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An Efficient Failure-Based Maintenance Decision Support System for Smalland Medium Industries

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1. Introduction

Small and Medium Industries (SMI) are the key contributors to economic growth in developing countries. SMI contributes in generating employment and engage in small and medium-scale manufacturing lines to generate profit and employment.

In fact, the largest portion of manufacturing firms fall into SMI categories and the SMI businesses are the backbone of the large-scale industry (Shamsuddin et al. (2004)). However, Junaidah (2007) reported that SMIs lacking appropriate decision making. According to her, SMI do not have a good system to evaluate the overall system of machines, contractors performance and their business's principles. Therefore, maintenance decision support system (DSS) is essential to ensure maintainability and reliability of equipments in industries. Poor machinery maintenance management will result in capacity loss, poor product quality and customer dissatisfaction. These downturns usually occur depending on the efficiency of the reliability programs executed by the organization.

This chapter reveals on the important DSS models i.e. Decision Making Grid (DMG) to be embedded with computerized maintenance management system (CMMS) to aid maintenance strategies for the machines as an adoption of technology management in SMI. Next this chapter demonstrates on how DMG model can be used as a decision support module in Failure-based Maintenance (FBM).

2. Brief description of the maintenance issues in SMI

Shamsuddin et al. (2004) conducted a survey to study FBM issues faced by SMI. They have listed issues related to equipment maintenance, as follows:

i.   Lack of human resources, both in terms of number and skill or expertise;
ii. Emphasis on short-term gains and lack of long-term plans;
iii. Lack of state-of-the-art modern technology;
iv. Lack of understanding about the role of technology;

v.   Insufficient funding for machinery investment;

vi.   Lack of time to think, and reengineering is expensive;

vii.   Operators have poor technical knowledge about the machine they are operating;

viii.   Poor participation from non-manufacturing units such as administration, marketing, and purchasing i.e. looking at the system from the point of sub optimization, which is contrary to Total Productive Maintenance or Total Quality Maintenance practices;

ix.   Overall low level equipment effectiveness evaluation, especially on availability, performance rates, and quality rates; and

x.   Slow response of the contractors on maintenance work.

Saleh and Ndubisi (2006) highlighted that SMI lack a comprehensive framework to be used in solving critical issues. Later, Kittipong (2008) conducted more comprehensive studies on technology relationships in SMI. He conducted the surveys and identified 20 factors of technology relationship and innovations. He conducted hypotheses and concluded that technology expertise is the first priority for SMI success in the area of manufacturing. SMI should start to look at the technology escalation procedure and manage their vendors or contractors efficiently. He has suggested a further research direction for factorial and decisional analyses using longitudinal data in his thesis. This motivates this study to aid maintenance decision-making in FBM for SMI.

3. Effects of the machinery failures in SMI

The primary functions of most machines in industries are concerned, in some way, with the need to earn revenue or to support revenue earning activities. Poor machinery maintenance will lead to more emergency breakdowns. The breakdowns affect the production capability of physical assets by reducing output, increasing operational costs, and, thus, interfering with customer services. Machinery failures in SMI production lines will increase the operation cost and reduce their profit margin.

ln brief, the effects of downtime are much greater than the cost of repairing the failures. For example, if a filling machine fails in a SMI production line, the end products will spill over. This also results in labour safety issues as well as business losses.

4. Related works

It has been a long journey for the evolution of maintenance management models and techniques from 1940 until now. Maintenance is a wide area, and involves planning, coordinating, controlling, supervising and managing activities in order to achieve the organization's purposes and goals. Palmer (1999) defines maintenance management as control that must be taken to keep the equipment in its working state, by preserving it from any failures. The goals of the maintenance study are to reduce downtime and cost, while improving the adequacy and quality of service to maximize the availability of equipment in an operative state. There are many literatures available from various researchers and practitioners in the field of maintenance management.

In general, Burhanuddin (2009) narrowed down maintenance literature into four main-classes, sub-classes and sub-divisions, as shown in Figure 1.

Some observations of the study in each of the above four main-classes in maintenance management and their fractions are presented in detail as follows.
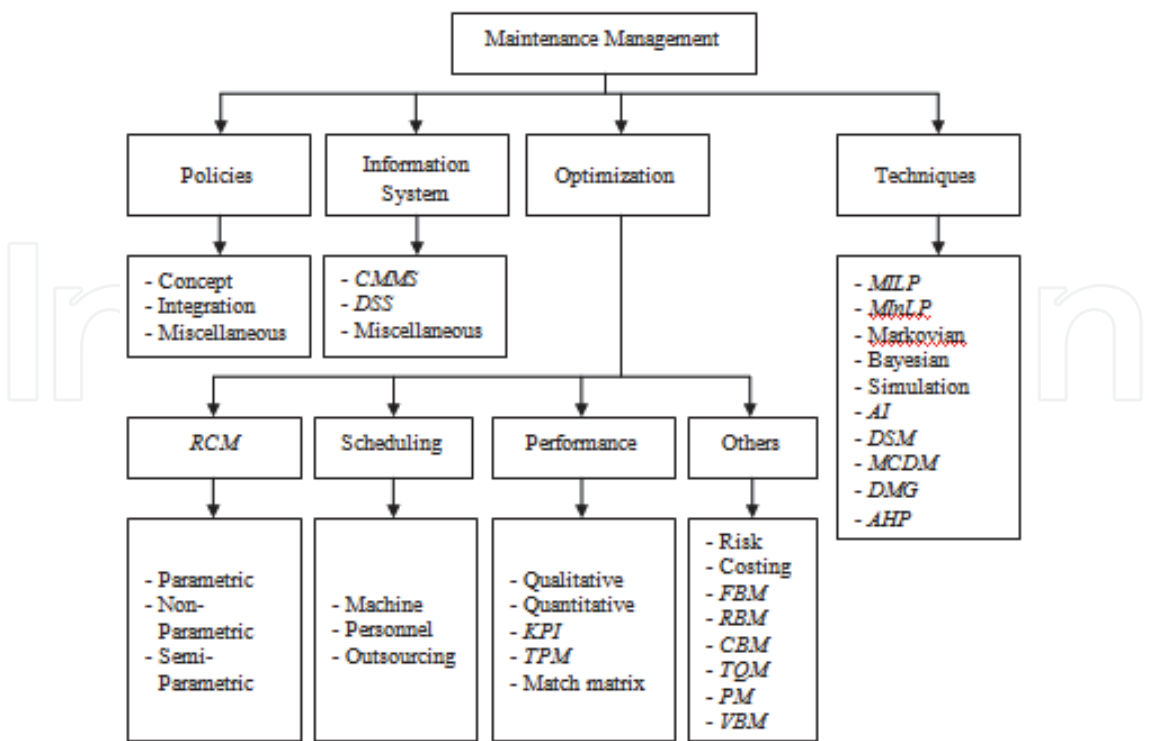
Abbreviation represent: CMMS: Computerized Maintenance Management System; DSS: Decision Support System; RCM: Reliability-centred Maintenance; KPI: Key Performance Index; TPM: Total Productive Maintenance; FBM: Failure-based Maintenance; RBM: Risk-based Maintenance; CBM: Condition-based Maintenance; TQM: Total Quality Maintenance; PM: Preventive Maintenance; VBM: Vibration-based Maintenance; MILP: Mixed Integer Linear Programming; MInLP: Mixed Integer non-Linear Programming; AI: Artificial Intelligence; DSM: Decision Support Model; MCDM: Multiple Criteria Decision-Making; DMG: Decision-Making Grid; and AHP: Analytical Hierarchical Process

Fig. 1. Sub-division Tree of Maintenance Management

4.1 Maintenance policies

Guy and Steve (1999) reviewed the general terms of maintenance. They studied maintenance development and the reason behind it changing from time to time. After that, they focused on the enhancement and evolution of information systems in maintenance.

Some important findings on enhancement of the development of information systems in maintenance are given, as they have discovered that new strategic development in maintenance is due to information system application and development.

Lam and Lin (2004) integrated some replacement policies into corrective maintenance. Corrective or Failure-based Maintenance (FBM) is unscheduled maintenance or repair to return the machine to a defined state. There are no interventions until a failure has occurred. Lewis (1999) addressed corrective maintenance as reactive maintenance, where any emergency breakdown will lead to a bigger impact on the operation. Since the failures are unplanned, they might result in a big loss to the organization in terms of cost and time. Therefore, a better maintenance concept must be introduced to prevent this unplanned downtime and reduce the cost of the failure. The breakdown maintenance concept is still applied to equipment that is not mission critical and where the downtime would not affect the main operation of the organization, such as light bulbs and consumable parts. Lam and Lin (2004) have introduced some numerical methods and designed optimal replacement policies in FBM.

According to Palmer (1999), if the plant spends a lot of time on breakdown maintenance, then it does not spend enough time on preventive maintenance. Thus, predictive maintenance is introduced to resolve deficiencies with scheduled downtime. Predictive maintenance involves monitoring certain conditions or variables associated with the equipment (Bentley, 1993). The simplest method of condition-based monitoring involves the four human senses of sight, sound, touch and smell to predict a failure. Repairing activities take place when the condition shows that a failure may be imminent.

Unlike the Condition-based Maintenance (CBM) policy, in predictive maintenance the acquired controlled parameters data are analyzed to find a possible temporal trend. This makes it possible to predict when the controlled quantity value will reach or exceed the threshold values. The maintenance staffs will then be able to plan when, depending on the operating conditions, the component substitution or revision is really unavoidable. The following main activities can help to avoid machine breakdown (Bentley, 1993):

i.   Fault detection,
ii.   Fault isolation,
iii. Fault elimination, and
iv.   Verification.

The same was demonstrated by Geert and Liliane (2004), who distinguished five basic maintenance policies in corrective and preventive maintenance. Preventive maintenance is carried out using a planned, periodic and specific schedule to keep a machine in a stated working condition, throughout the process of checking and reconditioning. Preventive maintenance is defined as the pre-breakdown model performed on equipment to either eliminate or reduce the emergency failures within pre-determined economic limits (Lewis, 1999). The model has been introduced to enhance reliability and confidence of the machine in advance. This maintenance is categorized as proactive maintenance. The service is repeated at a pre-determined frequency to avoid any unplanned breakdown of the machine. Bentley (1993) divides the preventive maintenance (PM) model into CBM with two main categories, as follows:

i.   Monitored PM, which involves monitoring when the machine is in operation. Triggers on any potential failure will be detected. Repair activities are to be conducted before any unplanned breakdown; and

ii.   Scheduled maintenance, where the service is being conducted on the same machine at specific counter or time intervals. The maintenance crew always follows the standard checklist to conduct PM activities, which involves scheduled replacement of parts, service, alignment, greasing, lubrication, confidence testing, etc.

Geert and Liliane (2004) distinguished five basic policies in maintenance, as follows:

i.   Failure-based Maintenance (FBM);
ii.   Use-based Maintenance (UBM);
iii. Condition-based Maintenance (CBM);
iv.   Detection-based Maintenance (DBM); and
v.   Design-out Maintenance (DOM).

They have suggested seven steps to follow in a modular framework on maintenance policies, before building any maintenance policies, as follows:

i.   Identification of the objectives and resources,
ii.   Selection of the most important maintenance systems,
iii. Identification of the most critical machines and their components,

iv. Maintenance policy selection,
v.   Optimization of the maintenance policy parameters,
vi. Implementation and evaluation, and
vii. Feedback.

Later, Geert and Liliane (2007) discovered more findings. They have designed concrete policies and developed a framework to set up an industrial management centre. There is a group of people in the centre to control all maintenance work and escalate the work to the respective site. Their model can be used to develop a customized maintenance concept that is suitable for multinational companies.

Since centralized maintenance control in a centre requires more people, Dhillon and Liu (2006) presented the impact of human errors on maintenance. They conducted a literature survey of human errors in maintenance and their impact on the manufacturing plant. They reported that human errors will reduce production profit. Imad (2007) highlighted the role of maintenance as a profit-generating functionality, by introducing a maintenance quality concept in the manufacturing system. He has intimated the relationship between a manufacturing system's capacity and the total manufacturing costs per unit of quality item, in order to describe and illustrate how maintenance generates profit to the company.

Finally, Imad (2007) proved that maintenance is not a cost centre, but a profit-generating centre in the manufacturing sectors. Attempting to fulfil maintenance as a profit-making centre, Alexandre et al. (2008) introduced the excellent-maintenance concept of doing more work with fewer people and less money. They stressed this new generation maintenance concept, which includes:

i.   Remote maintenance: By leveraging information, wireless and internet technologies, users may log in from anywhere and with any kind of device as soon as they get an internet connection. The maintenance operation team can connect remotely to the equipment in the factory, then run setup, control, configure, diagnose, debug, fix, monitor performance, or download data for analysis;

ii. Cooperative or collaborative maintenance: Excellent-maintenance symbolizes the opportunity to implement an information infrastructure connecting geographically dispersed subsystems;

iii. Immediate or on-line maintenance: The real-time remote monitoring of equipment status, coupled with programmable alerts, enables the maintenance operator to respond whenever any breakdown occurs. In addition, high-rate communications allow them to quickly obtain several kinds of expertise and to accelerate the feedback reaction in the local loop, connecting the product, monitoring agent and maintenance support system together. It has almost unlimited potential to reduce the complexity of traditional maintenance guidance through on-line guidance, based on the results of decision-making and analysis of product condition;

iv. Fault diagnosis or localization: Excellent-maintenance offers experts the ability to perform on-line fault diagnosis, share their valuable experiences with each other, and suggest remedies to the operators if an anomalous condition occurs in the inspected machine. In addition, lock-outs and isolation can be performed and recorded on location. Consequently, the amount of time it takes to communicate a production problem to the potential expert solution provider can be reduced, the quality of the information shared can be improved, and thereby the resolution time reduced. All these factors increase the availability of production and facilities equipment, reduce the mean time taken to repair, and significantly utilize field service resources and costs;

v. Repair or rebuilding: Remote operators could, via an electronic connection, tap into specialized expertise rapidly without any travelling or scheduling delays. Downtimes could be conceivably reduced through direct troubleshooting with source designers and engineers. In addition, diagnosis, maintenance work performed, and parts replaced are documented on the spot, through structured responses to work steps displayed on the mobile workstation; and

vi. Modification or improvement: The multi-source knowledge and data environment provided by excellent-maintenance allows efficient information sharing. With the availability of tools for interacting, handling, and analysing information about product state, the development of maintenance engineering for product lifecycle support, including maintenance and retirement stages such as disassembly, recycling, reuse and disposal, is becoming feasible.

The excellent-maintenance concept requires a good information technology system. There are very promising developments in information technology, which can help to improve maintenance practice. However, the information system development in maintenance is still relatively young in the business area, and its recent development is discussed in the next section.

4.2 Maintenance information system

The information system is becoming an important tool for achieving efficiency and effectiveness within maintenance, provided that the correct and relevant information technology is applied. In fact, there are many papers on the maintenance information system and technologies, where they are always integrated with other disciplines such as inventory control, supply chain management and communication technology on the manufacturing shop floor. Here, four reviews are worth discussing under this sub-section. The first review is given by Labib (2004), who discusses the CMMS development to facilitate the management of maintenance resources, to monitor maintenance efficiency and to provide appropriately analysed management information for further consideration. Labib (2004) has suggested some benefits that CMMS can offer, as follows:

i. It allows operators to report faults faster by filling-up the electronic-form. At the same time, it enables the maintenance team to respond to and update the form promptly;

ii. It can facilitate improvements in communication between operators and maintenance personnel, and is influential in ameliorating the consistency of information flow between these two departments;

iii. It offers insight into wear-and-tear in FBM activities;

iv. It provides maintenance planners with the historical information necessary for developing next PM schedules; and

v. It can track the movement of spare parts and requisition replacements whenever necessary.

In the second review, O'Donoghue and Prendergast (2004) proved that CMMS is very beneficial. They examined the basis of various maintenance management strategies used to date in international manufacturing. They have demonstrated how CMMS is used to capture maintenance activities, and analysed maintenance time and cost in an Irish textile manufacturing company.

Lately, rapid growth in computer technology has opened up new possibilities in CMMS development. This brings us to the third review, in which Mirka (2008) reported that CMMS

provides tremendous benefit to maintenance. She identified salient characteristics of CMMS by showing that information technology investment has a positive correlation to company profitability and competitiveness. She also developed information technology tools based on a company's factors of goal and purpose.

Despite providing significant characteristics of CMMS, which may fit in with the needs of the industries, Labib (2004) also discovered that the majority of available CMMS in the market lack decision support for management. Last but not least, the fourth crucial review, highlighted by Sherif et al. (2008). They managed to embed DSS into CMMS as an advanced software engineering approach. DSS constitutes a class of computer-based information systems, including knowledge-based systems that support decision-making activities. A computer program is written using available maintenance techniques to automate the analysis and results. The program is executed in sub-procedures in CMMS as a DSS module. Sherif et al. (2008) synthesized DSS with problem-solving in concrete bridge decks maintenance activities. They proposed different decisions for different types of repair, i.e. shallow repair, deep repair, protective repair, non-protective repair, and deck replacement. All decision-makers must consider the cost of repair when making any recommendation. Sherif et al. (2008) also deliberated on how DSS is used to model human reasoning and the decision-making process for concrete bridge decks. At the end of the study, they concluded that buying sophisticated hardware or software is not the complete answer. However, justification on middleware software, and an object-oriented system by integrating some maintenance techniques into the DSS, is another potential area to consider. There are various available techniques in maintenance that can be programmed into CMMS and can measure maintenance activities. The techniques are elaborated on in the next section.

4.3 Decision support system and optimization techniques

DSS gathers and presents data from a wide range of sources in a way that can be interpreted by humans. Important features of DSS are given as follows (Williams and Sawyer, 2006):

i.   lnputs and outputs;
ii. Assist tactical-level managers in making tactical decisions; and
iii. Produce analytical models, such as mathematical representation of a real system.

A quantitative approach in the DSS model allows maintenance manager to play a simulation what-if game to reach decisions. They can simulate certain aspect of the organization's environment in order to decide how to react to a change in the conditions affecting it. By changing the hypothetical inputs to the maximum and minimum levels, the managers can see how the model's outputs are affected. There are four aspects to maintenance optimization models, as follows (Amik and Deshmukh (2006)):

i.   Description of a technical system, its function and importance;
ii. Modeling of the deterioration of the system in time and possible consequences for this system,
iii. Description of the available information about the system and action open to management and
iv. Objective function and an optimization technique, which helps in finding the best practice.

An efficient DSS for SMI should have some real time data analysis capabilities, and be able to query from the database, perform the calculation and provide decisions such as:

i.   Which machines should go for FBM, fixed time maintenance, design-out maintenance, condition-based maintenance, preventive maintenance, etc.

ii.   When the next maintenance is due for every machine;

iii.   Which contractor should be called to perform the maintenance work;

iv.   Estimates of man-hours required;

v.   Description of the tasks involved and how much time is required;

vi.   Lists of all required replacement parts and their locations;

vii. Forecast on the spare parts, tools and their costs;

viii. Re-order level of the machine parts and other accessories; and

ix.   An estimate of the maintenance priorities and their impact.

The most prominent objective of the various techniques in maintenance DSS is to supply vital data and evidence, to derive better strategies to minimize machine downtime and maintenance cost. DMG is one of the famous techniques in DSS as suggested as follows.

5. Decision-making grid

The maintenance Decision-Making Grid (DMG), introduced by Labib (1998) acts as a map where the performances of the worst machines are placed based on multiple criterions, i.e. frequency of failures and downtime. The results provide guidelines for the action, which will lead to the movement of machines towards an improvement of the maintenance strategies with respect to multiple criterions. Labib (2004) defined the main input from the failures for DMG analysis as follows:

i.   The response time;

ii.   The diagnostic time;

iii.   The repair time; and

iv.   Frequency of failures.

Based on the input, machines are mapped into a two-dimensional matrix and appropriate maintenance strategies will then be implemented, such as total productive maintenance, reliability-centred maintenance, design-out maintenance, condition-based maintenance, fixed-time maintenance, etc.

There are many researchers who have studied the DMG and apply it in the equipment management area. Among those, there are three selected reviews that are worth discussing under this sub-section. In the first Labib (1998a) has introduced the DMG model to help maintenance management identify breakdown maintenance strategies. In short DMG is a control chart in two dimensional matrix forms. The columns of the matrix show the three criterions of the downtime, whilst the rows of the matrix show another three criterions of the frequency of the failures. The model consists of these three steps:

i.   Criteria analysis;

ii.   Decision mapping and

iii.   Decision support.

Here, a better maintenance model for quality management can be formed by handling both the rows and columns of the matrix respectively. The matrix offers an opportunity to decide what maintenance strategies are needed for decision-making such as to practice Operate to Failure (OTF), Fixed Time Maintenance (FTM), Service Level Upgrade (SLU), Condition-based Maintenance (CBM), Designed-out Maintenance (DOM), Total Productive Maintenance (TPM) and Reliability-centered Maintenance (RCM).

The second important review was undertaken by Fernandez et al. (2003), in which implementation of DMG in CMMS was discussed in detail. They extended the theory of the maintenance maturity grid and implemented it into a disk brake pad manufacturing

company in England. The results can provide maintenance policies in the respective functional group in production lines, to achieve their common goal to reduce downtime.

Later, Zulkifli et al. (2008), in the third review, comprehended the model and demonstrated the hybrid intelligent approach using the DMG and fuzzy rule-based techniques. In their study, the DMG is employed in small and medium food processing companies to identify their maintenance strategies. DMG is used in these study as the model is flexible, and considers OTF, FTM, SLU, CBM, DOM, TPM and RCM strategies in the same grid. The model is able to analyze multiple criteria and is the best choice when the number of machines is less than fifty (Pascual et al, 2009). It can be used to detect the top ten problematic machines on the production floor with several system conditions. This is with regards to failures such as fatigue, imbalance, misalignment loosened assemblies, and turbulence, which can occur in rotational or reciprocating parts such as bearings, gearboxes, shafts, pumps, motors and engines. Identifying the top ten problematic machines is in alignment with the 80-20 rule. The rule states that eighty percent of the problems arise from the same twenty percent of the root causes.

In another word, once twenty percent of the root cause had been fixed, then eighty percent of the problem is resolved. The application of the model can have a breakthrough performance, as it fulfils the purpose of the model to map machines into a certain grid in a matrix and suggests the appropriate maintenance strategies to comply with.

5.1 Development of the decision-making grid model

There are many publications on CMMS and DMG applications in the area of maintenance. Among them, there are three journal papers that are most related to this study of the DMG model, written by Labib (1998b and 2009) and Fernandez et al. (2003). Labib (1998b) introduced DMG as a maintenance decision-making tool to be embedded in CMMS. Later, Fernandez et al. (2003) included DMG as a sub-module in their CMMS. They tested the model in one of the brake pad manufacturing companies in England. Next Zulkifli et at. (2010) integrated DMG with a fuzzy rule-based hybrid approach. The DMG model was formed as a control chart by itself in two-dimensional matrix forms. The columns of the matrix show the three criterions of the downtime, whilst the rows of the matrix show another the criterions of the frequency of the failure.

A better maintenance model for quality management can be formed by handling both the rows and columns of the matrix respectively. The matrix offers an opportunity to decide what maintenance strategies are needed for decision-making such as to practice OTF, FTM, SLU, CBM or DOM. The matrix also suggests maintenance concepts that are useful for each defined cell of the matrix such as TPM or RCM approaches. The results can provide maintenance policies in the respective functional group in production lines to achieve their common goal, to reduce downtime. There are two basic steps to follow in the DMG model as follows:

Step 1. Criteria Analysis: Establish a pareto analysis of two important criteria:
   a. Downtime, which is the main activity conducted by a maintenance crew; and
   b. Frequency of breakdown calls, which is always a concern for a customer service centre.
      The objective of this phase is to assess how bad the worst performing machines are over a certain period of time. The machines, as regards each criterion are sorted and placed into a top ten list of high, medium, and low boundaries, which are divided into three categories using the tri-quadrant approach as follows (Burhanuddin (2009)). let x be the frequency of failures.

Let k = $\dfrac{x_{\max} - x_{\min}}{3}$, where max = maximum and min = minimum, then the intervals are obtained as:

$$\text{Highfrequency} \qquad = [\, x_{\max}, x_{\max} - k\,) \qquad\qquad (1)$$

$$\text{Mediumfrequency} \qquad = [\, x_{\max} - k, x_{\max} - 2k\,) \qquad\qquad (2)$$

$$\text{Mediumfrequency} \qquad = [\, x_{\max} - 2k, x_{\min}\,] \qquad\qquad (3)$$

Similarly, let y be the downtime of the machines. Let l = $\dfrac{y_{\max} - y_{\min}}{3}$, then the intervals are obtained as:

$$\text{Highdowntime} \qquad = [\, y_{\max}, y_{\max} - l\,) \qquad\qquad (4)$$

$$\text{Mediumdowntime} \qquad = [\, y_{\max} - l, y_{\max} - 2l\,) \qquad\qquad (5)$$

$$\text{Mediumdowntime} \qquad = [\, y_{\max} - 2l, y_{\min}\,] \qquad\qquad (6)$$

Using the above formulae, machines are mapped into a two-dimensional matrix based on their respective intervals on frequency of failures and downtime. Next, decision strategies for machines such as OTF, FTM, SLU, CBM, DOM, RCM or TPM can be implemented (Labib (1998b)).

Step 2. Decision Mapping: Those machines that meet both criteria and are ranked in Step 1, are then mapped on the grid as shown in Table 1.

Frequency	Downtime		
	Low	**Medium**	**High**
Low	OTF	*FTM1*	*CBM*
Medium	*FTM2*	FTM3	*FTM4*
High	*SLU*	FTM5	*DOM*

Table 1. Decision-Making Grid (Labib, 1998b)

In this phase the decision is developed by comparing two-dimensional matrices. The objective of this exercise is to implement appropriate actions that will lead to the movement of machines towards improved machine maintenance strategies, complying with Labib (1998b) in respect of the multiple criterions as follows:

a. Operate to failure (OTF): Machines that are very seldom failed (low frequency). Once failed, the downtime is short (low downtime). The machines in this region are performing well and are easy to repair

b. Skill levels upgrade (SLU): Machines that always fail (high frequency), but can be fixed quickly (low downtime). Basically, the problems faced by the machines in this grid are relatively easy to fix. Upgrading operators' skill levels in fixing the problem will help to reduce response time;

c. Condition-based maintenance (CBM): Machines that seldom fail (low frequency). However, this is a killer machine, as it takes a long time to bring it back to normal

operation (high downtime). Machines in this region should be monitored closely. It is a good idea to equip the machines with sensors or any condition-based monitoring devices to observe their performance;

d. Design-out maintenance (DOM): Machines that always fail (high frequency). Once failed, it takes a long time to bring them back to normal operation (high downtime). This region consists of the worst production machines and it is recommended that they be structurally modified. A maintenance department should consider a major design-out project and spend money to upgrade the machines in this grid; and

e. Fixed time maintenance (FIM): There are five categories as follows:

- FTMI: Concern about the timing of the maintenance. Maintenance department should revise when is the best time to conduct the preventive maintenance;
- FTM2: Maintenance department should study who is the most suitable person to conduct the maintenance job for those machines in this grid, i.e. operator, technicians, contractors or maintenance engineers;
- FTM3: Failure frequency and downtime are almost at the moderate cases,
- FTM4: Maintenance department should revise on their maintenance checklist and instructions. What are the instructions that must be included during maintenance; and
- FTM5: Maintenance department should revise on how the maintenance should be conducted and improved.

The TPM approach should be applied for the lower triangle of the DMG matrix, as shown in Table 2 (Labib, 1998b). TPM is applied globally and one of the TPM concepts is to empower the operators to maintain continuous production on totally efficient lines (Nakajima,1988). TPM is the continuous knowledge transfer to operators and the maintaining of the production equipment together with the maintenance crew. Hence, we can slowly reduce the waiting time for technicians to be in the production plant. On the other hand it gives operator the opportunity to eliminate the root causes of the machines' errors on a small level, before they become big ones.

Frequency	Downtime		
	Low	Medium	High
Low	OTF	FTM1	CBM
Medium		FTM3	FTM4
High	TPM		DOM

Table 2. DMG-TPM Strategy (labib 1998b)

The RCM approach should be applied for the upper triangle of the matrix as shown in Table 3. RCM involved a study and measurement of the probability that a machine will operate as expected at the desired level, for a specific period of time, under the design operating conditions, and without any failures. Once the problematic machines are identified, the maintenance strategy should be adjusted to ensure the longest survival of the machine to complete a mission at a specific

time (Elsayed, 1996). Strategies such as CBM or DOM are executed based on measurements and estimates.

Once the top ten worst performing machines are identified from DMG, the appropriate action to identify the next focused action is implemented. In other word, maintenance staffs need to move from the strategic systems level to the operational component level.

Frequency	Downtime		
	Low	Medium	High
Low		RCM	
Medium	FTM2		
High	SLU	FTM5	

Table 3. DMG-RCM Strategy (Labib, 1998b)

5.2 Empirical results

As a case study, the dataset from Fernandez et al. (2003) on the disk brake pad manufacturing company in England is used. Table 4 shows the level of the frequency of failures decision analysis using formulas in (1), (2) and (3).

ID	Frequency	Level
A	23	High
B	19	High
C	16	Medium
D	16	Medium
E	16	Medium
F	16	Medium
G	15	Low
H	14	Low
I	13	Low
J	12	Low

Table 4. Frequency of Failure Decision Analysis (Fernandez et al., 2003)

Decision analysis graph on frequency of failures is shown in Figure 2.

Once intervals of the machine are categorized correctly using formulae (4), (5) and (6), the DMG matrix can be constructed as shown in Table 6. Next, a strategic decision is identified by mapping at DMG in Table 1, given by Labib (1998b). Then, a valid recommendation can be given to the SMI maintenance management team to implement maintenance strategy.
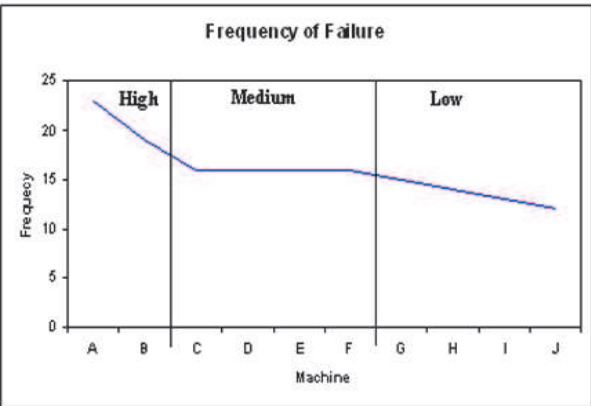
Fig. 2. Frequency of Failure Decision Analysis (Fernandez et al., 2003)

Table 5 shows the level of decision analysis on downtime in hours, from Fernandez et al. (2003) data using formulas in (4), (5) and (6).

ID	Downtime	Level
B	64	High
A	32	High
F	29	High
K	28	Low
H	27	Low
L	25	Low
C	25	Low
G	22	Low
D	20	Low
E	20	Low

Table 5. Decision Analysis on Downtime (Fernandez et al., 2003)
Decision analysis graph on downtime is shown in Figure 3.
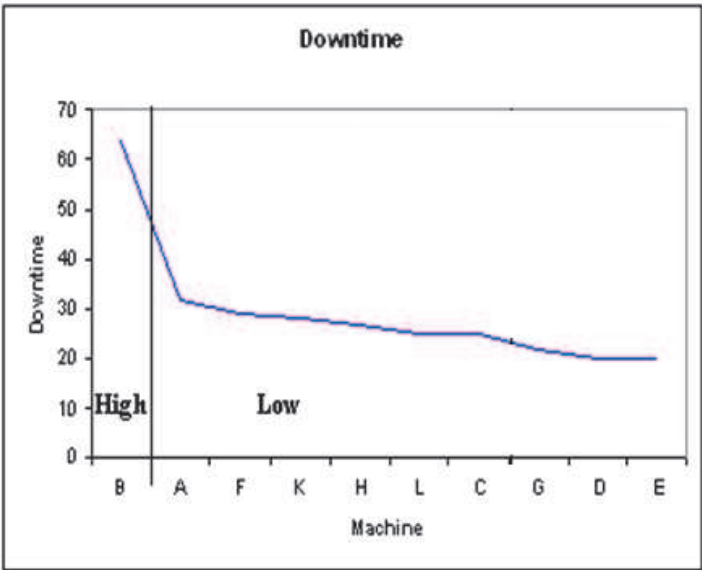
Fig. 3. Decision Analysis on Downtime (Fernandez et al., 2003)

7. Conclusion and further research

This chapter aim to improve maintenance strategies in FBM by extending some theoretical method introduced by Labib (1998b) and Burhanuddin (2009) in DMG model to provide maintenance strategies for SMI. The analysis provides insight by using collective approaches in two-dimensional matrices, and simultaneously measures multiple criterion of the downtime and frequency of failures.

Maintenance strategies are identified using the DMG model, based on important factors, including the machines' downtimes and their frequency of failures. The machines are categorized into the downtime criterions and frequency of failures, which are high, medium and low using tri-quadrant formulae. The experimental studies are conducted using maintenance dataset given by Fernandez et al. (2003). The proposed models can be used by decision makers to identify maintenance strategies and enhance competitiveness among contractors in FBM. There have been very promising development in computer science, which can help SMI to monitor and compare maintenance activities.

The analysis provides insight by using collative approaches in two-dimensional matrices, and simultaneously investigates three criterion of the downtime and frequency of failures. Tri-quadrant analysis is used to ascertain the model through the incorporation of multiple criterions of the decision-making analysis for SMI. The result of the analysis provides some decision-making strategies for machinery maintenance.

This study focuses on DMG based on few factors respond time, diagnostic time, repair time and frequency of failures. More research on organization procedures and underlying characteristics of the machines, such as their model, age, made, price, etc., can lead to a more comprehensive study in FBM. The external factors such as economic, geographical and social aspects could be incorporated into the models.

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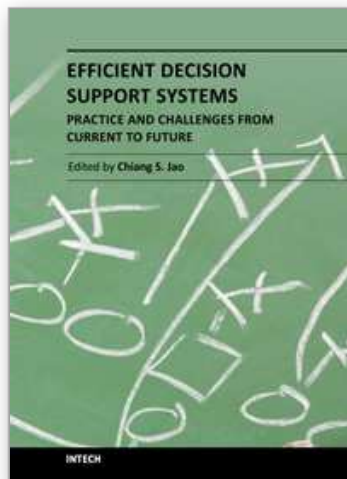
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