DEVELOPMENT OF DECISION MODEL FOR MAINTENANCE ANALYSIS OF NON-REPAIRABLE COMPONENT BY CONSIDERING THE EXTERNAL FACTOR

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by

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LIST OF SYMBOLS

$F(t)$	Cumulative distribution function
a	Row vector of the covariates
$C(T)$	Cost function at time, T
$C(T_s)$	Standard cost function at standard time, T_s
C_f	Cost of failure replacement
C_k	the critically index for failure mode k
C_p	Cost of preventive replacement
exp	Exponent
$f(t)$	Probability density function
$R(t)$	Reliability function
T	Failure time / Optimum time of replacement
t	Duration of time used in the FMECA
T_s	Standard optimal time of Preventive Replacement
x	Column vector of the regression parameters (covariate parameter)
α_{kp}	The fraction of the component p's failure having failure mode k (that is, the conditional probability of failure mode k given component p has failed)
β	Shape parameter of Weibull distribution model
β_k	The conditional probability that failure mode k will result in the identified failure effect
θ	Scale parameter of Weibull distribution model
θ_0	Actual scale parameter of Weibull distribution model by considering the covariate effect
θ_s	Standard scale parameter
$\lambda(t)$	Based line failure rate / hazard rate function
$\lambda_0(t)$	Actual (observed) failure rate / hazard rate function
λ_p	the failure rate of component p
ρ	Cost ration of C_f / C_p

LIST OF ABBREVIATION

ARM	Age Replacement Model
BRM	Block Replacement Model
CA	Covariate Analysis
CBM	Condition Based Maintenance
CDF	Cumulative Distribution Function
CM	Corrective Maintenance
FFTD	Fitting Failure Time Distribution
FMECA	Failure Mode Effect and Criticality Analysis
FTPT	Failure Time Process Test
LS	Log Saw
PA	Pareto Analysis
PDF	Probability Density Function
PFA	Physical Failure Analysis
PHM	Proportional Hazard Model
PM	Preventive Maintenance
PR	Preventive Replacement
RP	Roll Pack
TBF	Time Between Failure
TBM	Time Based Maintenance

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PEMBANGUNAN MODEL KEPUTUSAN UNTUK ANALISIS PENYELENGGARAAN BAGI KOMPONEN YANG TIDAK BOLEH DIPERBAIKI DENGAN MENGAMBILKIRA FAKTOR LUARAN

ABSTRAK

Penyelenggaraan pencegahan (Preventive Maintenance – PM) merupakan salah satu strategi yang digunakan untuk mengurangkan masalah kerosakan mesin yang berlaku secara tiba-tiba. Walaupun begitu, persoalan bilakah masa yang terbaik untuk menjalankan aktiviti PM merupakan isu terpenting dalam pengaplikasian strategi ini. Jawapan untuk persoalan tersebut ialah dengan berdasarkan analisis penyelenggaraan (maintenance analysis). Penyelidikan sedia ada mengenai penentuan masa untuk menjalankan PM kebanyakannya tidak berdasarkan analisis penyelenggaraan yang mencukupi yang mana ia tidak mengambilkira faktor luaran yang mengakibatkan kerosakan mesin dan tidak memahami bagaimana proses kerosakan mesin tersebut berlaku (analisis kerosakan fizikal). Oleh sebab itu, penentuan masa terbaik untuk menjalankan PM tidak cukup tepat dan ia akan mengurangkan faedah daripada strategi PM.

Dalam penyelidikan ini, satu model pembuat keputusan berdasarkan analisis penyelenggaraan dengan mengambilkira faktor luaran dan analisis kerosakan fizikal telah dibangunkan untuk menentukan dengan lebih tepat masa yang terbaik untuk menjalankan PM. Oleh itu, faedah daripada strategi PM ini dapat dimaksimumkan. Bagi penilaian model ini, satu kajian kes telah dijalankan di industri pemprosesan di Malaysia. Kajian kes ini memberi tumpuan pada kerosakan komponen mesin yang tidak boleh diperbaiki (non-repairable component).

Keputusan daripada analisis kerosakan fizikal telah mengenalpasti beberapa maklumat penting iaitu faktor luaran yang mengakibatkan kerosakan komponen mesin

dan pengkelasan data-data “censored” dan “uncensored”. Maklumat-maklumat ini merupakan input yang penting untuk analisis faktor luaran (covariate analysis) dalam model pembuat keputusan ini. Keputusan daripada analisis faktor luaran menunjukkan beberapa faktor luaran (covariates) yang dikenalpasti daripada analysis kerosakan fizikal memberi kesan yang serius kepada kerosakan komponen mesin. Oleh itu, nilai parameter daripada kesan tersebut digunakan atau diambilkira dalam pengiraan bagi menentukan masa untuk menjalankan PM dengan lebih tepat. Keputusan daripada pengiraan ini menunjukkan terdapat perbezaan masa PM yang ketara apabila pengiraan yang mengambilkira faktor luaran dan pengiraan yang tidak mengambilkira faktor luaran. Pada kesimpulanya, penentuan masa untuk menjalankan PM akan lebih tepat sekiranya faktor luaran diambilkira dalam pengiraan tersebut.

DEVELOPMENT OF DECISION MODEL FOR MAINTENANCE ANALYSIS OF NON-REPAIRABLE COMPONENT BY CONSIDERING THE EXTERNAL FACTOR

ABSTRACT

Preventive Maintenance (PM) is one of the strategies that can be applied to reduce the machine breakdown problems due to unplanned maintenance. However, the application of PM in term of when is the best time to carry out the PM is an important issue. The answer to this question should be based on an adequate maintenance analysis. The existing study in determining the PM time is not based on an adequate maintenance analysis, where there are not considered the external factor (covariate) and without understanding the failure mechanism (physical failure). Therefore, the determination of PM time is not accurate enough and reduced the PM benefits.

In this research, a decision model of maintenance analysis by considering the external factor (covariate) and physical failure has been developed in order to determine the more accurate time of PM. Therefore, the PM strategy that has been applied can maximise the benefits of PM. In order to validate this model, a case study was carried out on a processing industry in Malaysia. The case study only focused on non-repairable components in a machine.

The results from this physical failure analysis have identified the possible external factors (covariates) that influence the component failure and have classified the censored and uncensored data. This information is being used for the next analysis (covariate analysis) in the decision model. The result shows that some identified covariates have significant effects to the component failure. Thus, the parameter of covariates effects is used to determine more accurate time of PM. The result of PM

time determination shows that there has a significant difference of PM time with and without considering the external factor. Therefore, this result implies that more accurate time of PM should be determined by considering the external factor (covariate).

CHAPTER ONE
INTRODUCTION

1.0 Introduction

This chapter is divided into five sections. The first section gives an overview of the research background, the second section discusses the problem statement of the research, the third section deals with the research objective, the fourth section includes the research focus and delimitation and the fifth section describes the overview of this thesis.

1.1 Research Background

After the Second World War, manufacturing industries such as textile, steel and automotive played an important role in the growth of world economy. Western countries were the pioneered in these industries. For example, in 1960, 65% of the world's industrial production was monopolised by United States and Europe (Kister and Hawkins, 2006). While in Eastern bloc, manufacturing industries were dominated by Japan and Korea.

This situation increases the competition among the manufacturers to fulfill the customer's satisfaction in term of time delivery and quality products. Therefore, it forces the manufacturers to adopt "automation technology". The advantage of the automation technology is that it increased the productivity with constant quality level. However, the manufacturers have to invest very high cost in term of equipments, components and machines. To reach the targeted rates of return on this high investment, the machines should be fully utilised with minimum cost of stoppage and repair. In reality, machine's breakdown due to unplanned maintenance (sudden failure) will increase the repair cost and machine downtime (production lost) (Nakajima, 1986). Therefore, this has brought the role of maintenance as an important activity in the manufacturing industries.

Maintenance is defined as the combination of activities to restore the component or machine to a state in which it can perform its designated functions (Duffuaa et al, 1999; Dhillon, 2002). Historically, the application of maintenance started since the First World War for military purposed. At that time, maintenance was applied with the aim to extend the lifetime of military machines such as truck, tank and aircraft. In the industries, maintenance is an important element to achieve the organisation goal, which is for successful competition and increase the product quality (Duffuaa et al, 1999). One of the maintenance strategies is Corrective Maintenance (CM). CM is a traditional strategy that is used to restore the machine or its components to the required function after the machine failed (Blanchard et al, 1995). However, this strategy reflects to high machine downtime (production lost) and maintenance (repair or replacement) costs (Tsang, 1995). One of the alternatives of this strategy is by applying the Preventive Maintenance (PM).

PM strategy involves the preventive tasks such as repair, replacement or inspection at pre-determined interval (Gertsbakh, 1977). This interval is based on scientific approach such as PM optimisation. The aim of PM's strategy is to reduce the failure rate of the machine or component, thus the machine downtime and maintenance (repair or replacement) costs can be reduced. In practise, the application of PM still has a big gap and it is not based on the adequate analysis (maintenance analysis). This is because of some reasons, for example, the application of PM strategy required a deep understanding of the PM concept and the strict rule in maintenance analysis such as in reliability modelling.

1.2 Problem Statement

In applying the PM strategy, the most critical questions are; what is the task and when is best time to perform PM? These questions can be answered by carrying out a maintenance analysis (Duffuaa et al, 1999). Maintenance analysis refers to a process of understanding the failure mechanism and reliability characteristics of the component or machine. It includes the root cause analysis (physical failure analysis) for answering the questions such as why it failed, how failure occurs and what is the failure causes. Then the logical task such as replacement, repair or inspection is decided. While, the best time to carry out this task is determined by PM models (also known as PM optimisation model) such as the inspection model and the replacement model.

The research presented in this thesis is focused on the process of maintenance analysis in order to determine the accurate time of PM, thus the benefits of the PM strategy can be maximised. According to Dekker (1996), most of the maintenance analysis is performed without understanding the root causes of the machine failure. Therefore, it may result in the wrong information and data for reliability analysis and affected to the determination of PM time (using PM optimisation model). Furthermore, many of the researches and articles in the maintenance analysis assumed that the failure (lifetime) of the component or machine depends only on aging (time usage) factor (in this research it refers as internal factor) (see e.g. Clarotti et al, 2004: Percy and Kobbacy, 2000). However, in reality most of the component or machine failures are influenced not only by the internal factor (age-time usage) but also by the external factor (Lam and Zhang, 2003). The external factor would be the effects of environmental (dust, humidity and heat), human skills, product types and maintenance activities. In fact, when the external factor is not considered in the maintenance analysis, it may give rise to errors in the identification of machine characteristics (failure rate and failure distribution). Consequently, determination of the time of PM is not accurate enough and it reduces the PM benefits (cost saving, high failure rate and production lost).

The emphasis of this research is to develop a decision model for maintenance analysis by considering not only the internal factor but also the external factor. The advantages of this model are that it includes the root failure causes analysis (physical failure analysis) and covariate (refers to external factor) analysis before the time of PM is determined using the PM optimisation model. The main objective of the model is to determine a more accurate time of PM by minimising the failure cost.

1.3 Research Objectives

The general objective of this research is to apply the Preventive Maintenance (PM) strategy for solving machine breakdown problems. The specific objectives of this research are as below;

1. Develop a decision model for the maintenance analysis to analyse the failure data of non-repairable component by considering the external factors.
2. Verify and validate the decision model developed in real case study at a processing industry.
3. Identify the critical component (non-repairable component) that causes major machine breakdown using Pareto Analysis (PA).
4. Perform the Physical Failure Analysis (PFA) on critical component (non-repairable component) using Failure Mode Effect and Criticality Analysis (FMECA) techniques.
5. Codify and measure the effects of the external factor (covariate) on component failure time by carrying out the Covariate Analysis (CA) based on Proportional Hazard Model (PHM).
6. Determine the accurate time of Preventive Replacement (PR) using maintenance optimisation model based on results from previous objective.

1.4 Research Focus and Delimitation

This research is carried out based on some limitations, there are;

- The application of Preventive Maintenance (PM) strategy is based on Time-Based Maintenance (TBM) and it focuses on the determination of the Preventive Replacement (PR) time.
- Only the cost criterion is considered in the PR analysis.
- Only non-repairable components in repairable system (machine) are studied. In other words, only the critical components that contribute to the repairable system failure are studied.
- Only a processing industry has been considered in the case study.

1.5 Thesis Overview

The overview of this thesis is as follows; Chapter two provides a literature review of the related subjects. Chapter three, deals with the development of the decision model. Chapter four presents the decision model validation, which a case study is carried out at processing industry in Malaysia. Chapter five presents the discussion of the decision model validation. Chapter six addresses with the conclusions and recommendations of the future research.

CHAPTER TWO
LITERATURE REVIEW

2.0 Introduction

This chapter is focuses on the literature review on the topic of machine characteristic, factors of machine component failure, maintenance strategy and reliability issue. The flow of the literature review is illustrated in Figure 2.1. In the topic of machine characteristics, the components of a machine and their configuration are discussed. In the next topic, two failure factors are discussed; there are internal factors and external factors. In the topic of the maintenance strategy, the concept and application of Preventive Maintenance (PM) based on PM optimisation models are reviewed. In the topic of reliability issue, the emphasis is given on the reliability analysis of failure time based on time-dependent and time-independent analysis. The final topic in this chapter discusses the findings of the literature review.

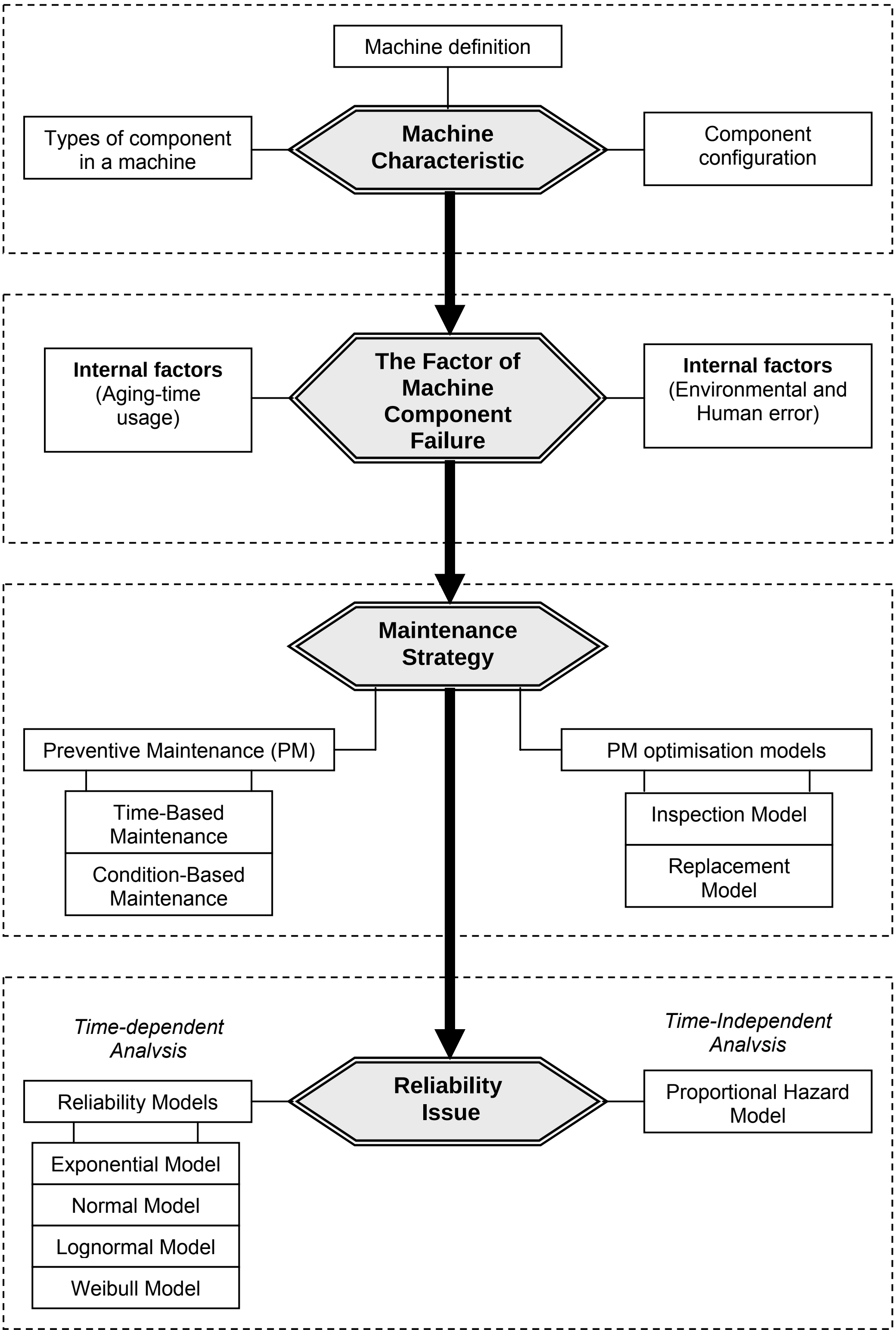

Figure 2.1: Flow of the Literature Review

2.1 Machine Characteristics

Machine can be described as any mechanical or electrical device that transmits or modifies energy to perform or assist in the performance of human tasks (Shigley and Mischke, 2001). Machine generally consists of three types of components i.e. mechanical, electrical and electronic. Figure 2.2 shows the combination of these three components in a machine, which refers to “a machine system” (Duffuaa et al, 1999; Bohoris, 1996). The function of the mechanical component is to transfer the energy into motion, or move materials in a controlled way. Electrical component is used to change electrical energy into another form of energy to perform a task. This energy can be mechanical (motion), magnetic, thermal (heat) or chemical. Electronic components are devices that are used for controlling the voltages and/or current in different signal.

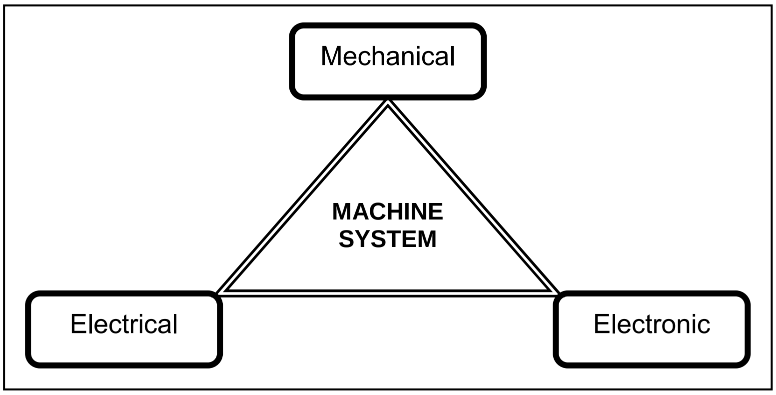

Figure 2.2: The Types of Components in a Machine System

These three components within a machine system may be related to one another in two primary ways, either in a serial or in a parallel configuration as shown in Figure 2.3 (Ebeling, 1997). Figure 2.3a and 2.3b show the diagram of serial and parallel configurations, respectively. The characteristic of serial configuration is that all the components must function for the machine to function, while in a parallel configuration, at least one component must function for the machine to function.

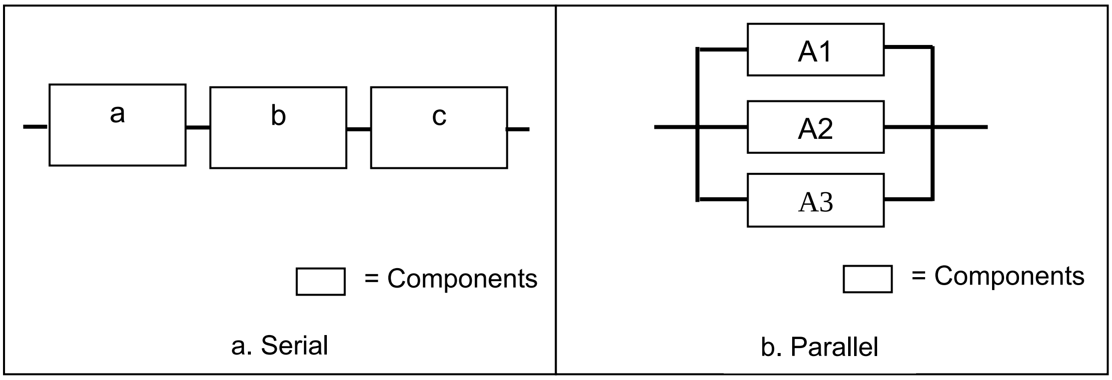

Figure 2.3: a. Serial Configuration and b. Parallel Configuration

In practice, most machines have been designed in serial relationship components. Consequently, failure in at least one of the component in serial configuration will cause the whole system (machine) to breakdown.

2.2 The Factor of Machine Component Failure

As mentioned before, most of the machines are designed in serial configuration and in many cases of the machine breakdown (failure) are due to unplanned maintenance. Most of the unplanned maintenance is due to component failures. According to Lam and Zhang (2003), failure of the machine component is influenced by internal and external factors and the classification of these factors is illustrated in Figure 2.4.

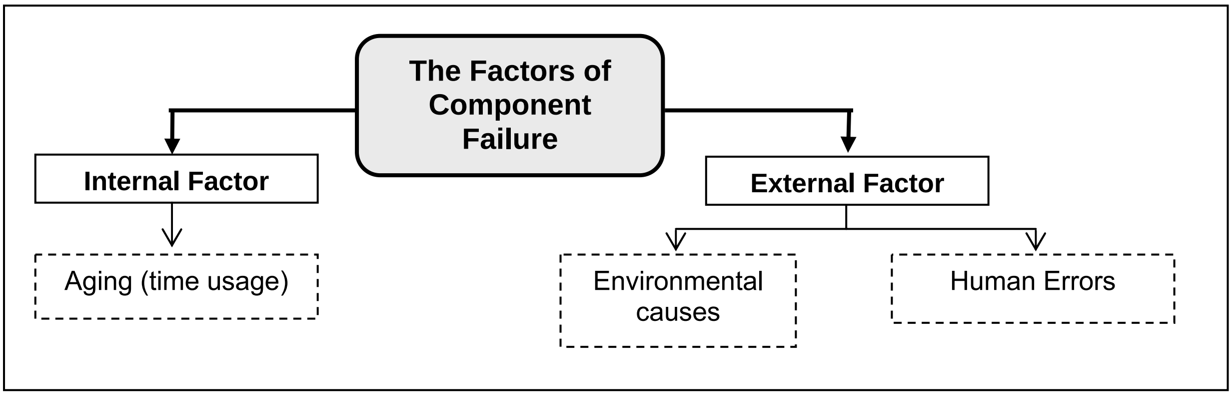

Figure 2.4: The Internal and External Factors Influence on the Machine's Component Failure

Referring to Figure 2.4, the internal factor refers to the cause of aging (time usage) (Lam and Zhang, 2003; Lam and Yeh, 1994), while the external factor consists of environmental causes (Lam and Zhang, 2003) and human errors (Clarotti et al, 2004). The details of internal and external factors are discussed in the following section.

2.2.1 Internal Factors

Internal factor refers to the age (time usage) of a component and it is normal causes of component failure (Lam and Zhang, 2003). In many cases, increasing in the component aging will be followed by reducing in the component performance due to failure and it occurs for all types of components (mechanical, electrical and electronic) (Valdez-Flores and Feldman, 1989: Moustafa et al, 2004). In other words, this situation is nature process in a component lifetime.

If we refer a component that operates in a machine (as a system), this factor also results on reliability reduction, means that the failure rate of the component is increased by machine age (time usage). Failure rate of a component (that operating in a machine) can exist in three states; there are decreasing failure rate (early state), constant failure rate (useful state) and increasing failure rate (deteriorating state)

(Ebeling, 1997). In reliability study, internal factor (age-time usage) is the basic measurement of failure rate. It can be measured in different unit of time including hours, days, working shifts, product cycle or some other units (Tong et al, 2002). For example, Freeman (1996) and Brown et al (2004) used the time unit of years in analysing the failure rate of transformer. Detail of reliability analysis based on internal factor (age-time) is discussed in Section 2.4.1.

As mentioned before, the failure of a component is not only because of internal factor but it also influences by external factor. External factor such as environmental causes and human errors may reduce the component lifetime and increase the component failure rate.

2.2.2 External Factors

The environmental causes such as over heated (temperature), high humidity level, extreme dust condition and over dosed radiation may influence to the component failure. For instance, Oyebisi (2000) discussed the effects of high temperature and humidity on electronic component. He states that when the working temperature and humidity drastically change (increase or decrease), it affects to the performance of the component due to failure. Other study carried out by Saka (1987), where he reports that the fungi which are the products of high humidity environment have a serious effect on the capacitance value of some types of capacitor. He found that a ceramic capacitor has a high percentage changes in capacitance value up to 167.75 when enclosed in a high fungous environment. Martorell et al (1999) studied the effects of environment in Nuclear Power Plant (NPPs) on the lifetime of the mechanical component and they found that over dosed of radiation from nuclear process has a significant affects on the material properties of mechanical component and will reduce the component lifetime.

Human error is another cause of external factor that may influence on the component failure. Human error is defined as the failure to perform a specified task that result in damage to property and equipment (Dhillon and Liu, 2006). According to Wang and Hwang (2004), human errors can be divided by two types: first is the critical human error which will cause system breakdown (unplanned breakdown) and second is latent human error which does not lead to immediate system breakdown. Unskilled technicians or maintenance crews may lead to the component failure as well as machine breakdown through maintenance activities. For example, Dhillon and Liu (2006) stated that component failure may occur due to maintenance error by carrying out incorrect repair or preventive action. For examples, incorrect calibration of component and application of the wrong grease at appropriate points of the component. In addition, Latorella and Prabhu (2000) presented the most common maintenance errors related to industry; there are incorrect installation of components, fitting of the wrong parts, electrical wiring discrepancies (including cross connection), loose objects (tools) and inadequate lubricant. Even the human error is unavoidable, but the percentage of error of unskilled operators and technicians can be reduced by intensive training program or improving the maintenance management system (Wang and Hwang, 2004).

In fact, both of internal and external factors are related to each other. Internal factor (age-time usage) presents the actual component lifetime (with certain failure rate state) and the effects of external factor may reduce or extent the component lifetime as well as the failure rate. For example, the effect of proper and adequate maintenance may extent the component lifetime (as well as reduce the failure rate), while maintenance error may reduce the component lifetime (as well as increase the failure rate). Therefore, determination of an appropriate maintenance strategy at the right time may extent the component lifetime and reduces the component failure rate (Martorell et al, 1999; Oyebisi 2000; Wang and Hwang, 2004).

2.3 Maintenance Strategy

As mentioned in Section 1.1, maintenance is a set of activities or tasks to restore a machine or a component to a state in which it can perform its designated functions (Duffuaa et al, 1999; Dhillon, 2002). In practice, maintenance is classified into two strategies; there are Corrective Maintenance (CM) and Preventive Maintenance (PM) (Hall, 1997) as shown in Figure 2.5. Detail of each strategy is discussed in the following section.

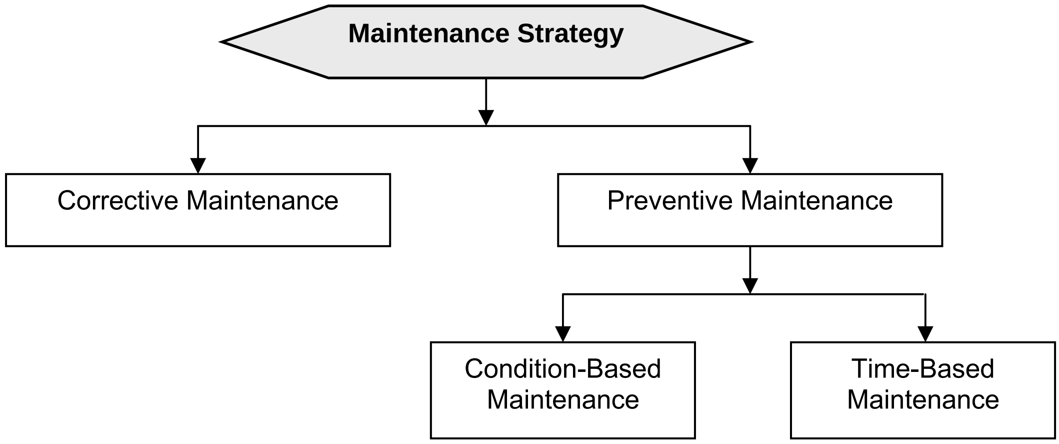

Figure 2.5: Maintenance Strategy Classification

2.3.1 Corrective Maintenance Strategy

Corrective Maintenance (CM), also known as Run-To-Failure or reactive strategy is a traditional strategy that used to restore (repaired or replaced) the machine or component to it required function after it has failed (Blanchard et al, 1995). This strategy reflects to high machine downtime (production lost) and maintenance (repair or replacement) costs due to sudden failure (Tsang, 1995). Moreover, continuous application of CM will effect to the machine performance. For example, Swanson (2001) shows that there are strong relationships between the application of CM strategy and PM strategy to the machine performance. Based on survey and analysis, the author found that the application of CM strategy significantly reduced the machine performance in term of reliability, availability, production lost and product quality.

Therefore, an alternative of CM strategy is by applying the Preventive Maintenance (PM).

2.3.2 Preventive Maintenance Strategy

Preventive Maintenance (PM) is widely applied in industry for asset management such as production machines. The concept of PM is to perform the maintenance activities before the machine fails (Gertsbakh, 1977; Lofsten, 1999). The main objective of PM is to reduce the failure rate or failure frequency of the machine. It contributes to reducing cost, minimising machine downtime (production lost), increasing productivity and improving quality (Usher et al, 1998). In other word, PM is a series of pre-planned tasks such as repair, replace, overhaul and inspection with the aimed to maximise reliability and availability of the machine. The application of PM's strategy can be carried out based on two approaches; there are Time-Based Maintenance (TBM) and Condition-Based Maintenance (CBM) (Duffuaa et al, 1999).

In TBM approach (also known as statistical-reliability based), PM is performed based on machine aging (time usage) (Mann et al, 1995). The aging of the machine is determined based on the use of statistical and reliability analysis. As mentioned before, aging can be measured in different unit of time such as operating time, cycle time, working shifts, working days or some others unit of time. The objective of TBM is to determine the optimum intervals (time) of PM in order to minimise the total cost of failure (reducing failure rate) and machine downtime (production lost). TBM is usually applied on single or non-repairable component such as machine tool (Jianqiang and Koew, 1997; Bahrami et al, 1998). In addition, TBM is feasible when the machine or component is in deteriorating state (or other word in increasing failure rate) and the cost of PM is less then the cost of CM (Mann et al, 1995). In relation of this, Mobley (1990) stated that the cost of CM can be in excess of three times of PM. Reasons for this include;

- CM will extend the downtime due to unavailability of components, or labour.
- CM can result in overtime.
- CM is not executed as efficiently as PM.

In CBM approach, PM is carried out will depend on the condition of the machine, which involves the use of sensor or other indicator (Andersen and Rasmussen, 1999). The condition of the machine is measured directly to its operation based on the different variables such as vibration, temperature, lubricating oil, contaminants and noise level. Under CBM, PM is performed only “when needed” or just before failure. One of the advantages of CBM is its feasibility to apply at any state of the machine lifetime, whether in early state (decreasing failure rate), useful state (constant failure rate) or uncertain state (random failure rate) (Tsang et al, 2006). In fact, CBM is suitable when applying on expensive equipment or complex system such as transformer, turbine system, electronic board, power station, electric motor, engine and generator. For instance, Han and Song (2003) reviewed the success of CBM application on electrical equipment such as power transformer, generator and induction motor. In other cases, Jardine et al (2001) applied CBM on mine haul truck wheel motor based on oil analysis and they determine the optimum time of repair. While Beebe (2003) applied CBM to study the steam turbine performance and determine the optimum time of PM based on vibration analysis and oil analysis.

However, the application of CBM requires an expensive equipment or system (such as special indicator) for continuous monitoring. Moreover, as discussed in Section 2.1 and 2.2, most of the machine failure (breakdown) in production line is due to the component failure. This component may fail without given any signs (based on failure mode only) and failure may influence by internal (age-time usage) and external factors (environmental causes and human error) (Dekker, 1996). Therefore, based on this reason, the application of TBM approach is more suitable for PM application.

2.3.3 Preventive Maintenance Application

The main issue in PM application is in determining the optimal time to carry out the PM's task (replacement or inspection) (Jardine, 1973). If the task is made too early, the components may not have been utilised to full capacity. If the interval is too long, it reflects too high machine down time due to unplanned maintenance (restoration due to sudden failure). Moreover, most manufacturers recommend that PM intervals must be followed to preserve warranty rights. The determination of these intervals by the manufacturer may not reach to maximum benefits of PM strategy (Bahrami et al, 2000). One of the solutions of this matter is using the maintenance optimisation model or PM optimisation model.

According to Dekker (1995), PM optimisation models refer to the mathematical models whose aim is to determine the optimum time/interval of PM which maximises or minimises some criteria such as failure cost, profit, downtime, availability and reliability. The concept of PM optimisation model is illustrated in Figure 2.6.

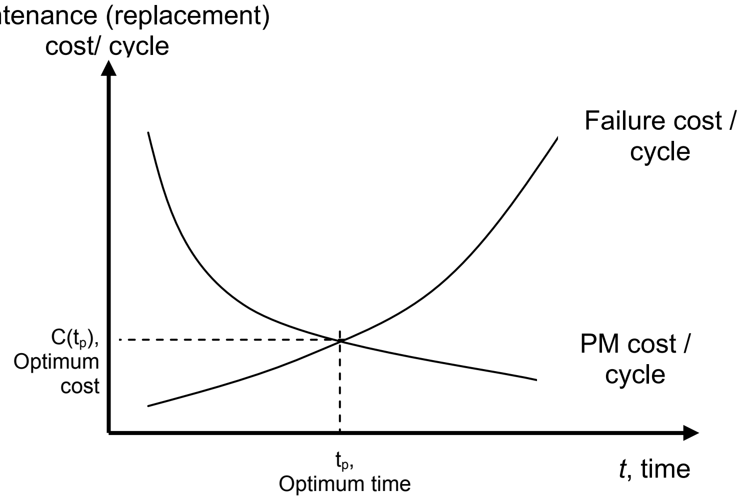

Figure 2.6: Determination the Optimum Time of PM by Minimising the Failure Cost Criteria

Referring to Figure 2.6, it shows that in reality the failure cost / cycle will increase, while the PM cost / cycle will decrease by aging (time usage). The cross point between the failure cost line and PM cost line presents the optimum time to perform PM in order to minimise the failure cost criterion. Inspection and Preventive Replacement (PR) models are examples of PM optimisation models that widely discussed in literature (Scarf, 1997). Detail of Inspection and Preventive Replacement (PR) models in solving various maintenance problems is discussed in following section.

2.3.4 Inspection Model

Inspection is a process of identifying the current state of the machine by detecting the hidden failure or sign that may lead to major damage and it is usually applies on complex system (Jardine, 1973). Hence, preventive actions such as minor modification, minor repair, minor replacement and/or cleaning can be taken before the major failure occurs (Hauge et al, 2002). Examples of inspection activities are physical records (checking) and condition monitoring techniques such as vibration, noise, radiation, oil and temperature tests. The benefit of inspection is to prevent the machine from major failure (Bahrami et al, 1998). Many inspection models have been proposed to determine the optimum time to carry out the inspection and the earliest basic model was introduced by Barlow et al (1963). Following the introduction by Barlow, various inspection models have been developed and modified based on various case study problems.

For example, inspection model is widely applied on emergency and storage equipment or system. For instance, Jardine (1973) proposed an optimal inspection model on the equipment that is used in emergency condition such as fire extinguisher and alarm system. The benefit of this model is to determine the optimum time of inspection in order to maximise the availability of these equipments that used in emergency condition. While the system which in storage for a long time, its reliability may go down with time. Thus, a system in storage should be inspected and maintained at periodic time to reach the higher reliability and availability. Ito and Nakagawa (1995) suggested an optimal inspection model for storage system such as weapon equipments. The objective of this model is to determine the optimum time of inspection to maximise the reliability of this storage system. On the other hand, Ito et al (1995) extended the optimal inspection model for storage system such as missiles and spare parts of aircraft, which the objective of this model is to maximise the reliability of the system.

In other cases, inspection model also has also been applied for the case of randomly failing or randomly shocks system. For instance, Mathew and Kennedy (2002) developed an optimal inspection model based on failure due to random shock load. The objective of this model is to reduce failure frequency as well as to minimise the failure cost. Chelbi and Ait-Kadi (1999) and (1995); Hariga (1996) developed and proposed an inspection model for determining the optimal inspection time for a system subjected to random failure. The objective of this model (inspection model) is to minimise the cost of preventive and corrective action. Chelbi and Ait-Kadi (2000) proposed the inspection models for the case of randomly failing system, which the objective is to maximise the system availability.

2.3.5 Preventive Replacement Model

According to Wang (2002), replacement is a perfect maintenance because component will function as good as new after it was replaced. Like inspection model, the main objective of PR model is to determine the optimum time (interval) of PR in order to maximise or minimise some optimisation criteria such as failure cost, profit, downtime, availability and reliability. However, the application of PR model is only feasible when the cost of PR is less than the corrective replacement (under CM strategy) cost and the failure rate of the component should be increasing mode, which can be determined based on reliability analysis (Jardine, 1973; Ebeling, 1997; Barlow and Proschan, 1965). There are two basic PR models which are widely discussed in the literature; first is Block Replacement Model (BRM) and second is Age Replacement Model (ARM) (Handlarski, 1980; Aven and Jensen, 1999).

In BRM (also known as constant-interval replacement model), a component is replace at constant intervals or time irrespective of the age of the component and carried out the failure replacement (sudden failure) whenever necessary (Barlow and Proschan, 1965). However, BRM is not a popular model for real application. The reason is BRM exist in complicated form and practically it is difficult to apply. Moreover, according to Bahrami et al (2000), BRM has the undesirable characteristic that relatively good components are replaced more frequently than required. Consequently, it reflects to high maintenance cost (component replacement), production lost (machine downtime due to PR) and the component is not fully utilised. The alternative of BRM is ARM. In ARM, a component is always replaced according to its age, *T* or failure, whichever occurs first, where *T* is constant (Barlow and Hunter, 1960). In fact, ARM is more practical and benefits to apply compared to BRM. For example Jiang et al (2006) shows that the cost saving by using PR based on ARM is higher compared with BRM. This is because PR by using BRM performs more PR actions (more then needed), which reflects to high maintenance cost and production lost.

In practice, the application of PR model has been modified and extended based on BRM or ARM in order to solve many maintenance problems and it is usually applies to non-repairable component. For instance, Huang et at (1995) proposed a standard solution of ARM in order to minimise the replacement cost of failure and it applied for the replacement problem of drilling tool. Jianqiang and Keow (1997) modified the ARM that applied in computer-integrated manufacturing environment. From the model they determined the optimum time of tool replacement in order to minimise the failure and production cost. Even the application of BRM is not practical and less benefit in term of cost saving, Bahrami et al (2000) proposed a new perspective of BRM in order to reduce this deficiencies and it is applied on machine tool in the crankshaft line at a car engine manufacturing company. The main objective of this model (new perspective BRM) is to determine the optimum time of PR with minimise the total machine downtime. The detail reviews of various PR models for solving the single-unit problem has been discussed by Wang (2002), which various existing replacement models were summarised, classified and compared.

According to Dekker (1996), the application of PM based on optimisation models can lead to totally wrong result if the information of failure characteristics (lifetime) of the component is not fully defined and understand. This information can be determined by carrying out the reliability analysis. Reliability analysis concerns about the failure data (aging-time usage) analysis in order to identify the state of component lifetime, whether decreasing failure rate, constant failure rate or increasing failure rate. The reliability analysis is discussed in detail in the following section.

2.4 Reliability Issue

Reliability is a word with many different connotations and applications. For example, when applied to human being, it refers to the ability of the person to perform certain tasks according to a specified standard. For a component application, reliability means the ability of the component to fulfil what is required of it (Crowder et al, 1991). Reliability is measured in different unit of time such as operating time, cycle time, working shifts, working days or some others unit of time. The basic measurement of reliability is the failure rate, where high component failure rate means lower reliability (Ghodrati, 2005).

In maintenance analysis (refers to PM application based on TBM approach), reliability is an essential part (sub-analysis) to present the characteristics of the component failure (lifetime) through it failure time distribution. In reliability analysis, the characteristics of the component failure can be represented by the random variable *T* (time to failure) and it can be formed into different failure time functions as shows in Table 2.1.

Table 2.1: The Failure Time Function (Ebeling, 1997)

Failure function	Purpose
Cumulative distribution function (CDF) $F(t) = 1-R(t) = Pr\{T < t\}$ (Probability that a failure occurs before time, *t*)	Presents the failure distribution in cumulative form
Probability density function (PDF) $f(t) = dF(t)/dt = - dR(t)/dt$	Describe the shape of the failure distribution
Failure rate or Hazard rate function $\lambda(t)= f(t)/R(t)$	Identify the characteristics of failure distribution, whether in Increasing failure rate (IFR), Constant failure rate (CFR) or Decreasing failure rate (DFR)

Referring to Table 2.1, the first failure function is Cumulative Distribution Function (CDF), $F(t)$ which presents the failure distribution of the component in cumulative form. The second failure function is Probability Density Function (PDF), $f(t)$ which describes the shape of failure distribution such as Weibull, Exponential, Normal and Lognormal distributions. The final failure function is failure rate or hazard rate, $\lambda(t)$ which determine the characteristics of failure distribution whether in increasing, constant or decreasing failure rates. In addition, each of these failure functions can be presented by different form based on different reliability models.

2.4.1 Reliability Models

The failure time (failure distribution) of a component can be modelled using different reliability models (also known as time-dependent failure model) such as Exponential, Normal, Lognormal and Weibull. Exponential distribution model is used to model the failure time with constant failure rate. This model is one of the important models for modelling the failure time of electric and electronic component or system (Ebeling, 1997). For instance, Tong et al (2002) applied the exponential distribution for assessing performance of lifetime (failure rate) index of electronic component. They developed more simple procedure for testing the lifetime performance index under the exponential distribution.

Normal and Lognormal distributions models are widely used to model the failure time with increasing failure rate for fatigue and wear-out phenomena (Ebeling, 1997). In many cases, it usually uses in modelling the failure time of the cutting tool. For example, Chelbi and Kadi (1999) used the Normal distribution to model the failure time of cutting tool and it applied for determining the optimum time of inspection. In other cases, Jianqiang and Keow (1997) used the Lognormal distribution to fit the failure time of the cutting tool for the purposed of determination the best replacement interval.

One of the most popular reliability models in maintenance application is Weibull distribution model. Weibull distribution model is widely used for characterising the mechanical component (Ghodrati, 2005; Jóźwiak, 1997). For example, Tam et al (2006) applied the Weibull distribution to model the lifetime of multi-component system in order to determine the optimal maintenance interval. While Farrero et al (2002) used the Weibull model for failure data analysis (failure time modelling) on production system in order to determine the optimum time of replacement stocks.

In addition, Weibull distribution model usually can be presented with two parameters. There are scale parameter, θ and shape parameter, β. Scale parameter, θ shows the lifetime of the component. While shape parameter β, presents the characteristic of component lifetime whether in decreasing, constant or increasing failure rate (Ebeling, 1997). The characteristics of component lifetime can be identified based on the different value of parameter, β, where;

$\beta < 1$, represents the decreasing failure rate

$\beta = 1$, represents the constant failure rate

$\beta > 1$, represents the increasing failure rate

However, the application of this conventional reliability models (Exponential, Normal, Lognormal and Weibull) that have been presented in this section assume that the failure data (failure time) used is time-dependent (internal factor). In the scope of this research, it means that the reliability analysis that carried out using these reliability models only considered the internal factor (age-time usage) influencing to the component failure (failure time). In practise, this assumption is not always true because, as discussed in Section 2.2, failure of a component may influence by both of internal and external factors (Lam and Zhang, 2003). Consequently, if only the internal factor is considered in reliability analysis, the result may not be accurate enough and effects in the calculation of PM time. Therefore, the reliability analysis should be performed by considering the external factor in order to reduce this effect. The reliability analysis which is considered the external factor can be performed by integrating the conventional reliability models (Exponential, Normal, Lognormal and Weibull models) with Proportional Hazard Model (PHM).

2.4.2 Proportional Hazard Model (PHM)

As mentioned before, in reliability analysis based on time-dependent (refers to internal factor), the conventional reliability models are used for modelled the failure distribution of the component. However, when the external factor is considered, which is referred to time-independent, the reliability analysis can be performed based on regression type analysis by integrating with Proportional Hazard Model (PHM) (Cox, 1972). Generally, PHM describes the relationship between the reliability analysis based on internal factor (time-dependent) and changing the external factors or covariates (Coit and English, 1999).

PHM is widely used to analyse the failure time data, where the failure time depends on external factor or covariates (time-independent). The basic assumption of PHM is that the actual hazard rate (failure rate), $\lambda_0(t)$ of a component is the product of a based line (time-dependent) hazard rate λ(t) and a positive (time-independent) functional term *exp(a,x)*, basically independent of time, incorporating the effects of a number of covariates. Mathematically, PHM can be expressed in failure rate function as below;

$$\lambda_0(t) = \lambda\ (t)\exp(a, x) \qquad \text{---------------------- (2.1)}$$

Where *a*, is a row vector consisting of the covariates and *x* is a column vector consisting of the regression parameters. On the other hand, the hazard rate (observed hazard rate) of a system or component will change when the covariates change.

The concept of covariates that have an effects on based line (time-dependent) hazard rate *λ(t)* are shown in Figure 2.7. Baseline hazard rate is the failure rate without covariate effects (only internal factor effects - aging and accumulative wear), while the