DEVELOPMENT OF MAINTENANCE POLICY SELECTION (MPS) MODEL TO SELECT THE OPTIMAL MAINTENANCE POLICY FOR A SYSTEM IN PALM OIL MILL

By

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Thesis submitted in fulfillment
of the requirements for the degree
of Master of Science

JUNE 2010

ACKNOWLEDGEMENTS

First and foremost, I would like to express my greatest gratitude to my supervisor, Dr. Shahrul Kamaruddin for his continuous guidance, invaluable advice and support which enable me to complete this project successfully.

I would also like to thank University Science Malaysia and United Palm Oil Mill for providing me the best facilities and its conducive environment throughout my postgraduate study.

Sincere gratitude and deepest appreciation to my parents Ding Chu Lin and Ngu Mooi Thea whose support for my life-long journey of learning has known no bounds.

Also, I would like to thank my friends whose always give a lot of encouragement and support in the journey of study.

Ding Siew Hong

November 2009

TABLES OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

S – System

SS- Sub-system

f – Failure Frequency

O – Occurrence

S – Severity

D – Detection

F – Functional Failure Cause

$\overline{O_F}$ - Mean Value of Occurrence

$\overline{S_F}$ - Mean Value of Severity

$\overline{D_F}$ – Mean Value of Detection

δ – Sum

A_1 – Autonomous Maintenance Policy

A_2 – Corrective Maintenance Policy

A_3 – Predictive Maintenance Policy

A_4 – Preventive Maintenance Policy

A+ - Nearest Distance from the Positive Ideal Solution

A- -Farthest Distance from the Negative Ideal Solution

p- – Score of the maintenance policy

$\overline{p}_{F_j A_i}$ - Average Performance of the Maintenance Policy

X – Number of Expert

r – Normalized Value

w – Weight

V – Weighted Normalized Value

A_*^+ - Positive Ideal Solution

A_*^- - Negative Ideal Solution

C – Relative Closeness to Ideal Solution

LIST OF ABBREVIATIONS

CM - Corrective Maintenance

AM - Autonomous Maintenance

PdM - Preventive Maintenance

PM - Preventive Maintenance

RCM – Reliability Centered Maintenance

TPM – Total Productive Maintenance

FMS - Flexible Manufacturing System

ARM -Asset Risk Manager

AI - Artificial Intelligence

GA – Genetic Algorithm

WIP – Work In Progress

TTT-Plotting – Total Time On Test Plotting

FMECA – Failure Modes Effect and Criticality Analysis

RPN – Risk Priority Number

MCDM- Multi Criteria Decision Making

AHP – Analytic Hierarchy Process

WSM – Weighted Sum Method

ELECTRE – Elimination and Choice Translating Reality

TOPSIS – Technique for Order Preference by Similarity to Ideal Solution

MPS – Maintenance Policy Selection

FMEA – Failure Mode and Effect Analysis

FBD – Functional Block Diagram

CS – Critical System

MTBF – Mean Time Between Failure

ICC – Intra Class Correlation

CPO – Crude Palm Oil

POM – Palm Oil Mill

MPOB – Malaysia Palm Oil Board

FBB – Fresh Fruit Bunches

SPSS – Statistical Package for the Social Sciences

PEMBANGUNAN MODEL UNTUK PEMILIHAN POLISI PENYELENGGARAN UNTUK SISTEM PEMBUATAN DI KILANG KELAPA SAWIT

ABSTRAK

Penyelenggaraan telah berubah dengan perkembangan teknologi. Di bawah perubahan ini, pelbagai jenis dasar penyelenggaraan telah dibangunkan. Antaranya termasuk dasar penyelenggaraan korektif sehingga dasar peyelenggaraan prediktif. Setiap dasar penyelenggaran mempunyai kelebihan dan kekurangannya. Maka, pemilihan dasar penyelengaran yang paling sesuai untuk satu sistem merupakan satu isu yang kritikal. Kebanyakan penyelidikan sedia ada menitikberatkan aspek ekonomi dan telah mengabaikan aspek teknikal seperti prestasi dasar penyelenggaran dalam mengurangkan kegagalan fungsi.

Dalam penyelidikan ini, satu model pemilihan telah dibangunkan untuk memilih dasar penyelenggaraan optimum yang boleh mengurangkan kejadian kegagalan. Untuk mengesahkan model ini, satu kajian kes telah dijalankan pada satu industri pemprosesan di Malaysia.

Dalam model ini, satu sistem yang kritikal dalam landasan pengeluaran akan dikenalpasti. Selepas itu, mekanisme-mekanisme kegagalan fungsi sistem kritikal akan dianalisis supaya mendapat maklumat yang berguna sebelum proses pemilihan dasar peyelenggaraan yang paling sesuai. Sebab kegagalan fungsi dan tahap kritikal kegagalan ialah keluaran yang utama daripada analisis ini. Maklumat ini akan digunakan dalam proses pemilihan penyelenggaraan di dalam model pemilihan ini. Prestasi dasar-dasar penyelengaraan itu dalam mengurangkan sebab-sebab kegagalan fungsi akan dinilai oleh pakar penyelenggaran dan seterusnya menentukan

kedudukannya dengan mengunakan "Technique of Prefrence by Similarity to Ideal Solution" (TOPSIS).

Model yang dibangunkan ini diaplikasikan pada kilang kelapa sawit. Keputusan yang didapati dari kajian kes menujukkan sistem perlucutan ialah sistem yang kritikal dalam ladasan pengeluaran. Melalui analisis, dasar penyelenggaraan preventif telah dikenalpasti sebagai dasar peyelenggaran optimum untuk sistem perlucutan.

DEVELOPMENT OF MAINTENANCE POLICY SELECTION (MPS) MODEL TO SELECT THE OPTIMAL MAINTENANCE POLICY FOR A SYSTEM IN PALM OIL MILL

ABSTRACT

The maintenance is change due to the development of technology. Under the changes, different maintenance policies have been developed, from corrective maintenance until predictive maintenance. These maintenance policies have advantages and disadvantages. Thus, how to select an optimal maintenance policy that is the most suitable to a system is a critical issue. The existing researches mostly focused on selecting a maintenance based on economic aspect but neglecting the technical aspect such as performance of these policies in reducing the functional failures.

In this research, a selection model is developed for selecting an optimal maintenance policy which can minimize the occurrence of failures. In order to validate this selection model, a case study was carried out on a processing industry in Malaysia.

A critical system is identified from the production line. The functional failure mechanisms of the critical system are analysed in order to gain useful information before the selection process. Functional failure causes and it failure criticality are the main output of the analysis. This information is being used for maintenance selection process in this selection model. The maintenance policies performance in minimizing the identified functional failure causes are evaluated by using expert judgment and ranked by using technique of Preference by Similarity to Ideal Solution (TOPSIS).

line. Through the analysis, the preventive maintenance policy has been identified as the optimal maintenance policy for the stripping system.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter consists of seven segments. The first segment states about the research background and further elaborated in second segments. The third section will discuss on the maintenance selection while the fourth segment discusses the research problem statement. Research objectives are stated in the fifth segment. The sixth segment mentions the research delimitation and its constraint while the final segment gives the overview of this thesis.

1.2 Research Background

In the globalization era, business environment are changing rapidly (Alsyouf, 2007). Markets are affected by diverse customer needs, which demand higher quality and lower price. Madu (2000) has mentioned that satisfying the customer needs is the only way for any industry to survive. Therefore, the manufacturing industry has changed from a labour intensive industry to a technology intensive industry which resulting in the increased use of mechanisation and automation in the manufacturing operations. By adopting high technology, better products quality is produced at a minimum cost. However, the high level of technology requires an elevated level of availability and reliability for the production line which widely known as system. Therefore, effective maintenance is critical in keeping up the system's reliability and availability (Swanson, 2003).

Maintenance has existed since people began to build physical assets such as houses, ships, machines etc. In general, maintenance is defined as the combination of all technical and administrative actions, including supervision, action intended to retain an item, or restore it to a state in which it can perform a required function (Swanson, 2001). The implementation of effective maintenance can reduce the consequences of failure and extend the life of the machines consist in the system (Wikstan and Jonansson, 2006).

Nevertheless, effective maintenance only comes from proper planning before implementation. Planning in the context of maintenance means the process by which all the elements required to perform a maintenance action is determined and prepared prior to starting the maintenance action (Duffuaa et al, 1999). In other words, the problem is identified and analyzed then the most suitable solution is planned to solve the problem. Without proper planning, it only gives negative effects to the company. For instance, Mobley (2002) pointed out one third of all maintenance costs is wasted as the result of unnecessary or improper maintenance activities. On the other hand, Bevilacqua and Braglia, (2000) has stated that maintenance cost becomes one of the main expenditure items for companies which can reach 15-70% of production costs, varying according to the type of industry. Therefore, it is a must for maintenance management to plan the maintenance properly in order to attain highest maintenance effectiveness. Typically, maintenance planning can be separated into two levels; component and system which are discussed in the following section.

1.3 Maintenance Planning Level

As mentioned before, maintenance planning can be viewed in two levels; the component and system as shown in Figure 1.1 (Alsyouf, 2004).

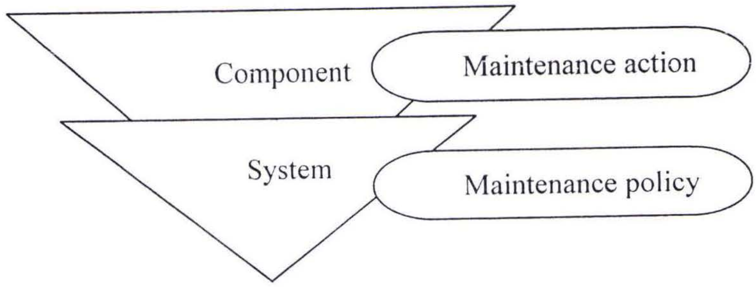

Figure 1.1: Maintenance planning level

The main activity on the component maintenance planning is to determine what maintenance actions should be performed. On the other hand, finding an optimal maintenance policy is the core activity on the system level of maintenance planning.

The maintenance planning on the level of component will focus on deciding the type of maintenance actions suitable for each component. Maintenance action that comes under component is the process to determine the optimal parameters to be implemented on the component. The components are the basic elements of the machines; the components may include mechanical, hydraulics, electrical and electronic (Ahmad, 2007). Maintenance actions may include distance based maintenance, time based maintenance, reliability based maintenance or vibration based maintenance. The parameters used in distance based maintenance and time based maintenance is usually based on the distance and duration of operation. Reliability of the component is the main issues considered in reliability based maintenance. Minimum repair, minimum replacement, major repair and planned replacement are the main actions carried out under this maintenance. The vibration frequency or amplitude before failure is the main parameter needed in the vibration based maintenance.

The second part of maintenance level is system which is referred as the combination of various components or combination of several machines. The maintenance planning on the system level is mostly focused on choosing proper maintenance policy referring to certain aspects such as system availability, machine performance, maintenance costs etc. The definition of the maintenance policy in this context is a deliberate plan of action to provide guidance for maintenance management in maintenance planning (Waeyenbergh and Pintelon, 2004). The maintenance policy is important in giving direction and guideline for further maintenance required by the system. A brief principle of the maintenance policy is given in the following section.

1.4 Maintenance Policy

In general, there are four maintenance policies identified; corrective maintenance policy, preventive maintenance policy, predictive maintenance policy and autonomous maintenance policy. Each of the maintenance policy mentioned has their special attributes and will generate dissimilar maintenance effect when implemented in different shop floor maintenance environment. Further discussion on the attributes of these policies will be given in Chapter 2. An analysis should be carried out before selecting which maintenance is suitable and optimal to be implemented on the shop floor environment.

In reality, the effectiveness of the maintenance policies is difficult to justify due to the maintenance policy may not yet implemented in the related company or sometimes although already implemented, but lack in the systematic documentations. Without this information, maintenance management have the difficulties in judging the effectiveness of the maintenance policy.

As mentioned by many researchers, selection of optimal maintenance policy is not only important but also a difficult task for maintenance management (Al-Najjar and Alsyouf, 2003). Improper maintenance policy selection may have an adverse effect on the operating budget of the company due to unplanned maintenance cost and improper maintenance investment. Thereby, it will reduce productivity as well as profitability (Wang, 2002). In contrast, company can increase the productivity and profitability with an optimal maintenance policy being implemented.

1.5 Problem Statement

The maintenance policy selection has always been considered to be fuzzy in nature when compared to other areas of operation. This has been due to the fact that maintenance tasks are not repetitive in the same manner as operational tasks. Therefore, an evaluation and determination of an optimal maintenance policy is required but one need to ask in the maintenance selection; how to identify the optimal maintenance policy?

The selection process is a complicated task as it requires the in depth knowledge about the maintenance policies and the technical requirements of the maintenance. The difficulties and complexity of selection process may arise when it involves combination of conflicting maintenance constraints such as available spares, number of workforce and maintenance skills.

In general, maintenance policy selection could be performed in two ways: theory and real world. In the theory based selection, different assumptions are generated to overcome the difficulties of capturing the implicit data. However, utilization of different assumptions may reduce the accuracy of the final outcome due to incorrect or unreliable assumptions. In the real world based selection, the implicit data are captured by referring to the experienced personnel in the industry. Unfortunately, gathering data which required a rigorous selection process can lead to a long delay and will need a considerable investment in time and work.

Although assumptions are useful in solving the difficulties in obtaining required data, it will limit the accuracy of the maintenance policy selected. This is because assumption is done by referring to certain condition. It is not enough to represent the actual condition in the real world especially in the industries that is always fluctuating. Therefore, the number of assumptions should be minimized when the maintenance policy selection process is performed.

Besides using numerous assumptions, large amount of time spent for collecting data is also another limitation in maintenance policy selection process. For industry, time is equal to money; the longer the duration taken for completing the data collection, the higher will be the cost in the selection process. It will also reduce the commitment and interest of maintenance management to conduct the selection process. Beside, the technology used in the industry always change due to the rapid development of technology itself. Thus, the selected maintenance policy based on the previous collected data which referred to earlier technology may be inaccurate.

In order to identify the real world maintenance policy for the existing system at the minimum cost, the duration required for data collection and assumption made should be minimized. By considering the importance and the complexity of these problems, detail efforts concerning the development of effective and systematic guideline that are able to ensure the maintenance policy effectiveness in maintenance policy selection process and identifying the optimal maintenance policy will be the focus of this research. Finally, the developed model can be used to justify which maintenance policy suit to remedy the company maintenance problem in the shortest duration.

1.6 Delimitation of Research and Constraint

Every research done will be subjected to certain delimitation and constraint. Thus the development of the maintenance policy selection model in this research also undergone certain delimitations and constraints.

In this research, the maintenance policies performance analysis is concentrating on minimizing the failure impact on the system. Several criteria will be proposed as the criticality index to measure the maintenance policies performance. More importantly, the developed maintenance policy selection model should be practical and economical in industrial maintenance application.

Due to the difficulty in acquiring related maintenance information, the judgments from the experts in related industry will be the main reference in the assessment. This is because experts can quantify the intangible information by referring to their knowledge and experience about the system. For this research, only one case study was used for verification and validation purposes due to the time limitation.

1.7 Thesis Overview

The overview of this thesis is as follows: Chapter 2 gives a literature review of the related issues such as maintenance in general, maintenance policy in detail and model development. The development of the selection model is presented in Chapter 3. Chapter 4 consists of a case study carried out at manufacturing industry in Malaysia for the maintenance selection model verification and validation. Chapter 5 presents the discussion of the developed and validated maintenance selection model. Finally, Chapter 6 gives the conclusions and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

A lot of effort has been put in finding solution to solve the difficulties faced in the maintenance policy selection process and it is proving fruitful for researchers. A review is done to find the outcome of these efforts while seeking for better improvement.

The literature review starts by giving a general overview of the researches done in maintenance aspect. It is followed by the review on the maintenance selection issues. Then the most common maintenance policies involved in maintenance selection process is discussed under the maintenance policy classification. Maintenance policy selection models are the final topic that will be reviewed in this chapter. It will be ended with the literature findings and the objectives of this research..

2.2 Maintenance: An Overview

As mentioned briefly in Chapter 1, the fundamental purpose of maintenance is to ensure the system operates at the required levels of efficiency and effectiveness. Other than ensuring the system is running smoothly, maintenance is also responsible to ensure the product produced do not affect the safety of consumer as well as environment (Li and Xu, 2007). Due to the positive effect of maintenance, a lot of researches have been carried out in order to gain a better and effective maintenance.

Over several decades, maintenance has rapidly changed due to the increasing complexity in the manufacturing process and the growth of technology. These changes have transformed the maintenance perspective from reactive maintenance where fix when broken to aggressive maintenance; prevent failure before it occurs, and nowadays it moves to proactive maintenance that refers to avoiding occurrence of the causes of failure. Under this perspective, various maintenance policies and maintenance actions with different attributes have been developed. Therefore, there is a need to have selection process to identify the most effective maintenance. Research in the maintenance has focused on various aspects; one of them is about the maintenance selection. This study is to formulate the best life span for system or a component. Such research could be found in several papers such as Al-Najjar (1999) and Bevilacqua and Braglia (2000). The research focused on formulating the best life span for component or system.

Apart from maintenance selection, another field that has been the main focus is maintenance scheduling. The task of maintenance scheduling involves specifying dates at which manpower is to be allocated to an overhaul of a major functional component or group of components (Yamayee, 1982). The objectives of the maintenance scheduling are to ensure the overall system security level is acceptable and at the same time the maintenance costs is at a minimum level. For example, Mukerji and Parker (1991) have proposed a maintenance scheduling model to help maintenance management in identifying the most cost effective yet reliable maintenance schedule for a power plant.

Maintenance performance measurement also received a great amount of attention from researchers in recent years due to a paradigm shift in maintenance. Major issues related to this field concern with "what to measure and how to measure it" at a practical, feasible and cost effective way. Through the measurement, it will give the status of the applied maintenance action. The results will then be compared with a target or standard after which suitable actions that should be taken will be proposed. For example, Parida and Chattopadhyay (2007) proposed a cost and time-effectiveness model for maintenance performance measurement. The developed model not only considered different criteria for evaluation but it also can be adopted on different maintenance planning level.

Although research related with maintenance issues are widely explored, the main attention should be focused on finding the optimal maintenance policy before proceeding to maintenance scheduling and maintenance performance measurement. As quoted by Labib et al (1998), it will be more effective by doing the right thing compare with doing the thing right. It means that maintenance will be more effective if correct maintenance policy is identified at the initial stage of maintenance planning rather than randomly using the maintenance policy without proper justification.

2.3 Maintenance Policy Classification

In order to take into consideration to do the right thing, better understanding of how the maintenance policy is classified should be the starting point. Maintenance policy can be classified into four categories; in general, corrective maintenance (CM), preventive maintenance (PM) and predictive maintenance (PdM) and autonomous maintenance (AM).

Corrective maintenance (CM) policy which also named as failure based maintenance policy or breakdown maintenance policy is the oldest maintenance policy among the maintenance policies. CM policy is the original maintenance policy implemented in industry (Mechefske and Wang, 2001). When CM policy is applied, maintenance will only be carried out after the failure occurs. This policy is considered a feasible policy to be adopted in the cases where profit margins are large

(Sharma et al, 2005). However, CM may cause large production losses, serious damage to the system, person and environment due to the unexpected failure.

Therefore, in order to reduce the system breakdown and increase utilization, the maintenance responsibility is given to the owner of the machine. The owner is responsible of detecting the deterioration process of the machine while simple maintenance actions are taken to prevent the occurrence of failure. This concept is known as AM. AM policy also named as detection based maintenance policy is the latest developed maintenance policy among the maintenance policies (Waeyenbergh and Pintelon, 2002). AM policy has brought out a new maintenance concept where maintenance and production department are cooperating to accomplish the maintenance jobs (Tajiri and Gotoh, 1992). It means that maintenance were no longer become the sole responsibility of maintenance department itself, but the operators in the production department also should take part in maintaining the system. Simple maintenance such as cleaning and repair is carried out by production operators in order to prevent the occurrence of failure. Furthermore this will ensure the system is running correctly. An effective AM policy will require education and training for operators to gain sufficient skill and knowledge before the full benefit of this policy can be achieved (Promoski, 2004).

Other than AM policy, PM policy is also a popular maintenance policy that is adopted by the industry. Maintenance under the PM policy is planned and preformed after a specified period of time or amount of the system used to reduce the probability of failure (Kimura, 1997). Mechefske and Wang (2001) stated that most system is maintained with a significant amount of useful life remaining when PM policy is applied. Nevertheless, it is difficult to identify the most effective maintenance interval and will leads to unnecessary maintenance when lacking of historical data (Wang et al, 2007). The alternative to this is PdM policy.

PdM policy which also referred to as condition based maintenance policy is developed due to the growth of technology. Basically, sensors are used to recognize the changes in the condition or performance of a system. The maintenance will be carried out when the system reach the critical point before failure. In other words, the maintenance under the PdM policy is carried out according to the actual condition of the system. Temperature, vibration, noise, lubrication and corrosion testing are the common parameters that were used to monitor the system's actual condition (Swanson, 2001). Maintenance management can easily and clearly point out an abnormal situation by monitoring the data collected by the sensors. The maintenance will then be carried out before the failure occurs (Bevilacqua and Braglia, 2000).

As been discussed, each of the maintenance policy has their special attributes and one must know that selecting an optimal maintenance policy is not an easy task especially when the production consists of several different systems with different maintenance characteristics. Thus a maintenance selection process is required to determine the optimal maintenance policy that suit the system by taking into consideration different maintenance characteristics existed.

2.4 Maintenance Policy Selection

Research in the maintenance selection focused on two main areas that are maintenance policy selection and maintenance action selection. The different between two maintenance selections is that the maintenance policy selection is focused on the system level where the type of maintenance policy for the system is identified. On the other hand, maintenance action such as optimal maintenance interval and optimal replacement interval for the component will be decided in the maintenance action selection process.

Most literatures related to the maintenance selection are focusing on identifying the optimal maintenance actions. For instance, Al-Najjar (1999) work is in selecting the most cost effectiveness vibration frequency for a bearing in the paper industry. Similar with Al-Najjar (1999), Santarisi and Almomany (2005) also used costs as criteria to determine the most cost effective maintenance interval for shell liner in the cement mill. Another study conducted by Jun et al (2006) is to determine the optimal time to change the automotive engine oil based on the oil quality indicator.

There are several literatures that focused on identifying the optimal maintenance policy for a system. In general, the optimal maintenance policy selection involves evaluating the performance of the proposed maintenance policies according to different criteria. For example, Vineryard et al (2000) have conducted a study to evaluate and identify the optimal maintenance policy for flexible manufacturing systems (FMS). Four criteria included machine utilization, downtime, through-put and flow times are considered.

As discussed in Chapter 1, maintenance policy plays an important role in giving direction and guideline for further maintenance required by a system. Moreover, an optimal maintenance policy could influence the profitability of a manufacturing process through its direct impact on quality, efficiency and effectiveness of operation (Alsyouf, 2007). On the other hand, maintenance manager who is responsible for the maintenance policy selection will face a lot of difficulties such as too many maintenance policies available, lack of method to evaluate the capability of these maintenance policies and the process consume a lot of time in order to identify the optimal policy for the system. It shows that there is a need to determine the suitable maintenance policies prior the selection process. Also a systematic and simple guideline will assist maintenance manager to select an optimal maintenance policy for the system.

Since the effect of selecting and implementing optimal maintenance is significant, a lot of researchers have come out with different type of selection models to justify the optimal maintenance policy. It adopted various methods either in identifying the optimal maintenance for system or component level. This will be the main subject matter for discussion in the following section.

2.5 Maintenance Policy Selection Model

Before going into detail of the selection model, a brief definition of a model would be appropriate. This will give better appreciation of the detail discussion on the maintenance policy selection model. In general, a model is a description of a process, system, or concept, in simple and systematic way. A model to an engineer is normally an abstraction that involves an explicit mathematical formalism of the process being studied (Young, 2003). In maintenance selection aspect, a model is a description of a process to select the optimal maintenance policy under certain maintenance requirement and constraints. According to Marais and Saleh (2009) models used to derive optimal maintenance generally cover four main aspects:

(1) A description of the system being maintained

(2) A model of how the system deteriorates and the consequences thereof

(3) A description of the available information on the system and the available response options

(4) An objective function and an analytical framework (or tools) according to which the optimal maintenance policy or action is to be derived.

Typically, the maintenance selection model can be divided into two groups which are quantitative and qualitative selection model. Figure 2.1 illustrated the classification of the maintenance selection models.

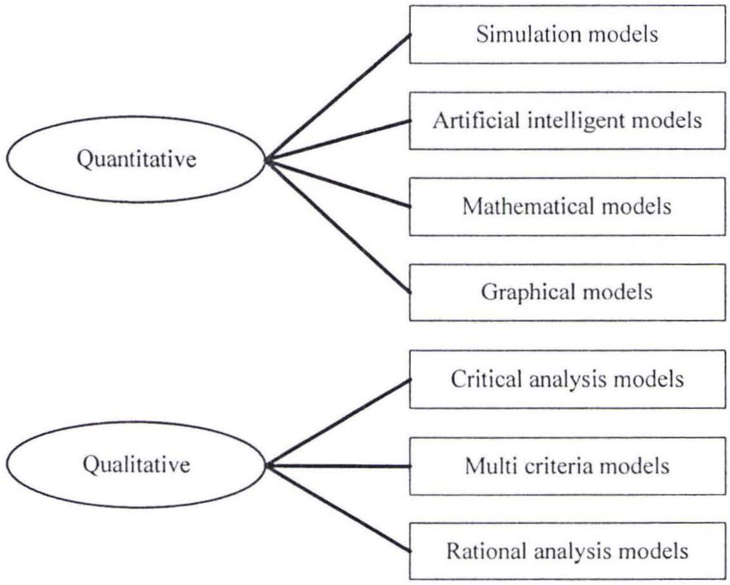

Figure 2.1: Classification of the maintenance selection model

Information that is conveyed by words, images and subjective views is defined as "qualitative" while information that is conveyed by numbers, logic and objective findings is called "quantitative" (Wiksten and Johansson, 2006). Quantitative maintenance selection model emphasizes on the measurement and analysis of the causal relationships between variables. Examples of quantitative models included laboratory experiments and numerical models such as mathematical model. In qualitative maintenance selection model, it usually focused in the meaning and understanding of a studied process. Examples of qualitative models included critical analysis model and multi criteria model that usually involved interviews, questionnaires, impressions and experience from related personnel. In order to give a better understanding about the classified models, a review of each model (shown in Figure 2.1) will be given as following.

2.5.1 Quantitative Maintenance Selection Models

Basically, quantitative model is a formal and systematic process in which numerical data are utilized to obtain information about the world (Cormack, 1991). Therefore, objectivity, generalizability and numbers are features often associated with quantitative model. Information required for quantitative model can be obtained through various aspects such as historical documentations, experimental or just simply assigning several reasonable numerical values.

Quantitative model is commonly used to investigate different research problem in the maintenance selection. As mentioned in section 1.5 (page 5), maintenance selection is fuzzy in nature, therefore, it is difficult to quantify in a numerical form. In order to make the analysis easier so that obtained clear results, different models that are able to extract maintenance information in the numerical form are developed. Simulation, artificial intelligent, mathematical and graphical are the four models that can be grouped under quantitative maintenance selection models.

i) Simulation model

A 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 used different algorithms (Young, 2003). In maintenance, simulations are useful in gaining the insight of the system's operation or to observe their behavior. The information obtained can be applied in identifying a suitable policy for the system.

Among the simulation method, Monte Carlo simulation is one of the popular methods being used in the maintenance selection process. Monte Carlo simulation methods are computational algorithms that rely on repeated random sampling to compute their results. It is largely to be used when it is unfeasible or impossible to compute an exact result with mathematical methods. Generally, Monte Carlo simulation is used to solve several problems included;

(1) Optimization, which is to find an optimal value under certain constraints;

(2) Integration, which is referred as the process of finding a value under multi-dimensional mathematical functions;

(3) Inverse problems - to predict the possible value by referring to certain existed values.

Research adopting Monte Carlo simulation in the maintenance selection generally focuses in identifying the optimal cost effectiveness of maintenance policy. For example, work by Krishnan (1992) to select the most cost effective maintenance policy for the Shugmag machine in a rolling mill. Availability percentage is the criterion suggested for evaluating the maintenance policies in the simulation process. The developed model is focusing on combining maintenance actions for various components to achieve economics of joint maintenance whenever possible, in place of separate maintenance actions for each component. Similar to Krishnan (1992), Borgonovo et al (2000) also adopted Monte Carlo simulation to identify the most cost effective maintenance interval for a component. In addition, the authors have also proposed different practical performance evaluation criteria that included profit function, obsolescence, aging and renovation.

There is also several papers found using simulation method other than Monte Carlo simulation in choosing effective yet cost-efficient maintenance action. For example, Anders and Sugier (2006) proposed a simulation method named Asset Risk Manager (ARM) to compute the life curves, cost curves or probabilities of failure for each maintenance action independently. By using the ARM, it can identify the cost efficient maintenance actions in the shorter duration.

Moreover, Li and Liao (2008) proposed a simulation method to investigate the performance of deteriorating systems maintained under different maintenance policy using a simulation method. In the simulation process, the best maintenance policy is chosen with the highest steady-state availability. The main outcome of this simulation model is the ability to conduct the maintenance selection process for a complex system.

Although simulation model is useful in describing certain maintenance issues such as aging, repair, obsolescence, renovation which is not easily captured by mathematical models, in most situations however, simulation model is not preferred by industries because it is costly in purchasing related simulation software and the need of special training for the personnel to run the simulation. In addition to that, the simulation model cannot fully replicate reality. Thus the accuracy of the data obtain may be low. As the technology grows, new computerized methods have been developed such as artificial intelligence. Now it has become one of the adopted methods in the maintenance selection process.

ii) Artificial intelligence model

As depicted in Figure 2.1, artificial intelligence (AI) model is also one of the models that have been grouped under quantitative models. Different methods include expert system, neural networks, fuzzy logic and genetic algorithm has been proposed in associating with the development of AI. Fuzzy logic and genetic algorithm (GA) are the most common methods that have been adopted in solving the maintenance selection problem.

Fuzzy logic is useful in coping with imprecise, uncertain and subjective information in more consistent and logical manner (Sharma et al, 2005). Recently, fuzzy logic has been widely applied in maintenance selection. For instance, fuzzy logic is used by Sharma et al (2005) to search the most effective and efficient maintenance policy that able to detect failure causes on a machine. Through the analysis, total productive maintenance (TPM) has obtained the highest ranking, follow by predictive maintenance (PdM), reliability based maintenance (RCM), preventive maintenance (PM) and corrective maintenance (CM). Thus, TPM has been selected as the most preferable policy.

Fuzzy logic also been proposed for a real-time decision making concerning the maintenance selection problem. Real-time maintenance environment has a lot of uncertainty due to the lack of accurate information. Lu and Sy (2009) have adopted the fuzzy method to help the maintenance management to obtain fast and accurate maintenance decision in a motor engine company. It shows that the complexity and difficulty of maintenance selection process has been significantly decreased.

Other than fuzzy logic, Genetic Algorithm (GA) is also one of the methods that have been adopted in the maintenance policy selection process. Recently, GA has received considerable attention with regard to its potential as an optimization method for complex problems and has been successfully applied in the area of industrial engineering and one of its applications is in the maintenance aspect (Gen and Cheng, 1997).

GA has been adopted by Azadivar and Shu (1998), Tsai et al (2001) and Lapa et al (2006) in solving maintenance selection issues. In the selection model based on GA developed by Azadivar and Shu (1998), work in progress (WIP) inventories have been integrated into the selection process. As described by the authors, work in progress (WIP) inventories can affect the performance of a given maintenance policy by reducing the effects of machine breakdowns. Besides that, Tsai et al (2001) also implemented GA to determine the optimal maintenance interval for components in a mechatronic system. With the integration of GA into the selection process, the determined maintenance intervals not only can maximize the unit-cost life of component but also reduce the time of complete calculation process.

Moreover, Lapa et al (2006) have taken the advantage of the GA to solve the problem with great amount of criteria simultaneously. In the process of selecting the optimal maintenance action for components in the high pressure injection machine, the authors has considered different criteria included the probability of needing a repair, the cost of repair, typical outage times, preventive maintenance costs, impact of the maintenance in the system and probability of imperfect maintenance. By applying the developed model, it is able to identify the maintenance interval which provides the highest level of reliability at lowest cost.

Savic et al (1995) implemented GA to determine the optimal opportunistic maintenance action. Opportunistic maintenance action is a maintenance that takes opportunity to carry out maintenance on other components during the failure of a component. As similar with other models, maintenance costs are the criteria that used to determine the optimal opportunistic maintenance action. From the results obtained, it shows that group replacement is almost 18% cheaper than single component replacement.

It can be concluded that it is certainly can identify the optimal maintenance with various evaluation criteria by implementing the AI model. However, when implementing AI, it is unavoidable to use certain software for analysis. In other words, investment is required for purchasing the software and training in order to utilize the concept developed. This has minimized the interest of the industries in adopting the model.

iii) Mathematical model

Another frequently used model under the quantitative maintenance selection model is the mathematical model. It is an abstract model that uses mathematical language to describe the system or component. Implementation of mathematical models is common in maintenance especially in maintenance selection. Weibull method, Bayesian method, Proportional Hazard method and Markov method are several common mathematical methods applied in maintenance selection.

Proportional hazard method uses the proportional age reduction factor to the base line of hazard rate or to operation time (Samrout et al, 2009). Zhao (2003) proposed proportional hazard method to determine the optimal replacement maintenance interval for component in the loading and unloading machine. Assuming that a component after replacement maintenance action starts a new failure process, the author has introduced a parameter called degradation ratio to represent the imperfect effect of maintenance on the component. By integrating the degradation ratio into the proportional hazard method, the determined maintenance interval will be more accurate and economical.

In the real world environments, it is usually difficult to specify the quality of a maintenance action precisely. Thus, Wu and Clements-Croome (2005) have come out with a maintenance action selection model that assumes the maintenance quality is a random variable with a certain probability distribution. When the life distribution of the component is illustrated by using Weibull method and the quality of maintenance distributes uniformly, explicit expressions of the optimal maintenance interval can be obtained. The numerical example shows the effect on the long-run average cost of choosing the uniform distribution for the maintenance quality is lower than choosing the affixed value of maintenance quality.

Weibull method is also used to illustrate the malfunction probability of a machine. This has resulted in improving the availability of the machine. For example, Luce (1999) proposed a model with Weibull method to illustrate the malfunction probability of a machine in the iron industry. The maintenance policy was determined according to the ratio of maintenance cost between the maintenance policies. Through the analysis, predictive maintenance policy has been identified as the most cost effective policy and expected almost 20,000 francs per year can be saved by implementing this policy.

On the other hand, Badia et al (2002) have proposed a model to determine the optimal inspection and maintenance interval for a component based on Weibull method. Unlike other selection models, the developed model considered the probability of inspections failure in this selection process. As indicated by the authors, it is useful to consider the probability of error in inspection because every inspection done by human may subject to error. By considering this factor, more accurate inspection and maintenance interval can be obtained and also resulting in improvement in term of availability of component.

Markov method and Semi-Markov method are other methods used for modelling the component deterioration. According to Ge et al (2007), previous works mostly ignored the possibility of doing inspection before the maintenance that is usually practical in real world situation. Therefore, the authors have proposed a model that incorporates inspection into the selection process by using Semi-Markov model. Circuit breaker has been used as an example to demonstrate the developed model. The results show that the model could determine the maintenance interval and inspection rate at the most cost effective.

Markov model also been proposed by Chu et al (1998) to determine the optimal replacement interval by referring to the state of the component. The authors have noticed the complexity of implementing mathematical model in the selection process, thus, a general probability rules are used to characterise the component behaviour. Markov method also been proposed by Castanier et al (2005) to illustrate the deterioration process of a component. The developed model has extended the study of mono-component maintenance to two unit component maintenance in order to minimize the long-run maintenance cost.

In the research conducted by Gurler and Kaya (2002), Markov method has been suggested to described the stochastic nature of the system and classified it into several stages varying from perfect functioning to complete failure. In this study, the authors have tried to reduce the complexity of the analysis by using cost as an approximation. Similar research also been conducted by Nourelfath and Ait-Kadi (2007), but more specific on the series-parallel system. The authors also considered the limitation of the maintenance workforce. Besides that, the authors try to reduce