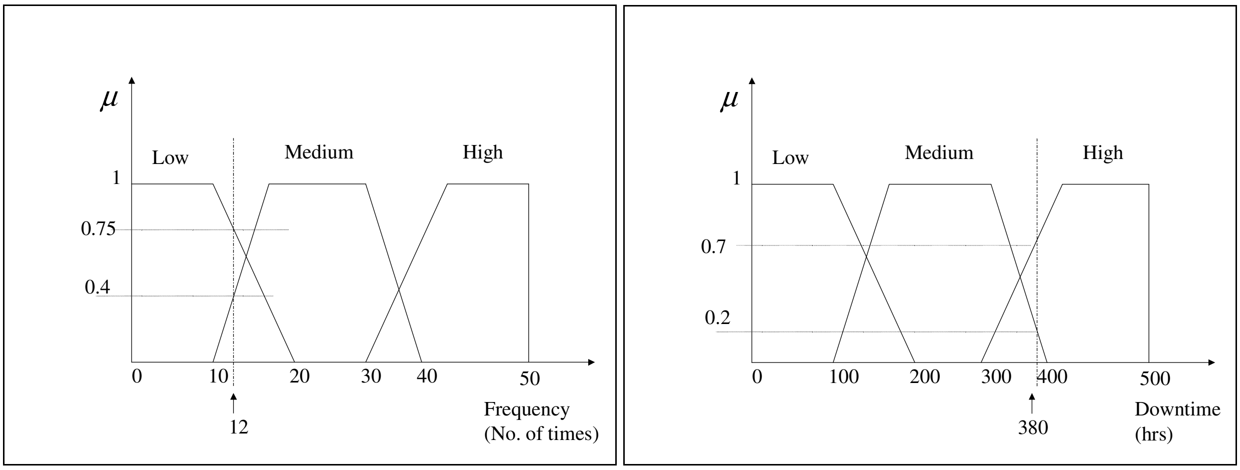

Figure 8 (a) Membership function of Frequency, (b) Membership function of Downtime

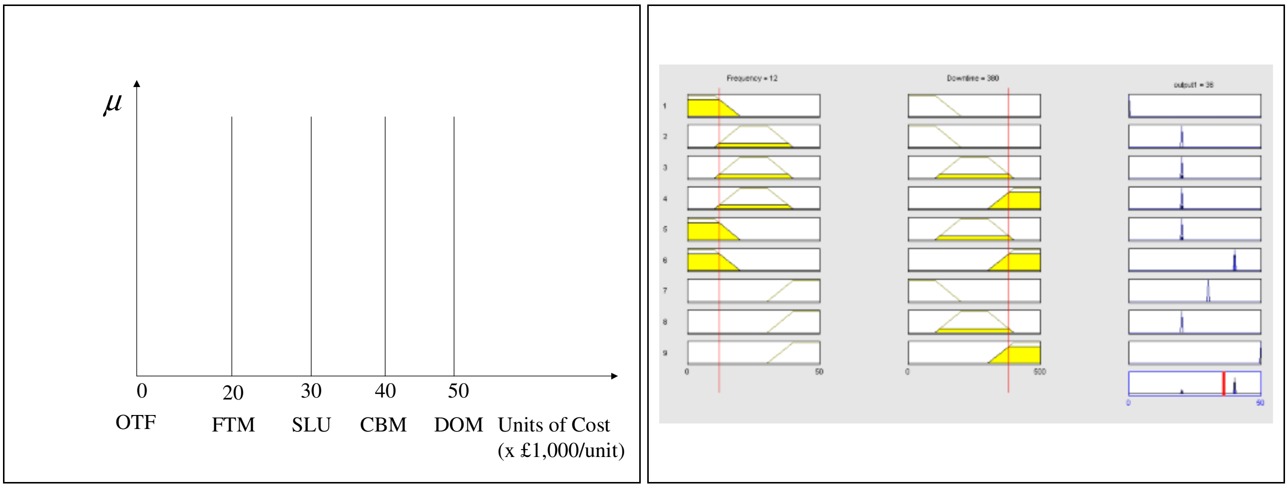

Figure 9 (a) Output (strategies) membership function, (b) The nine rules of the DMG.

The fuzzy decision surface is shown in Figure (10). In this figure, given any combination of frequency (x-axis) and downtime (y-axis) one can determine the most appropriate strategy to follow (z axis).

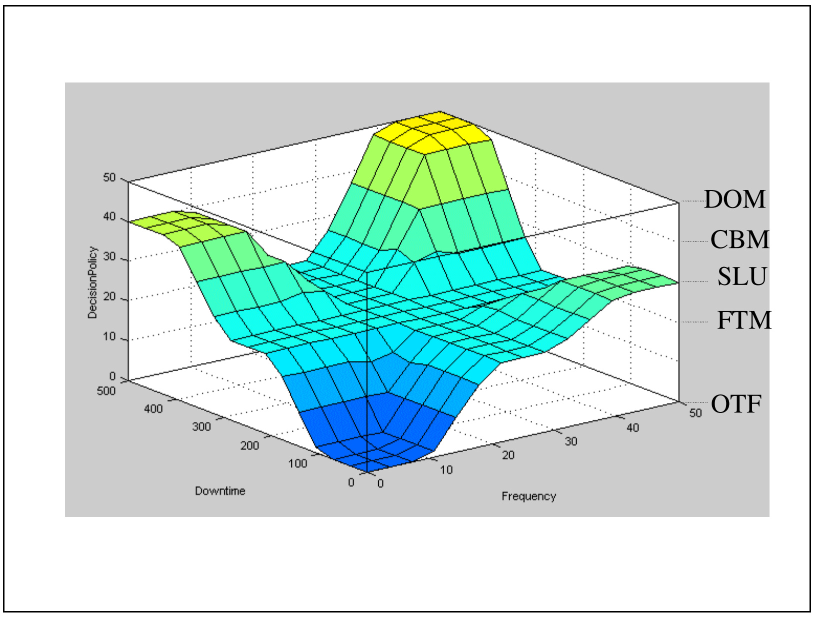

Figure 10 The Fuzzy Decision Surface.

It can be noticed from Figure (11) that the relationship of (DOM > CBM >SLU > FTM > OTF) is maintained. As illustrated in Figure (11), given a 380 hrs of downtime and a 12 times Frequency, then the suggested strategy to follow is CBM.

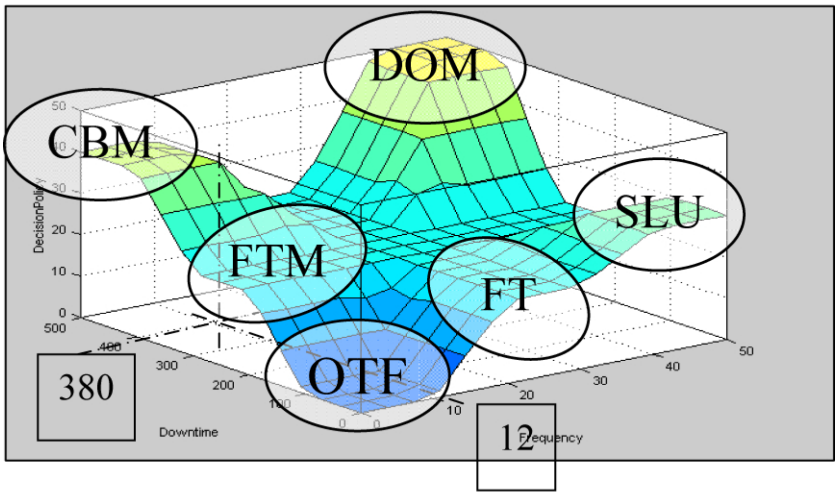

Figure. 11 The Fuzzy Decision Surface Showing The Regions of Different Strategies

5.5 DISCUSSION

The concept of the DMG was originally proposed by (Labib, 1996). It was then implemented in a company that has achieved a World-Class status in Maintenance (Labib, 1998(a)). The DMG Model has also been extended to be used as a technique to deal with crisis management in an award winning paper (Labib, 1998(b)), where it was presented in the context of crisis management rather than maintenance management.

The DMG could be used for practical continuous improvement process because when machines in the top ten have been addressed, they will then, if and only if, appropriate action has been takes, move down the list of top ten worst machines. When they move down the list, other machines show that they need improvement and then resources can be directed towards the new offenders. If this practice is continuously used then eventually all machines will be running optimally.

If problems are chronic, i.e. regular, minor and usually neglected; some of these could be due to the incompetence of the user and thus skill level upgrading would be an appropriate solution. However, if machines tend towards RCM then the problems are more sporadic and when they occur could be catastrophic. Uses of maintenance schemes such as FMEA and FTA can help determine the cause and may help predict failures thus allowing a prevention scheme to be devised.

Figure 12 shows when to apply TPM and RCM. TPM is appropriate at the SLU range since Skill Level Upgrade of machine tool operators is a fundamental concept of TPM. Whereas RCM is applicable for machines exhibiting severe failures (high downtime and low frequency). Also CBM and FMEA will be ideal for this kind of machine and hence a RCM policy will be most applicable. The significance of this approach is that in one model we have RCM and TPM in a unified model rather than two competing concepts.

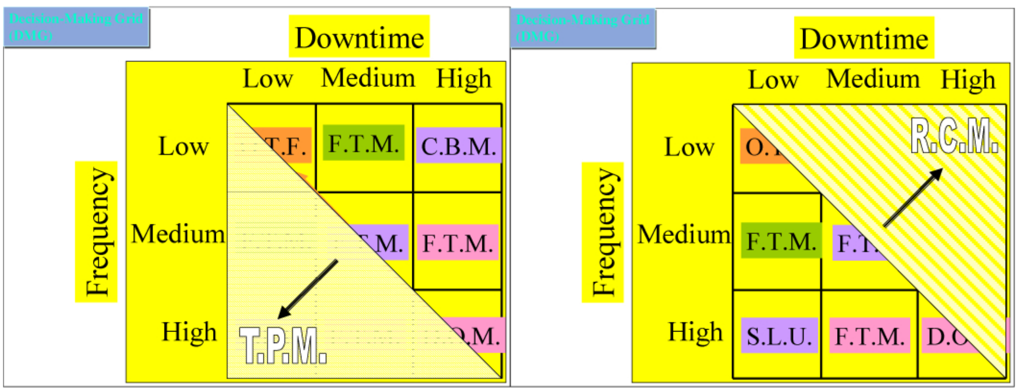

Figure 12 when to apply RCM and TPM in the DMG

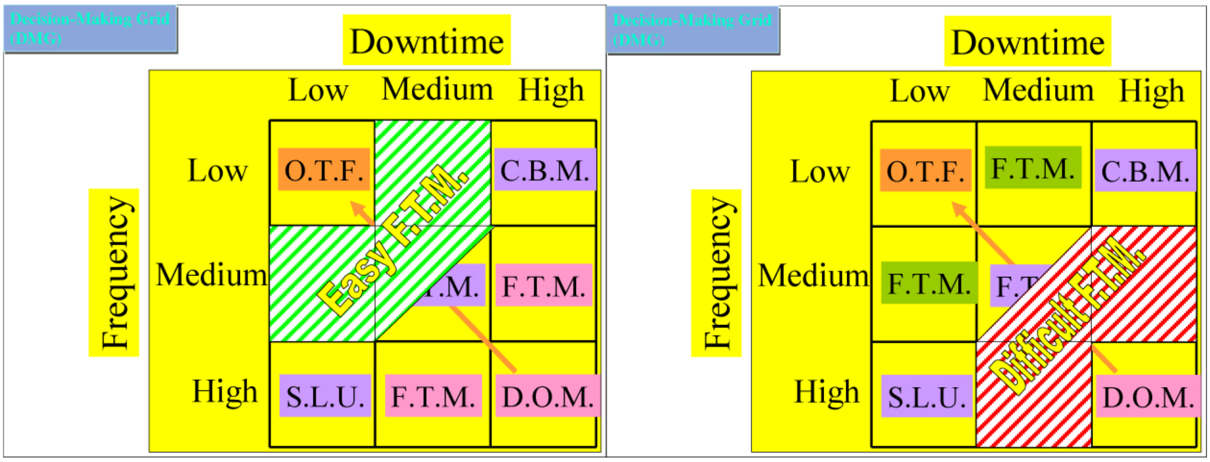

Figure 13 Parts of PM schedules that need to be addressed in the DMG.

Generally the easy Preventive Maintenance (PM), Fixed Time Maintenance (FTM) questions are Who? and When? (efficiency questions). The more difficult ones are What? and How? (effectiveness questions), as indicated in the Figure (13).

6 UNMET NEEDS IN RESPONSIVE MAINTENANCE

According to Professor Jay Lee, of the National Science Foundation (NSF) Industry/University Cooperative Research Centre on Intelligent Maintenance Systems (IMS) at the University of Cincinnati, unmet needs in responsive maintenance can be categorised as follows:

A. machine intelligence – intelligent monitoring, prediction, prevention and compensation and reconfiguration for sustainability (self-maintenance);

B. operations intelligence – prioritisation, optimisation and responsive maintenance scheduling for reconfiguration needs; and

C. synchronisation intelligence – autonomous information flow from market demand to factory asset utilisation.

It can be concluded that the challenges, and research questions, facing research and development (R&D) concerning next generation maintenance systems are:

a. how to adapt PM schedules to cope dynamically with shop-floor reality;

b. how to feed back information and knowledge gathered in maintenance to the designers;

c. how to link maintenance policies to corporate strategy and objectives; and

d. how to synchronise production scheduling based on maintenance performance.

7 FUTURE DIRECTIONS AND CONCLUSION

Training and educational programmes should be designed to address the existence of the considerable gap between the skills that are essential to maximise the potential benefits from these advanced systems and technologies in the area of maintenance and asset management and the skills that currently exist in the maintenance sections of most industries.

Existing ERP and CMMS systems tend to put much emphasis on data collection and analysis rather than on decision analysis. Although the existing teaching programmes already address some of the issues related to next-generation maintenance systems, there is still room for considering other issues, such as:

a. Emphasis on CMMS and ERP systems in the market, as well as their use and limitations.

b. Design awareness in maintenance and design for maintainability.

c. Learning from failures across different industries and disciplines.

d. Emphasis on prognostics rather than diagnostics.

e. e-maintenance and remote maintenance, including self-powered sensors.

f. Modelling and simulation using OR tools and techniques.

g. AI applications in maintenance.

As the success of systems implementation are based on two factors, human and systems, it is important to develop and nurture skills as well as to use advanced technologies.

In this paper, we have investigated the characteristics of Computerised Maintenance Management Systems (CMMSs) and have highlighted the need for them in industry and identified their current deficiencies. A proposed model was then presented to provide a decision analysis capability that is often missing in existing CMMSs. The effect of such model was to contribute towards the optimisation of the functionality and scope of CMMSs for enhanced decision analysis support. We have also demonstrated the use of AI techniques in CMMS's.

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