INTEGRATION OF CLUSTERING CONCEPT AND FUZZY TOPSIS FOR MAINTENANCE POLICY DECISION MAKING MODEL

By

DING SIEW HONG

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$\widetilde{w}_j$	Fuzzy rating of criteria significant j
$\widetilde{x}_{ij}$	Fuzzy rating of maintenance policy i with respective to criteria j
CC_i^*	Closeness coefficient of maintenance policy i
$\widetilde{D}$	Fuzzy decision matrix
G_{pq}	Number of same failure mechanism occur on both System p and System q
H_{pq}	Number of failure mechanism occur either on System p or System q
$\widetilde{R}$	Normalized fuzzy decision matrix
RS_{pq}	Rescaled distance coefficient
S^-	Fuzzy negative ideal solution
S^+	Fuzzy positive ideal solution
S_{pq}	Similarity coefficient between System p and System q
$\widetilde{V}$	Weighted normalized fuzzy decision matrix
d_i^-	Separation distance from fuzzy negative ideal solution
d_i^+	Separation distance from fuzzy positive ideal solution
$\tilde{r}$	Normalized fuzzy rating
s_{max}	Maximum similarity coefficient
s_{min}	Minimum similarity coefficient
$\widetilde{v}$	Weighted normalized fuzzy rating
$\widetilde{w}$	Fuzzy number of linguistic variable w
w^a	Minimum value of fuzzy number for linguistic variable w
w^b	Exact value of fuzzy number for linguistic variable w
w^c	Maximum value of fuzzy number for linguistic variable w
w_j^a	Minimum value of fuzzy number for criteria j

$\boldsymbol{w_j^b}$	Exact value of fuzzy number for criteria j
$\boldsymbol{w_j^c}$	Maximum value of fuzzy number for criteria j
$\boldsymbol{\tilde{x}}$	Fuzzy number of linguistic variable x
$\boldsymbol{x^a}$	Minimum value of fuzzy number for linguistic variable x
$\boldsymbol{x^b}$	Exact value of fuzzy number for linguistic variable x
$\boldsymbol{x^c}$	Maximum value of fuzzy number for linguistic variable x
$\boldsymbol{x_{ij}^a}$	Minimum value of fuzzy number of maintenance policy i with respective to criteria j
$\boldsymbol{x_{ij}^b}$	Exact value of fuzzy number of maintenance policy i with respective to criteria j
$\boldsymbol{x_{ij}^c}$	Maximum value of fuzzy number of maintenance policy i with respective to criteria j
$\boldsymbol{a}$	Minimum value of the linguistic variable
$\boldsymbol{b}$	Exact value of the linguistic variable
$\boldsymbol{c}$	Maximum value of the linguistic variable
$\boldsymbol{f}$	Failure mechanism
$\boldsymbol{i}$	Number of maintenance policy
$\boldsymbol{j}$	Number of criteria
$\boldsymbol{K}$	Number of expert
$\boldsymbol{t}$	Triangular fuzzy number
$\boldsymbol{u(t)}$	Value of the membership function

LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AM	Autonomous maintenance
ANP	Analytic Network Process
CM	Corrective maintenance
COPRAS	Complex Proportional Assessment
DEMATEL	Decision Making Trial and Evaluation Laboratory
DMG	Decision making grid
DOM	Design out maintenance
E	Economical
EI	Equally important
F	Fair
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Modes Effect and Criticality Analysis
FMS	Flexible Manufacturing System
GA	Genetic Algorithm
H	High
ICC	Intra Class Correlation
L	Low
MCCE	Multicriterion classification of critical equipment
MCDM	Multi criteria decision making
MI	Moderately important
MPDM	Maintenance Policy Decision Making
P	Production
PdM	Preventive maintenance

PHM	Proportional hazard model
PM	Preventive maintenance
SAW	Simple Addition Weighting
SI	Strongly important
SLINK	Single Linkage Clustering
SPSS	Statistical Package for the Social Sciences
T	Technical
TAOD	Taguchi orthogonal array design
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VH	Very High
VI	Very strongly important
VL	Very Low
XI	Extremely strongly important

INTEGRASI DI ANTARA KONSEP PENGGUGUSAN DENGAN TOPSIS KABUR UNTUK MODEL MEMBUAT KEPUTUSAN POLISI PENYELENGGARAAN

ABSTRAK

Penentuaan polisi penyelenggaraan yang paling sesuai merupakan perkara yang amat mencabar memandangkan bahawa proses membuat keputusan itu teramat kabur dan rumit kerana melibatkan pelbagai aspek penilaian yang subjektif. Oleh itu, pengajian ini bertujuan untuk membangunkan satu model membuat keputusan yang boleh digunakan untuk menentukan polisi penyelenggaraan yang optimal untuk pelbagai sistem yang mempunyai mekanisma kegagalan yang hampir sama. Secara khususnya, pembangunan model untuk membuat keputusan polisi penyelenggaraan (MPDM) boleh dibahagikan kepada tiga peringkat bermula daripada penggugusan pelbagai sistem kepada beberapa sel maya berdasarkan persamaan mekanisma kegagalan. Di samping itu, satu set langkah-langkah juga dibangunkan di peringkat kedua pada model MPDM untuk mengumpul informasi yang diperlukan untuk membuat analisa pada peringkat ketiga di model MPDM. Teknik penyusunan kecenderungan berdasarkan persamaan kepada penyelesaian unggul (TOPSIS) kabur telah digabungkan pada peringkat ketiga model MPDM untuk mendapatkan susunan kecenderungan polisi penyelengaraan untuk setiap sel maya. Polisi penyelenggaraan yang mempunyai kecenderungan yang tertinggi merupakan polisi penyelenggaran yang optimal untuk sel maya tersebut. Ketegapan model MPDM telah diujikaji dan dikesahkan melalui beberapa kes kajian di kilang menghasilkan papan litar. Keputusan yang dihasilkan daripada kes-kes kajian tersebut telah membuktikan

ketegapan model MPDM dalam menentukan polisi penyelenggaran untuk setiap sel maya. Secara keseluruhan, model MPDM telah dibuktikan bahawa ia boleh digunakan untuk membuat keputusan dalam pemilihan polisi penyelenggaraan secara sistematik untuk pelbagai system.

INTEGRATION OF CLUSTERING CONCEPT AND FUZZY TOPSIS FOR MAINTENANCE POLICY DECISION MAKING MODEL

ABSTRACT

Maintenance policy decision making has become a great challenge in view of the fact that decision making process is highly fuzzy and complicated given that it involves multiple subjective evaluation perspectives. Thus, this study aims to develop a decision making model that is capable to determine the optimal maintenance policy for multiple systems with similar failure mechanisms. Particularly, the development of maintenance policy decision making (MPDM) model is separated into three stages starting from grouping multiple systems into virtual cells according to the similarity of failure mechanisms. Mean while, a set of procedures are proposed in second stage of the MPDM model to obtain required information for analysis purposes in third stage. The Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) will be integrated in the third stage of the MPDM model to provide preference order of the maintenance policies for particular virtual cell. In the end, the maintenance policy with highest ranking will be pointed as the optimal maintenance policy for respective virtual cell. The robustness of the MPDM model had been verified and validated through six case studies in a circuit board manufacturing plant. The results obtained from case studies had proven the robustness of the MPDM model in determining optimal maintenance policy for each virtual cell. Overall, the MPDM model has been proven capable in providing systematic way of maintenance policy decision making for multiple systems.

CHAPTER 1

INTRODUCTION

1.0 Overview

There are five segments presented separately in this chapter. The first segment gives a general elaboration regarding the research background with specific explanation of the problem statement discussed in the following section. Third segment will reveal the research objectives while the fourth section presents the scope of research. The final segment aims to give an overview with regard to the organization of the thesis.

1.1 Research Background

Better product quality, higher productivity with less cost becomes an essential element for a manufacturing plant to survive under great competitive environment (Kushwaha, 2013). In other words, retaining and improving the system performance in manufacturing plant becomes a crucial issue. System in the manufacturing plant usually referred as the combination of different mechanism such as hydraulic, mechanical, pneumatic, electrical and electronic to perform a specific function (Ahmad, 2007). Nevertheless, system malfunctioning happens to be one of the most immense subject that affects the manufacturing plant performance. For instance, a malfunctioning system could experience a costly and disruptive breakdown or even produce products with questionable quality or produce scrap product. In the worst case, the operation of whole manufacturing plant could be halted due to a single system malfunctioning.

Thus, maintenance is obligatory to retain or restore the system to a state in which it can perform the required function through the combination of all technical and administrative actions, including supervision, action intended to retain or restore the system function (Hong et al., 2012). Obviously, an effective maintenance will definitely uphold or even improve system’s performance furthermore increase the manufacturing plant performance (Ierace and Cavalieri, 2013). Conversely, poorly maintained system will have a shorter life cycle while experiencing more frequent and costly breakdown, leading to lower productivity and delayed of production schedules.

Even though maintenance is important in retaining the system function, however, it has always been treated as ‘necessary evil’ since maintenance costs become one of the largest expenses in manufacturing plant expenditure. It is imperative to highlight that maintenance costs have contributed from 30-70 percent of the total manufacturing plant expenditure, varying according to the type of manufacturing plant (Sharma et al., 2011; Fraser, 2014). One third of these amounts spent is unnecessary or waste on over maintenance and ineffective maintenance. Over maintenance occurs due to excessive maintenance activity that actually does not require. Whereas maintenance activities that unable to produce significant results are classified as ineffective maintenance. Either over or ineffective maintenance, it is mainly can be traced from ineffective maintenance planning. Thus, maintenance requires a thorough planning to ensure that maximum maintenance effectiveness can be achieved (Lu and Sy, 2009).

Particularly, an effective maintenance planning begins with having a maintenance policy as guidance for the industrial practitioners in accomplishing all maintenance activities. Generally, maintenance policy can be described as a deliberate plan of action, usually containing a set of rules, used to provide direction for industrial practitioners during maintenance planning (Waeyenbergh, 2005; Gupta et al. 2009). Taken as a whole, maintenance policy used to address maintenance related queries like what type of maintenance is required by system to achieve respective goals which could be varied according to objectives of the manufacturing plant. Moreover, a maintenance policy not only could influence the profitability of a manufacturing plant through its direct impact on product quality and productivity, but also the potential consequence of maintenance could go far beyond monetary value such as safety and environmental related issues (Alsyouf, 2007, Jagimoggala et al. 2011).

1.2 Problem Statement

Due to the noteworthy impact of maintenance on manufacturing plant, different maintenance policies have been proposed from time to time. Amongst which the most widely known in manufacturing plants are corrective maintenance policy, preventive maintenance policy, autonomous maintenance policy, predictive maintenance policy as well as design out maintenance policy. Fundamental concepts of these maintenance policies vary according to the development background and will be further elaborated in the following chapter.

Apparently, the potential performance of these maintenance policies is highly depended on several factors such as the maintenance objective, the nature of the system to be maintained and the working environment (Schuh et al. 2009; Zaied and Abhary, 2009). In other words, maintenance policy is varying between systems and also alters between manufacturing plants. This has lead to a necessitation of the decision making process for selecting a maintenance policy that could maximize the benefit according to the respective objective within given constraints.

According to Kobaccy (2008), maintenance policy decision making which involves the process of maintenance policy decision making has been proven difficult since it often relates to various criteria such as manpower, spare parts availability as well as employees' safety. In addition, Mousavi et al. (2009) had also revealed that increasing number criteria would certainly raise the computational time as well as complexity. Besides that, considering the numbers of systems exist in the manufacturing plant, it will be extremely time consuming to decide maintenance policy for every single system. Thus, it is essential to structure the maintenance policy decision making properly for analysis, furthermore lead to better decision outcomes with minimum computational time.

At the same time, maintenance policy decision making process has always been considered to be fuzzy in nature since maintenance activities are non-repetitive in the same manner as production activities. Accomplishment of maintenance activities is varied according to the individual skill, system complexity and technology available which are difficult to capture and documented quantitatively. Nevertheless, this information is necessary during maintenance policy decision making to indicate the potential strengths of maintenance policies. The challenge of obtaining adequate yet precise information under fuzzy environment will eventually increase the difficulties in the accomplishment of maintenance policy decision making (Faccio et al. 2012).

Despite the fact that there exists a lot of decision making models which has been developed for maintenance policy decision making, but these decision making models usually consist of restrictive assumptions referring to certain condition. It is insufficient to reflect the actual maintenance status (Horenbeek and Pintelon, 2010). Meanwhile, the decision making model is usually structured with complex algebraic which is beyond the understanding of industrial practitioner. Consequently, industrial practitioners have lost confidence due to the decision models complexities and the number of unrealistic assumptions contained in the decision making model (Garg and Deshmukh, 2006, Sharma et al. 2011).

Justification of maintenance policy becomes critical and complex due to the involvement of varying contrasting evaluation criteria, inadequacy assessment information and lack of realistic decision making modeling. Thus, further efforts concerning the development of a decision making model which can synchronize with the actual manufacturing environment and accessible to industrial practitioners is the main emphasis of this research. Eventually, the developed maintenance policy decision making model will provide a systematic approach to facilitate the industrial practitioners in maintenance policy decision making process.

1.3 Objectives

The main objective of this research is to develop a decision making model for determining the ranking of maintenance policies. On the whole, the objectives of this research are:

1. To develop maintenance policy decision making model to assist industrial practitioners in ranking the maintenance policies.
2. To group multiple systems into clusters based on similarity of failure mechanisms.
3. To integrate the fuzzy TOPSIS as maintenance policies ranking method in the decision making.

4. To verify and validate the robustness of the developed maintenance policy decision making model using case studies.

1.4 Scope of Research

Selecting right maintenance policy has a great impact due to their role in indentifying problems at early stage and improving the effectiveness of maintenance planning. The lack of maintenance planning can significantly restrict the maintenance department in achieving its objectives. Thus, the research is concentrated on ‘how to decide a suitable maintenance policy’ instead of ‘when to do’.

The development of the maintenance policy decision making model is also undergoing certain limitations. By considering the time limitation and familiarity of maintenance policy in industrial perspective, only several well known maintenance policies are suggested as the potential candidates during the decision making process. Meanwhile, the evaluation criteria will basically focus on four fundamental measurement indexes including economical, technical, failure and production oriented perspective. In view of the fact that focusing on essential evaluation criteria can reduce computational time and complexity, yet it is also sufficient to measure the performance of maintenance policy.

In the maintenance decision making model, the judgments from the industrial practitioners in related industry will be the main reference to obtain required data. This is because they are capable to assess and justify the intangible information along with their knowledge and experience. However, reliability analysis will be done to ensure the qualification of these decision makers in producing reliable assessment.

During the verification and validation process, a total of six different cases were conducted due to the time line limitation. In the verification process, three development phases of decision making model were verified using three case studies separately to ensure each phase of decision making model could produce expected results. Meanwhile, three case studies on different systems with varying objectives were conducted for the validation purposes.

1.5 Thesis Overview

The overview of thesis is as follows: Chapter 2 gives a literature review of the related issues such as maintenance research overview, maintenance policy classification and development of maintenance policy decision making model. In Chapter 3, methodology of maintenance policy decision making model is briefly illustrated. Meanwhile the detail regarding with the development process of the decision making model is presented in Chapter 4. Then, Chapter 5 describes the verification and validation process of the developed decision making model in a manufacturing plant. Afterward, discussion corresponded with the notable aspects of maintenance policy decision making model is highlighted in Chapter 6. Finally, Chapter 7 gives the conclusion of this research as well as recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

A lot of efforts have been done in solving the difficulties faced in the maintenance policy decision making processes and it is proving fruitful for researchers. A detailed review is presented to justify the outcome of these efforts while seeking for improvement. The literature review starts by giving an overview of existing maintenance related research areas. Types of maintenance policies are described, subsequently followed by the discussion regarding with the maintenance policy evaluation perspectives. Afterward, maintenance policy decision making models are reviewed and classification of literature is performed. Then, literature findings from reviewed decision making model are presented. The summarization of the Chapter 2 is given at the end of the chapter.

2.1 Maintenance Research: An Overview

Research in maintenance can generally be classified into three major families including maintenance policy decision making, maintenance scheduling and maintenance performance measurement as depicted in Figure 2.1.

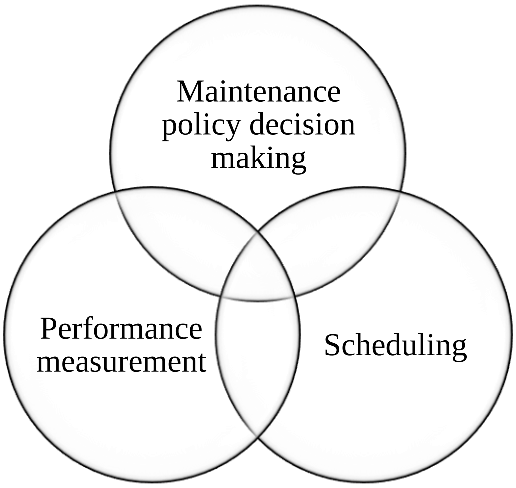

Figure 2.1: Maintenance research overview

Maintenance policy decision making as depicted in Figure 2.1 is typically referred as the process of determining the maintenance policy that best suit to the systems while satisfying the objectives of the manufacturing plant within the resources available (Meselhy et al, 2010). Such research could be found in publications such as Marais and Saleh (2009), Jajimoggala et al. (2011) and Nezami and Yildirim (2013). Apart from maintenance policy decision making, maintenance scheduling is another focus of maintenance research. The task of maintenance scheduling involves specifying times in which manpower is to be allocated to conduct maintenance activity to a system (Schutz et al., 2013). Publications such as Sortrakul et al. (2005) and Aissani et al. (2009) had presented an excellent research on maintenance scheduling.

Meanwhile, the maintenance performance measurement receives a great amount of attention from researchers in recent years due to a paradigm shift in maintenance. For instance, the work presented by Visser and Pretorious (2003), Parida and Chattopadhyay (2007), Muchiri et al. (2011) and Kumar et al. (2013). Major issues related to this field concerned with “what to measure and how to measure it” at a practical, feasible and cost effective way. Through the measurement, it will give the performance of the applied maintenance on the systems and the results will act as a benchmark for further improvement.

Among these maintenance issues, maintenance policy decision making should be given priority before proceeding to maintenance scheduling and maintenance performance measurement. Associated with this issue, Takata (2004) and Khaizraei and Deuse (2011) had greatly emphasized that maintenance effectiveness was vastly depended on the maintenance policy determined via decision making process. Meanwhile, Labib et al. (1998) had also highlighted maintenance would be more effective by doing the right thing compared with doing the thing right. In other words, maintenance will be more effective if the maintenance policy is justified according to the manufacturing plant remedy rather than randomly implementing the maintenance policy without proper justification. Before proceeding to the detailed discussion regarding the maintenance policy decision making subject, a particular review of several well-known maintenance policies will be given in the following section.

2.2 Maintenance Policies Classification

As briefed in Chapter 1, Section 1.2 (page 3), different maintenance policies have been invented due to the noteworthy of maintenance in a manufacturing plant. This section aims to give a further elaboration about the type of maintenance policies popular in a manufacturing plant. Taken as a whole, maintenance policies can be grouped according to the concept of dealing with system malfunction as illustrated in Figure 2.2.

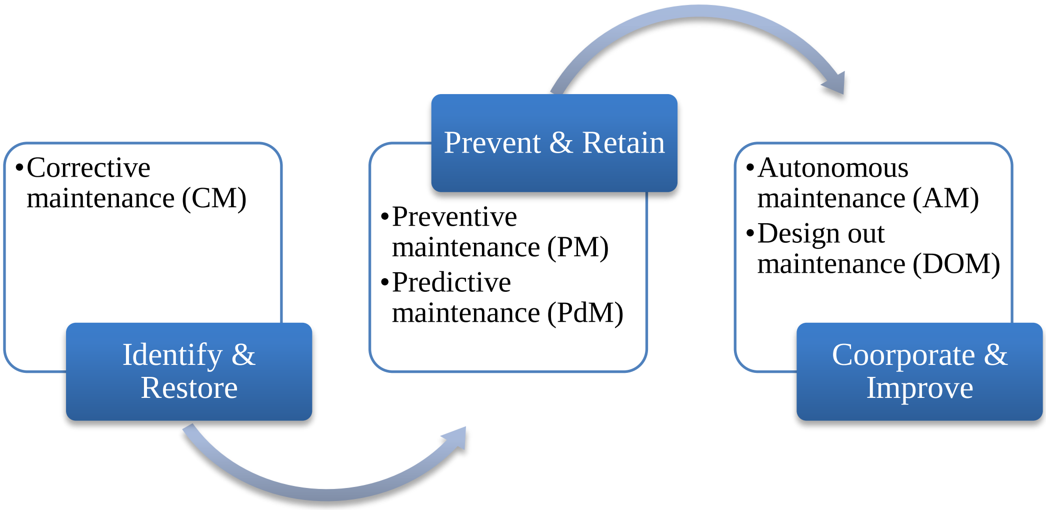

Figure 2.2: Classification of maintenance policy

As displayed in Figure 2.2, the concept of maintenance can be segregated into three including 'Identify & Restore', 'Prevent and Retain' and 'Cooperate & Improve'. The concept of 'Identify & Restore' is the most conventional concept invented before World War II (Mechefske and Wang, 2001). The aim of this concept is simply to identify the malfunction element on the system and restore the system back to it's operational condition without scientific study. The corrective maintenance (CM) policy is the only maintenance policy falls under the category of 'Identify & Restore'. CM policy is also named as failure based or breakdown maintenance policy. It is a passive maintenance policy which may cause large production losses, serious damage to the system**,** person and environment due to the unexpected failure. Nevertheless, this policy is considered a feasible policy to be adopted in the cases where profit margins are large (Sharma et al., 2005).

Manufacturing plants tend to be more flow oriented and high capital intensive after World War II. With the increasing size and complexity of manufacturing plant, a single failure can cause a complete shutdown of the manufacturing plant implying the loss of large amounts of money. Thus, manufacturing practitioners expect to achieve a trouble-free manufacturing process with ‘Prevent & Retain’ maintenance concept. Overall, ‘Prevent & Retain’ concept aims to avoid the failure and ensure the systems is well functioning. Therefore, preventive maintenance (PM) policy associated with reliability engineering was introduced. Maintenance under the PM policy is planned and performed after a specified period of time or the amount of the system used to reduce or even prevent the possibility of failure. Mechefske and Wang (2001) had stated that most of the systems are maintained with a significant amount of useful life remaining when the PM policy is applied. In spite of this, it is difficult to identify the most effective maintenance interval without reliable data and led to unnecessary maintenance (Wang et al, 2007).

Meanwhile, another ‘Prevent & Retain’ based maintenance policy named as predictive maintenance (PdM) policy has been proposed with the growth of technology. In the case of PdM, sensors are used to monitor and diagnose the condition of the system and action is taken when symptoms of failures are recognized (Bevilacqua and Braglia, 2000). In other words, maintenance under the PdM policy is carried out when the abnormal condition is detected in the system. However, PdM is not always the best policy of maintenance, especially from the cost effectiveness aspect (Arunraj and Maiti, 2010). Sometimes, there will be a number of systems for which condition monitoring is not particularly appropriate and not all systems can be monitored due to the economic constraints (Mechefske and Wang, 2003).

Nowadays, maintenance is no longer considered as a necessary evil and turn into profit maker as industrial practitioners attempt to increase profit through maintenance (Alsyouf, 2007). Hence, maintenance is no longer simply ‘Identify & Restore’ (CM policy) or ‘Prevent and Retain’ (PM policy, PdM policy) but becomes

‘Cooperate & Improve’. Currently, maintenance has advanced to improve the system reliability from other aspect like engaging operators from production department in maintenance activities and redesign the system according to the operational environment.

With this, autonomous maintenance (AM) policy has been introduced where maintenance and production department are cooperating to accomplish the maintenance (Tajiri and Gotoh, 1992). It has turned the maintenance function into a partnership relationship where every individual in the manufacturing plant is sharing the responsibility of maintaining the systems. Nevertheless, an effective AM policy will require education and training for all level individuals in the manufacturing plant to gain sufficient skill and knowledge before the full benefit of this policy can be achieved (Promoski, 2004).

Besides, design out maintenance (DOM) policy is a policy aims for improvement rather than just conduct maintenance of the system operation is also one of the maintenance policy categorized under ‘Cooperate & Improve’. The focus of DOM is to improve the system design to reduce or even eliminate the failures (Waenbergh and Pintelon, 2002). Mean while redesigning a more ergonomic system to make the maintenance easier is also another major task of DOM. However, improvement based maintenance policy requires a high level of knowledge, experience, training as well as the resources available in the manufacturing plant (Persona et al. 2010).

Referring to the description of presented type of maintenance policies as well as its merits and demerits, it has further highlighted the necessity of determining an optimal maintenance policy. Besides, maintenance policy decision making is also influenced by factors from economical, technical, failure and production perspectives which will be further explained in following section.

2.3 Maintenance Policy Evaluation Perspectives

A set of measures, rules and standards derived from technical, economic or legal condition that used to evaluate the potential performance maintenance policies is an indispensable in the process of decision making (Thor et al., 2013). From the papers reviewed such as Belilacqua and Braglia (2000), Gassner 2010, Ratnayake and Markeset (2010), Chen and Tsao (2010), Tan et al. (2011) and Kumar and Maiti (2012), it can be found that various evaluation perspectives had been used for maintenance policy decision making. Even though the evaluation perspective is highly relayed upon the objectives as well as focuses of industrial practitioners but the evaluation scope can generally be sorted into four aspects including economic oriented, technical oriented, failure oriented and production oriented as depicted in Figure 2.3.

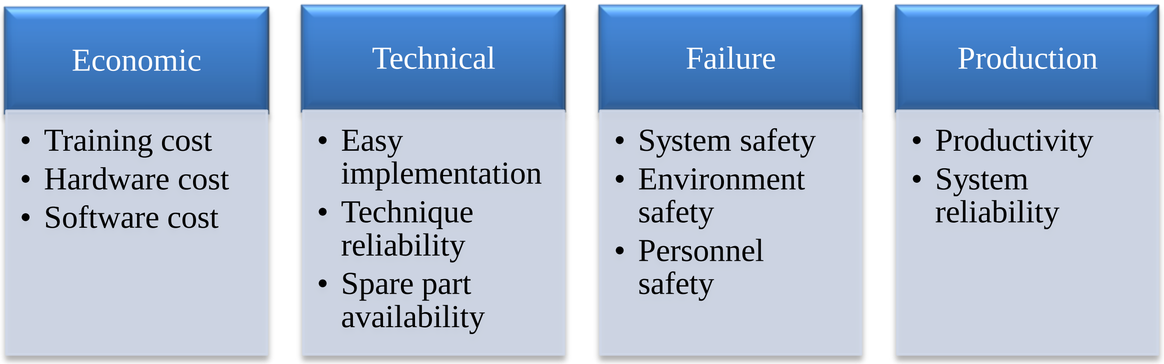

Figure 2.3: Maintenance policy evaluation perspectives

Economic oriented evaluation perspective always gain a significant amount of consideration from industrial practitioners during the decision making process.

Bear in mind, the full potential of respective maintenance policy is unable to reach without investment on the amount of capital in groundwork to establish the maintenance policy. Figure 2.3 has illustrated three different cost criteria usually involved in maintenance policy decision making process. These cost criteria including training cost, hardware cost and software cost are the fundamental investments on supplying adequate equipments, tools as well as competent skilled individual required for accomplishing respective maintenance policy. Nevertheless, given that budget allocation and expectation are different among manufacturing plants have led to the requirement to find the balance point between the available investment cost as well as the return of investment.

Meanwhile, technical oriented evaluation perspective is also an important aspect during the decision making process given that a successful maintenance policy requires a competent level of technical support. Easy implementation, technique reliability and spare parts availability are the few popular criteria in technical oriented evaluation perspective. As known, capability of providing sufficient technical support is highly subjected to the compliance of industrial practitioners in the manufacturing plant. Thus, justification is necessary to investigate and predict the possible outcome before investing too much time and money.

Regardless the type of manufacturing plants, providing an environment which is free from the occurrence of risk of injury, danger or loss is fundamental obligation. A single carelessness in maintenance can lead to high risk failure and cause serious impact to the operators, maintenance individuals, systems or event environment directly or indirectly which is unable to be quantified in monetary value. Thus, industrial practitioners who bear the responsibility on safety issues have seriously emphasised on failure oriented evaluation perspectives during maintenance policy decision making process.

The fourth perspective involved in decision making is production oriented perspective. It involves the process of justifying to what extend the value created by maintenance policy is perceived by production department that closely related with the maintenance. Usually, production oriented perspective involves evaluation in terms of the maintenance policy performance in improving productivity and system reliability. Subsequently, maintenance policy decision making model developed using these evaluation perspectives will be reviewed in the following section.

2.4 Maintenance Policy Decision Making Model

The significance role of maintenance policy discussed in Chapter 1 (Section 1.1, page 1) has given a sufficient evidence to justify that effective maintenance can only be achieved by choosing an optimal maintenance policy. At the same time, problems faced while determining the maintenance policy also had been thoroughly discussed in Chapter 1 (Section 1.2, page 3). Due to the imperative challenges faced in maintenance policy decision making, a lot of efforts have been done by researchers to overcome the stated problems (Facio et al, 2012).

From the hard work of these researchers, various maintenance policy decision making models with different operational principles were developed. Before going into detail on this issue, a brief definition of a model would be appropriate to give a better appreciation on the detail discussion afterwards. Typically, a model is a description of a process or concept in a systematic way. From the engineering perspective, a model usually referred as an abstraction that involves an explicit mathematical formalism of the process being studied (Razak et al., 2011). In maintenance policy decision making aspect, a model is a description of a set of procedure used to determine the optimal maintenance policy under several evaluation perspectives. The maintenance policy decision making model of this study is classified in term of a certainty theory continuum: certainty, risk and uncertainty (Tersine, 1985). Generally, the degree of certainty refers to the subjectivity of information about the states of nature that influencing the respective circumstances. By adopting the certainty theory into the decision making model classification, the certainty degree is defined as the subjectivity degree of input information involved in the maintenance policy decision making process. Usually, the input information subjectivity exists due to the vague information that could not be represented in crisp value. Figure 2.4 shows the overall classification of maintenance policy decision making model.

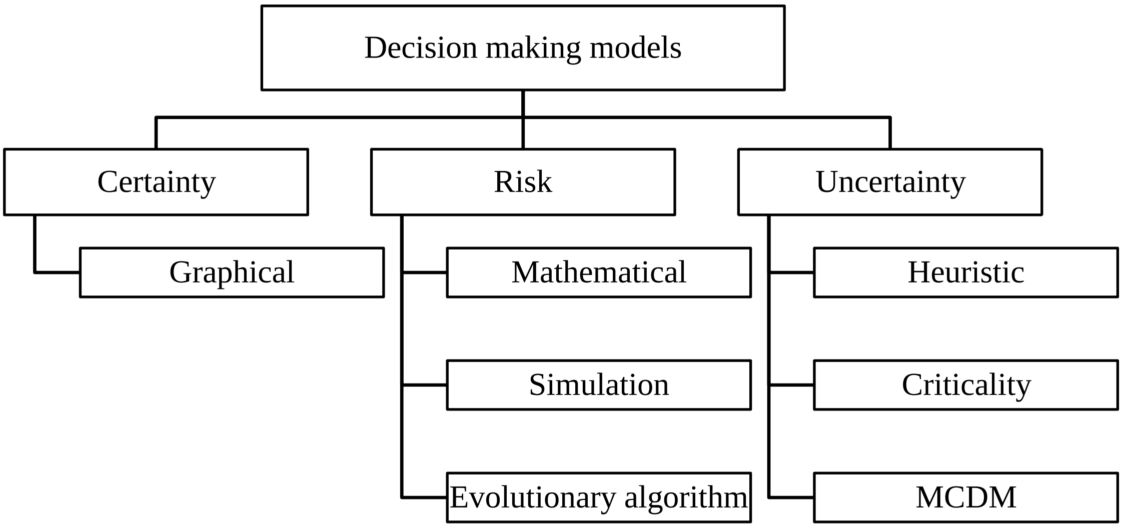

Figure 2.4: Classification of maintenance policy decision making model

The graphical model displayed in Figure 2.4 is the only decision making model falls under certainty category. Mean while risk category consists of three decision making model included mathematical, simulation and evolutionary algorithm. Heuristic, criticality and multi criteria decision making (MCDM) are other three decision making models classified under uncertainty category. The detail about each decision making model will be discussed in the following section.

2.4.1 Certainty Category

In essence, the probability of specific states of nature will occur is one (perfect knowledge) (Tersine, 1985). In the context of this review, it is referred as the input information is completely accessible in crisp form. As depicted in Figure 2.4, graphical model is the only type of decision making model grouped under certainty category. Typically, the maintenance policy in graphical model is pre-assigned according to the specified value range of evaluation criteria. Then, maintenance policy for respective system can be directly appointed according to the value falls under a specified range of evaluation criteria.

Decision making grid (DMG) that originally proposed by Labib (1998) is the common method used in graphical based decision making model. Labib (1998) had used the DMG to decide maintenance policy in an automotive industry based on downtime and failure frequency. Then, Fernandez et al. (2003) had further extended the application of DMG to monitor the performance of the worst system in the disc brake pad manufacturing company and chose the optimal maintenance policy accordingly. Besides, Khalil et al. (2005) had come out with a modified DMG to decide the maintenance policy for aero-industry by using failure cost and failure frequency as evaluation criteria. The extension work of DMG also can be found in Burhanuddin et al. (2007). Authors put more efforts on altering the DMG to focus on measuring system’s efficiency in a food processing industry and decided the optimal maintenance policy accordingly. Later, the application of DMG had been further improved by Shanin and Attarpour (2011) where authors had replaced one of the criteria with overall equipment effectiveness instead of failure frequency. In other words, the performance of system had been taken into consideration during the maintenance policy decision making process. A validation of the modified DMG had been demonstrated in a steel manufacturing plant.

Besides, there also exists of several studies aim to improve the effectiveness of DMG in maintenance policy decision making. For example, Tahir et al. (2008) had conducted a research on integrating the fuzzy logic into DMG. However, the practicality of the proposed method was only demonstrated through an analytical test case based on the information taken from Burhanuddin (2007 et al.). While Tahir et al. (2009) had integrated tri-quadrant technique into the DMG to increase the effectiveness of the DMG for small and medium size manufacturing plant. In addition, fuzzy logic was also integrated to the DMG in order to specify which maintenance policy most suitable to the system based on the criticality and reliability in prone manufacturing system (Labib and Yuniarto, 2009).

Unquestionably, DMG has a certain degree of flexibility where the maintenance policy for the system will change according to the total downtime and number of failure frequency accumulated by the system. Nevertheless, a comprehensive maintenance policy decision making model should have an extensive focus on different evaluation perspective such as economical and technical aspects. Besides, it is a relatively low possibility to have complete information in the actual manufacturing environment due to factors such as data management system.

2.4.2 Risk Category

Under risk category, the input information is not available directly in crisp form, however, it can be obtained by knowing the probability distribution and predict the possible condition of the state of nature through mathematical formulation and computation. As shown in Figure 2.4, typical decision making model falls under risk category are mathematical, simulation and evolutionary algorithm

a. Mathematical model

The mathematical model is an abstract model that uses mathematical language to describe the system's state of nature. It is very useful in estimating the system's state of nature by using limited information with various probability estimations. Subsequently, maintenance policy decision making process can be conducted along with the predicted information. The review of the mathematical model mainly focuses on the methods used to model the state of deterioration process and also the evaluation perspective involved.

One of the popular methods used in the mathematical model is proportional hazard method (PHM). PHM has been widely used to model system variables; external factors included environmental conditions and working conditions and age of manufacturing system (Lugtigheid et al., 2004). Practically, it is difficult to specify the maintenance policy precisely since the failure of the system always affected by different aspects. Therefore, PHM uses the proportional age reduction factor to the base line of hazard rate or to operation time (Samrout et al, 2009). There were several works that had been conducted in maintenance policy decision making process. For example, Lugtigheid et al. (2004) used PHM as modelling repairable system reliability with different repair concepts such as 'as good as new' and ‘as bad as old’. However, authors just presented the developed model without any example demonstration. Besides, Samrout et al. (2009) had adopted PHM as modelling tool to integrate the effect of maintenance on reliability through its influence on the aging process. The validation process was performed by using a set of numbers that used to express the application of the mathematical formulation named as numerical example.

Other than using PHM, Markov method is also being applied in modelling the system state during the process of determining maintenance policy. Markov method is a stochastic process in which changes of state occur according to a Markov chain (El-Gogary, 2004). In the research conducted by Gurler and Kaya (2002), Markov method had been suggested to describe the stochastic nature of the manufacturing system as well as the respective maintenance costs required in determining the optimal maintenance policy. The application of the proposed methodology was demonstrated through a numerical example.

Muller et al. (2008) had suggested Markov method to describe the dynamic degradation of a system in an unwinding metal strip manufacturing plant and determined the best policy that was able to improve the system availability and safety. Besides, Markov method also was adopted by Marais and Saleh (2009) to model the deterioration process and determined the optimal maintenance policy according to the net present value of different maintenance policy. Two numerical examples were presented to clarify the application of the developed method. Similar research also conducted by Ponchet et al. (2010) but the determination of optimal maintenance policy was based on the average long-run cost per unit time. The proposed algorithm was also exemplified by numerical examples.

Semi-Markov method was also suggested by Ge et al. (2007) to model the system deterioration in order to determine the maintenance policy that able to maximize the system availability. An example based on air-blast circuit breaker had been used to demonstrate the application of the developed method. In addition, Continuous-Markov method was adopted by Kenne and Nkeungoue (2008) to describe the dynamics of the system and determined the maintenance policy which would optimize the system life cycle while minimizing the overall cost. A numerical example was used to illustrate the effectiveness of the model.

There are also few publications found using different mathematical methods such as Marquez et al. (2003), Pongpech et al (2006) and Nielsen and Sorensen (2011). Marquez et al. (2003) had modified the Powell method to determine the maintenance policy by comparing the performance between maintenance policies in terms of buffer capacity and production rate. Numerical example was used to validate the developed method. While, Pongpech et al. (2006) had adopted Non-homogenous Poisson process to represent the lease period of system failures and determined the maintenance policy that was minimal in total expected cost. Nevertheless, the application of the proposed method had also been demonstrated through numerical example. Nielsen et al. (2011) had suggested using Bayesian pre-posterior decision theory in determining the optimal maintenance policy for a wind turbine system. The focus of authors was mainly to emphasis on different type of costs including repair cost, power price and inspection cost.

Over the years, decision making model has emerged from the fundamental of mathematical model through a combination and integration of simulation method. Thus, simulation based decision making model has become another research area that gains high popularity in finding the optimal maintenance policy.

b. Simulation model

Simulation model or a computational model is a computable method for running an abstract model over time, where the model can be implemented using computational techniques such as mathematical formalism that uses different algorithms (Razak et al. 2011). In maintenance, simulations are useful in gaining the insight of the manufacturing system's operations or to observe their behaviour. The information obtained can be applied to identify a suitable policy for the manufacturing system. Either way, the simulation model is used to generate and predict the potential results by using current or past data.

Monte Carlo simulation is one of the popular methods being used in the maintenance policy decision making process. Monte Carlo simulation is a computational algorithm that relies on repeated random sampling to compute their results. It is largely used when it is unfeasible or impossible to compute an exact result with mathematical methods. Most researchers that adopt Monte Carlo simulation in the maintenance policy decision making usually focus on identifying the cost effectiveness maintenance policy. For example, Borgonovo et al. (2000) had adopted Monte Carlo simulation to evaluate the maintenance policy under economic constraints included profit function, obsolescence, aging and renovation. The application of the simulation was shown by the gas compression system taken from Vant (1997). Rather than minimizing general maintenance cost, Barata et al. (2002) aimed to focus on choosing a maintenance policy which could minimize maintenance service cost by using Monte Carlo simulation. The application was also illustrated by using a hypothetical case which consisted of a series system with two components.

Moreover, Silva et al. (2004) had incorporated the reliability issues associated with costs into a Monte Carlo simulation to measure the respective impact of maintenance policies. Generation and transmission system were adopted to validate the usefulness of the proposed method. Besides, application of Monte Carlo simulation also could be found in Nguyen et al. (2009) to determine the maintenance policy that could improve the accuracy of variable estimators used in chemical plant while maximizing the economic benefit. Similar approach also had been utilized by Clavareau and Labeau (2009) to decide the maintenance policy of a system under technology obsolescence based on the estimation of the costs incurred. An analytical test case referring to Mercier and Laeau (2004) was used to accredit the application of the proposed simulation method. Besides, Huynh et al. (2012) had put on an idea to consider the system degradation level with maintenance costs during maintenance policy decision making analysis by using Monte Carlo simulation. However, the proposed approach had only been verified through a numerical example. Hu and Zhang (2014) had proposed using Monte Carlo simulation to determine the maintenance policy that could minimize the risk of failure. However, the application of proposed approach was illustrated through a numerical example.

Instead of focusing on reliability as well as cost issues, several papers have stressed on simulating the relationship between the maintenance policies with spare parts provision. The spare parts provision can influence the decision on maintenance policy since spares are ordered, carried in limited quantity and depending on procurement lead time. Thus, Sarker and Haque (2000) joined the spare parts provisioning into the maintenance policy decision making with minimum costs using simulation package SIMSCRIPT II.5. The input and statistical parameter obtained from Kabir and Olayan (1996) were put forward to justify the effectiveness of the proposed approach.