DEVELOPMENT OF OUTPUT-BASED DECISION SUPPORT MAINTENANCE MODEL (OBDSMM) FOR PRODUCTION MACHINES

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LIST OF ABBREVIATION

CA	Cost Analysis
CBM	Condition-Based Maintenance
CCA	Cause-Consequence Analysis
CCEB	Current Condition Evaluation-Based
CM	Condition Monitoring
CM	Corrective Maintenance
CMP	Critical Machining Process
DES	Double Exponential Smoothing
ES	Exponential Smoothing
FCPB	Future-Condition-Prediction-Based
IDEF	Integrated DEFinition Language
IRA	Individual Risk Analysis
ISO	International Organisation for Standardisation
MAD	Mean Absolute Deviation
MAPE	Mean Absolute Percentage Error
MSC	Maintenance Significant Component
MSD	Mean Squared Deviation
MTTF	Mean-Time-To-Failure
OBDSMM	Output-Based Decision Support Maintenance Model
OBM	Output-Based Maintenance
OEM	Original Equipment Manufacturer
PA	Pareto Analysis
PM	Preventive Maintenance

TA	Trend Analysis
TBM	Time-Based Maintenance
TTF	Time-To-Failure

LIST OF DEFINITIONS

Term	Description	References
Condition Monitoring	Activity performed either manually or automatically, intended to observe the actual state of an item	SS-EN 13306. (2001)
Condition-Based Maintenance	A scientific maintenance approach, which the maintenance decisions are determined based on the information collected through condition monitoring process	Jardine et al. (2006)
Corrective Maintenance	A maintenance strategy that perform maintenance activities after failure occurs	Lofsten. (1999)
Deterioration	A process where the condition of the component gradually worsens and the process will lead to failure	Sim and Endrenyi. (1988)
Diagnosis	A process of finding the source of a fault	Jeong et al. (2007)
Failure	Termination of the ability of an item to perform a required function	SS-EN 13306. (2001)
Maintenance	A set of activities or tasks used to restore an item to a state in which it can perform its designated functions	Dhillon. (2002)
Mean-Time-To-Failure	The expectation of time between failures	Ebelling. (1997)
Non-Repairable	Component that can not be repaired (only replace) once it failed, is discarded (as repair is physically not feasible or non-economical	Louit et al. (2009)

Preventive Maintenance	A maintenance strategy that perform maintenance activities before failure occurs	Lofsten. (1999)
Prognosis	Prediction when a failure may occur	Lewis and Edwards. (1997)
Quality Characteristic of Attribute type	The quality characteristic for variables type refers to the specification limit(s) requirement that a quality characteristic should meet. This requirement may be expressed as an upper specification limit; or a lower specification limit; or both upper and lower specification limits, called herein a double specification limit	MIL-STD 105E. (1989)
Quality Characteristic of Variable type	The quality characteristic for variables type is that characteristic of a unit of product that is actually measured, to determine conformance with a given requirement	MIL-STD 414. (1957)
Repairable	Component that can be repaired to recover its functions after each failure rather than be discarded	Crow. (1974)
System	A group of objects that are joined together in some regular interaction or interdependence towards the accomplishment of some purpose	Banks et al. (1996)
Time-Based Maintenance	A scientific maintenance approach, which the maintenance decisions are determined based on failure time analyses	Mann et al. (2006)

LIST OF SYMBOLS

b	Least-squares fit
$C(t)$	Physical changes parameter function
C_{DownT}	Machine downtime cost
C_f	Failure cost
C_{Main}	Maintenance cost
C_{pR}	Cost of preventive replacement/overhaul
C_{pr}	Cost of preventive repair
$C^{pR}{}_{mdt}$	Cost of machine downtime due to preventive replacement/overhaul
$C^{pr}{}_{mdt}$	Cost of machine downtime due to preventive repair
C_{proRej}	Cost of product reject
C_R	Cost of replacement/overhaul
C_r	Cost of repair
C_{rew}	Cost of rework
$C^{R}{}_{mdt}$	Cost of machine downtime due to unplanned replacement/overhaul
$C^{unp}{}_{R}$	Cost of unplanned replacement/overhaul
$D_{t/hour}$	Downtime per hour
e_t	Forecast error in t
$F(t)$	Density function of MTTF
h_1	Smoothing parameter for the level of the series
H_2	Smoothing parameter for the trend
$L_{c/day}$	Normal lifecycle per day
$M_{c/cycle}$	Maintenance cost per cycle
$M_{c/year}$	Maintenance cost per year

$P_{l/hour}$	Production loss per hour
$P_{l/year}$	Production lost per year
$Q(t)$	Product quality parameter function
R_{cost}	Cost of risk
S_t	Level (mean) of the series at the end of t
t	Time monitored
$T_{C/year}$	Total cost per year due to maintenance
$T^{main}{}_{cost}$	Total maintenance cost per lifecycle
T_t	Trend at the end of t
$T^{unext\text{-}f}{}_{cost}$	Total unexpected failure cost
X_t	Observed value of the series in period t
$\ddot{X}_t(m)$	Forecast made at the end of t for m steps ahead
ϕ	Trend modification parameter

PEMBANGUNAN MODEL PEMBUAT KEPUTUSAN PENYELENGGARAAN BERDASARKAN 'OUTPUT' UNTUK MESIN PENGELUARAN

ABSTRAK

Penyelidikan yang dibentangkan di dalam tesis ini adalah berkaitan tentang proses analisa untuk membuat keputusan penyelenggaraan bagi menentukan masa terbaik untuk melaksanakan penyelenggaraan, komponen yang patut diselenggarakan dan jenis penyelenggaraan yang paling sesuai dijalankan. Dalam industri, analisis untuk membuat keputusan-keputusan ini adalah penting untuk mengurangkan kos keseluruhan penyelenggaraan dan mengelakkan kegagalan yang tidak dijangka, di mana dalam kebanyakan kes ianya adalah sangat mahal.

Dalam kajian literatur, banyak teknik telah diperkenal dan dicadangkan untuk membuat keputusan penyelenggaraan. Semua teknik-teknik ini boleh dikelaskan di bawah teknik penyelenggaraan berasaskan masa dan teknik penyelenggaraan berasaskan keadaan. Tinjauan literatur menunjukkan bahawa aplikasi teknik penyelenggaraan berasaskan masa tidak praktikal dalam kebanyakan kes di industri berbanding dengan aplikasi teknik penyelenggaraan berasaskan keadaan. Penemuan daripada tinjauan literatur ini boleh dijelaskan dengan merujuk kepada tiga kriteria asas pengaplikasianya; jenis data yang diperlukan dan proses pengumpulannya, analisis data/pemodelan data dan proses membuat keputusan.

Walaupun aplikasi untuk teknik penyelenggaraan berasaskan keadaan dilihat lebih realistik untuk kebanyakan kes (dipersetujui oleh ramai penyelidik), tetapi teknik ini masih mempunyai kelemahan dan kekurangan ke arah proses membuat keputusan penyelenggaraan. Dari kajian literatur, didapati bahawa kebanyakan

aplikasi teknik penyelenggaraan berasaskan keadaan yang dilaporkan hanya tertumpu kepada proses pemantauan keadaan dan tidak kepada proses membuat keputusan penyelenggaraan. Penemuan lain adalah parameter pemantauan yang digunakan dalam teknik penyelenggaraan berasaskan keadaan adalah merujuk kepada isyarat perubahan fizikal (seperti getaran, bunyi, haus, dan lain-lain), di mana ia hanya berguna untuk memantau keadaan/kesihatan komponen yang disasarkan. Walaubagaimanapun, untuk membuat keputusan penyelenggaraan, isyarat pemantauan yang perlu digunakan mesti mewakili dan merujuk kepada proses kegagalan sebenar komponen itu sendiri. Oleh itu, keputusan penyelenggaraan yang betul berdasarkan perspektif kegagalan sebenar komponen boleh dibuat.

Oleh itu, dengan kesedaran ini, teknik penyelenggaraan yang baru yang dinamakan teknik penyelenggaraan berasaskan ‘output’ telah diperkenalkan dalam tesis ini. Teknik penyelenggaraan berasaskan ‘output’ menyediakan cara yang unik ke arah membuat keputusan penyelenggaraan, yang mana prinsipnya adalah menggunakan ukuran ‘output’ mesin seperti ciri-ciri kualiti produk sebagai parameter utama untuk pemantauan kemerosotan (keadaan) dan had kegagalan proses pemesinan. Dalam erti kata lain, maklumat tentang ciri-ciri kualiti produk akan digunakan untuk membuat keputusan penyelenggaraan supaya ia lebih dipercayai.

Di samping itu, model pelaksanaan teknik penyelenggaraan berasaskan ‘output’ yang dinamakan model sokongan membuat keputusan penyelenggaraan berasaskan ‘output’ telah dibangunkan. Model ini direkabentuk dan dibangunkan dengan menggunakan kaedah ‘Integrated DEFinition Language (IDEF)’ yang mana ia terbahagi kepada tiga langkah utama iaitu proses persediaan awal, proses pemantauan kemerosotan prestasi dan proses membuat keputusan. Umumnya, model ini menyediakan tatacara yang sistematik dalam mengenal pasti, menilai, memantau dan membuat keputusan penyelenggaraan berdasarkan teknik penyelenggaraan berasaskan 'output'. Kesudahan yang diharapkan dari model ini adalah untuk mengelakkan atau sekurang-kurangnya mengurangkan kesan kegagalan yang tidak dijangka berdasarkan perspektif kegagalan sebenar komponen pada masa yang sesuai, untuk komponen mesin yang betul dan dengan tindakan penyenggaraan yang terbaik. Di dalam tesis ini kebolehlaksanaan model sokongan membuat keputusan penyelenggaraan berasaskan 'output' disahkan berdasarkan tiga kajian kes khusus yang dijalankan di industri pemprosesan.

Umumnya, keputusan daripada kajian kes tersebut menunjukkan model yang diperkenalkan dalam tesis ini sesuai digunakan untuk kes-kes sebenar di industri. Keputusan-keputusan penyelenggaraan berkaitan yang dicadangkan oleh model ini juga adalah logik, iaitu ia dicadangkan di dalam lingkungan masa dan keadaan yang boleh dipercayai. Bagi menunjukkan proses membuat keputusan dalam model ini adalah unik dan lebih realistik daripada model-model/teknik-teknik sedia ada, empat kriteria perbandingan telah digunakan untuk dibincangkan, iaitu teori dan asas setiap model, data-data yang diperlukan, data analisis yang digunakan, dan proses membuat keputusan yang diaplikasikan. Daripada perbincangan ini dapat disimpulkan bahawa model yang diperkenalkan dalam tesis ini mempunyai banyak kelebihan berbanding model-model/teknik-teknik sedia ada.

DEVELOPMENT OF OUTPUT-BASED DECISION SUPPORT MAINTENANCE MODEL (OBDSMM) FOR PRODUCTION MACHINES

ABSTRACT

The research presented in this thesis is concerned about maintenance decisions analysis to determine when is the right time to perform maintenance, what is the appropriate type of maintenance action should be carried out and which component is required maintenance. In industry, these series of decisions analysis is essential for minimising the overall maintenance costs and avoiding the unexpected failure, where in most cases it is very expensive.

In literature, many maintenance techniques were introduced and proposed towards maintenance decisions making, which all of them can be classified under time-based maintenance (TBM) and condition-based maintenance (CBM) approaches. Literature review reveals that the application of TBM is not practical in real industrial practice compared with CBM. This literature finding can be argued according to the three application criteria; data required and collection, data analysis/modelling and decision process.

Although the application of CBM is more realistic in real cases (agreed by many researchers), but there are some missing part of CBM towards maintenance decisions making process. From the literature review study, it is found that most of CBM application reported only focused on the condition monitoring process rather than maintenance decisions making. Another finding is that the monitoring parameter used in most CBM research is towards physical changes signals (e.g. vibration, sound, wear, etc), where it only useful to monitor the condition/health of the targeted component. In fact, in order to make the maintenance decision, the

monitoring signal to be used must represent the actual failure process of the component its self. Thus, the right maintenance decisions towards actual failure perspective of the component can be made.

Therefore, with this concern, a new maintenance technique called output-based maintenance (OBM) is proposed in this thesis. OBM provides unique way towards maintenance decisions making, which its principle is to use the machine output measure such as product quality characteristic as the main monitoring parameter to indicate the deterioration (condition) and failure limit of the machining process (sub-production machine system). In other words, the information of product quality characteristic will be considered for making more reliable maintenance decision.

Furthermore, the implementation of decision support model by adopting OBM technique called Output-Based Decision Support Maintenance Model (OBDSMM) is developed and described in this thesis. OBDSMM is designed and developed by using 'Integrated DEFinition Language (IDEF)' method, where it can be divided into three main steps; initial setup, deterioration monitoring and decision making processes. The model provides a systematic guideline to identify, evaluate, monitor and making maintenance decisions based on OBM technique. The expected output from OBDSMM is to avoid or at least minimise the effects of unexpected failure based on actual failure perspective of maintenance significant component at the right time, for the right machine component(s) and with the right maintenance actions. OBDSMM is validated based on three specific industrial cases that were carried out at a processing type industry.

The validation results show that the proposed model is applicable to be applied in real industrial cases. The related decisions suggested by the model are also logic that is within the reliable condition and time domain. In order to show the uniqueness of the model in making more realistic decision, four comparison criteria are used to be discussed; basic theory and principle, data required, data analysis and decision process. It can be concluded that the proposed model has many advantages compared with existing models or techniques.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this chapter, a brief introduction is given in order to introduce the reader about the research problems. It covers the underlying background and problem area of the research project. It also discusses the research question with limitations and finally the structure of the thesis is specified.

1.2 Background

In industry, maintenance plays an important role in order to ensure that the company assets (e.g., production machine) are always available and reliable for the purpose of production process. Maintenance generally can be performed based on two strategies (Duffuaa et al., 2001); reactive and preventive strategies. Reactive strategy (also known as corrective maintenance (CM) or emergency maintenance (EM)) is the oldest maintenance practice, which takes place only after failure occurs. Meanwhile, preventive strategy (also known as preventive maintenance (PM)) is to perform maintenance before failure occurs.

In terms of cost that involves in maintenance, several studies reveal that maintenance cost in industry may contribute a significant fraction of the total production costs. For example, McKone and Weiss (1998) generally stated that a company can spend as much as its net income on maintenance. Specifically, Maggard and Rhyne (1992) estimated the maintenance expenses on a yearly basis usually range between 15% and 40% of the total production cost. Meanwhile, Coetzee (2004) reported that the maintenance cost can be as much as 15% to 50%, and Bevilacqua and Braglia (2000) declared that the maintenance cost for heavy industry can represent as much as 15 to 70% of the total production cost. A consensus of the above-mentioned percentages is that the maintenance costs represent at least 15% or higher of the total production cost. On the other hand, Wireman (1990) generally reported that one-third of the maintenance cost is spent unnecessarily because of circumstances such as bad planning, overtime costs, poor usage of work order systems, and limited or misuse of preventive maintenance. In relation, another survey carried out in Swedish industries indicates that although about 13% of the maintenance department time is spent on planning maintenance tasks, nevertheless, about one third of the time is spent on unplanned tasks (Alsyouf, 2009). Therefore, there is no doubt that many industries with traditional maintenance practice (reactive strategy) consider maintenance as a costly support function of production process.

Although maintenance cost cannot be totally avoided, it can be minimised by performing maintenance at the right time, at right place and for the right maintenance actions. Therefore in today's industries, maintenance is one of the support functions that has become increasingly important in the production machine system in order to reduce cost and protect its commercial margins and at the same time enhances the productivity (Cholasuke et al., 2004). The major challenge of the maintenance engineers is to implement a proper maintenance programme, which maximises availability and efficiency of the machine, control the rate of machine deterioration, ensures the safe and environmental friendly operation, and minimises the total cost of the operation**.** Therefore, the application of preventive maintenance (PM) strategy is the main key to maximise the efficiency of production machine by minimising the unplanned maintenance (corrective maintenance). As stated by Khanlari et al., (2007) there is a critical need to design and implement a proper maintenance program towards PM strategy. Proper maintenance can be defined as very few corrective maintenance events, while performing as little as possible the maintenance actions (Cooke and Paulsen, 1997). In other words, ideally, PM should be performed only when needed or just before the equipment fails. Thus, the costs of unexpected failure can be minimised and at the same time the equipment lifetime can be fully utilised.

In reality, designing and implementing a proper maintenance programme towards PM strategy on complex system such as production machine is not a simple task. The main reason is that production machine is typically structured and connected with many sub-systems and components, which each of them has their own functions, characteristics and failure behaviours. Therefore there is no general, formal or flexible technique to be used for all types of problems and situation. As stated by Viles et al. (2007) maintenance technique to be used must be unique, based on certain situations and must be adapted to the specific needs of the company. Therefore, research in maintenance towards designing and developing an alternative technique is still relevant in current industrial practice.

1.3 Problem Statement

Most of the maintenance research towards preventive maintenance (PM) strategy is concerned with decisions analysis (Percy, 2004). Since the principle of PM is to perform maintenance before failure occurs, thus there are three fundamental decisions faced by maintenance management (Van Dijkhuizen, 1998). The most important decision deciding when is the right time to carry out maintenance. Then, if the targeted component is classified under repairable type, the next decision must be decided is identifying the appropriate maintenance action to be performed (e.g., repair or replace). Another decision that is relevant for the case of multi-components structure is to identify the component that requires maintenance.

The keyword towards making these decisions is to understand how the failure of the targeted component is defined. Although failure can generally be defined as *termination of the ability of an item/component to perform a required function (SS-EN 13306, 2001),* when and how the targeted component is considered failed is varied from one perspective to another. In production machine scenario, the failure of the component(s) and its effects are varied and it can be classified into three types.

The first type of component failure is physical failure, where the function of the component is terminated due to its physical changes (e.g., crack, broken). The effect of this type of failure will result in the whole machine is totally stopped from operation (sudden breakdown). The second type of component failure is functional failure. It refers to the performance of the component that does not reach the requirement. This type of failure may not result with the whole machine suddenly stop from operation, but the machine output (e.g., product quality characteristics) that has been produced is out of specification. The third type of component failure is the combination of functional and physical failures. In reality, the second and third failure types are the typical cases occur because in production machine perspective there is a close relationship between maintenance and product quality, as product quality depends on machine component(s) condition (Arunraj and Maiti, 2007).

Moreover, failure of the component towards functional failure or combination with physical failure (the second and third failure types) is more critical to be solved. The main reason is that the economic impact from these types of failure will involve not only the internal cost but also the external cost. Internal cost refers to the increasing of the production cost due to corrective maintenance events, where it includes the cost of unplanned downtime, spare part delay and rework. Meanwhile, external cost refers to the costs claims by the customers due to unsatisfied business, for example costs of products reject, product delay and reliance of customers.

Currently, there is very limited research in maintenance decisions making deals with the interaction between component failure and the effect of machine output (e.g., products quality characteristics) (Linderman et al., 2005). Literature review reveals that the existing maintenance techniques (e.g., TBM and CBM) seem to focus only on the first type of failure without considering the failure effect to the machine output. It is supported by Chen and Jin (2006) who stated that traditional or conventional maintenance policies only focused on the direct downtime or performance loss of component(s), while the impact of the state of the component(s) on the output (e.g., product quality characteristics) is not well addressed.

1.4 Research Questions

Based on the discussion in the previous sections, the following research questions are posed on the basis of the research problem:

1. What is the most appropriate maintenance technique that can be applied towards implementing proper Preventive Maintenance (PM) programme for the second and third failure types of machine component that has been mentioned in previous section?
2. How the maintenance technique stated in previous question can be dealt with different types of component(s) characteristics such as structure type (single-component or multiple-components) and design type (non-repairable and repairable) towards maintenance decisions making?
3. How the process of maintenance decisions making (e.g., when to perform maintenance, what is the appropriate maintenance action needs to be carried out and which component is actually required maintenance) towards Preventive Maintenance (PM) strategy can be carried out based on previous questions?

1.5 Research Objectives

The main objective of this research is to propose a new maintenance technique and to develop its implementation decision support model towards preventive maintenance strategy for the case of production machine component(s) that are classified under the second and third types of failure. This objective was achieved through accomplishment of the following sub-objective;

1. To investigate and identify the real problems faced by industries in applying Preventive Maintenance (PM) on production machine towards maintenance decision making processes.
2. To identify, classify and clarify the existing maintenance techniques based on their concept, tools, application, limitation, advantages and disadvantages.
3. To propose a new maintenance technique to improve maintenance decision making process for production machine component(s) based on objectives 1 and 2.
4. To develop the decision support implementing model by adopting the proposed maintenance technique.
5. To validate and verify the model through real industrial case studies.

1.6 Limitations of the Research Study

This research is governed by some limitations and there are:

- The developed decision support system in this research is focused on production machine perspective.
- The accuracy of the information and data used in this research is highly dependent on the records provided by the case study company.
- The reliability of collected data and collection process from statistical point of view is not the main concern in this research.

1.7 Thesis Structure

The structure of this thesis is presented in Figure 1.1. The brief descriptions of each chapter are as follows.

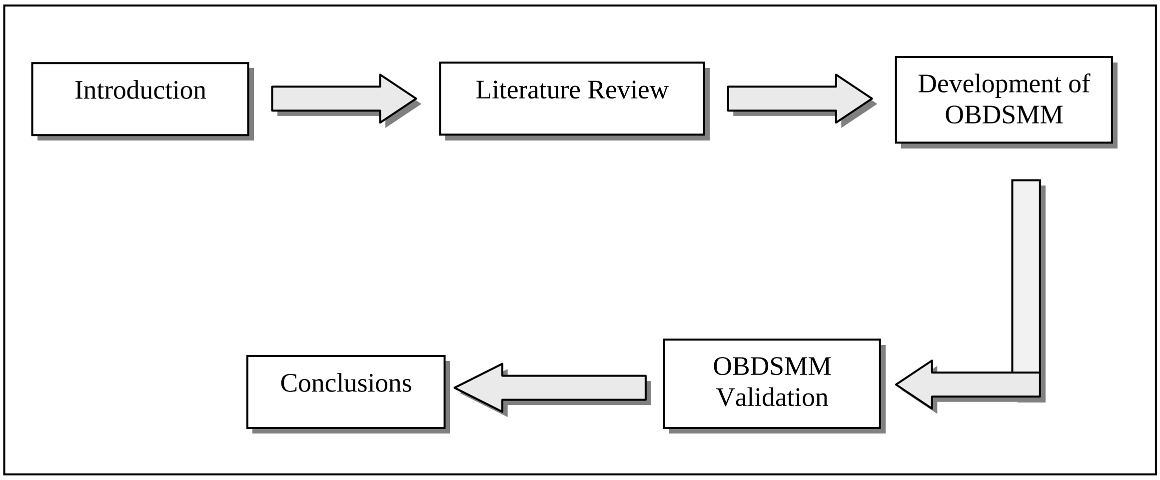

Figure 1.1: Illustration of thesis structure

The first chapter (Introduction) starts with a description of the background and research problem. It is followed by the aim, research question, research objectives, limitations and thesis structure. In the second chapter (Literature Review) the theoretical review related with the research topic will be discussed. At the end of this chapter, the finding from the literature review will be presented. In the third chapter (Development of OBDSMM) the new maintenance technique namely output-based maintenance (OBM) and its maintenance decision support implementation model called output-based decision support maintenance model (OBDSMM) is proposed and presented, respectively. In the fourth chapter (OBDSMM Validation) several case studies are used to validate the developed model will be presented. In Chapter five (Conclusions), the general conclusions drawn from the research will be presented and finally the contribution of the thesis and further research work will be dealt with.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter aims to describe and discuss the existing theories and practices that can be found within the research topic in order to place the research into a context as well as to give the readers an overview of related research. The flow of the literature review is illustrated in Figure 2.1. The next section starts with the topic of production machine. This topic discusses characteristics and failure scenario of the production machine. It is followed with the section to discuss on the topic of maintenance classification and practices. This topic discusses the theory of maintenance research and its practices. The next section explores how the time-based maintenance (TBM) and condition-based maintenance (CBM) approaches work toward maintenance decision making. Then, the review of past research works according to TBM and CBM application is presented. The final section of this chapter discusses the findings of the literature review and conclusion.

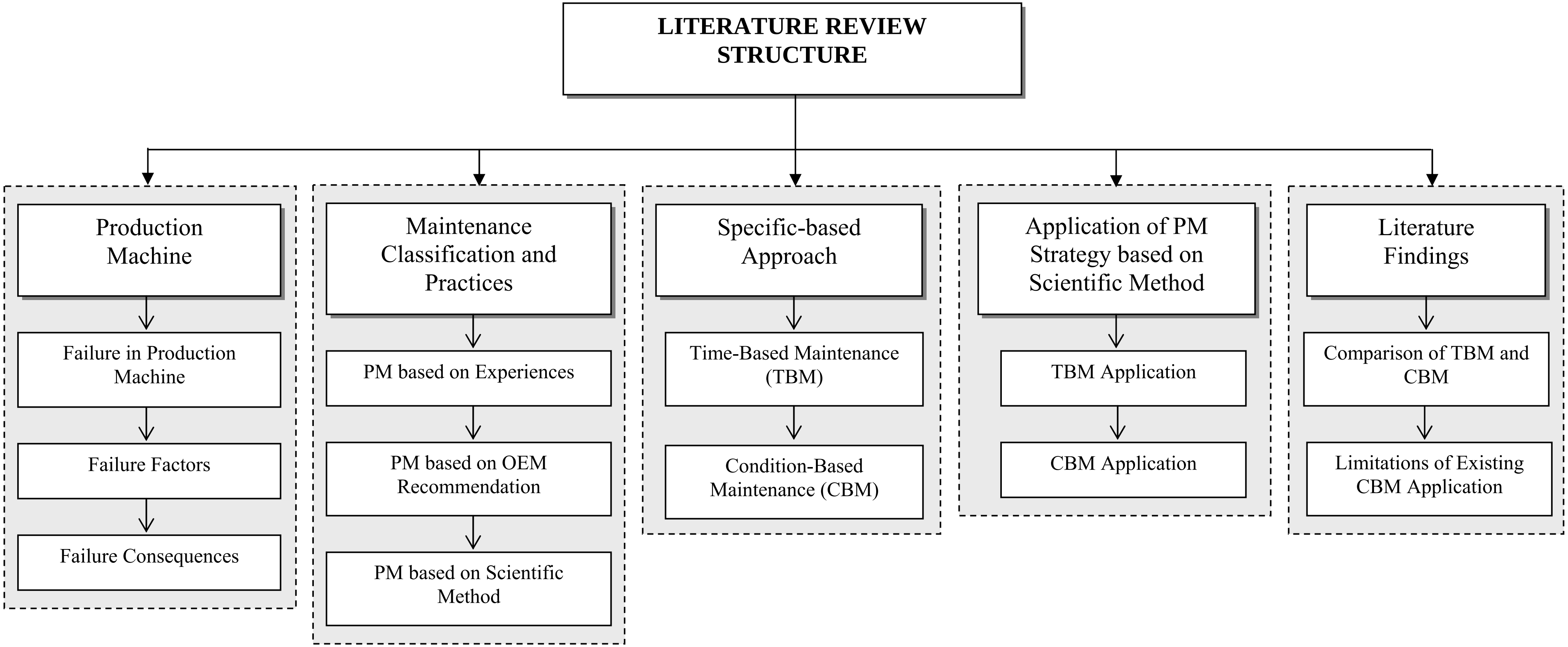

Figure 2.1: Literature review structure

2.2 Production Machine

According to Shigley and Mischke (2001), machine can be described as any mechanical, electrical or electronic devices (or combination of them) that transmits or modifies energy to perform or assist in the performance of human tasks. In other words, machine is a system for doing work. Typically, machine is structured and connected with many sub-system, components, and parts, which each of them has their own function and characteristics.

Production machine, on the other hand, is considered as a complex system that is designed to perform one or more particular machining processes. In manufacturing industries, various types of production machines that are responsible for specific machining processes (e.g., rewinding, embossing, cutting, packaging machines) are connected in a particular flow to form a production line. The efficiency of production machine plays the main key in producing products with high quality in the right time and the right scale. However, failures of production machine will disturb the machine output and its quality thus affects the company profits. In the following sub-sections, discussion regarding failure in production machine is presented.

2.2.1 Failure in Production Machine

In the literature, much has been written about failures and their classifications and clarifications are based on various perspectives. For example, Nowlan and Heap (1978) divided failure into two types: functional failure and potential failure. Functional failure is the inability of an item (or the component containing it) to meet a specified performance standard, while potential failure is an identifiable physical condition which indicates a functional failure is imminent.

Meanwhile, Badía and Berrade (2006) classified failure of a machine into two types; minor failure and catastrophic failure. Minor failures can be avoided by a minimal repair, while the catastrophic failures are removed by a major or perfect repair. According to SS-EN 13306 (2001) failure can be defined as termination of the ability of an item (any part, component, device, subsystem, functional unit, component or system that can be individually considered) to perform a required function. In other words, failure can be referred to as an event or process of component deterioration.

Failure of production machine can be described into two views. The first view is failure of the machine or system as a whole, which it refers to machine breakdown. Meanwhile, second view is the failure of one or more component(s) in the machine, which it contributes to the machine breakdown.

2.2.2 Failure Factors

The factors of failure can be divided into internal factor and external factor. Internal factor refers to the age (time usage) of the component due to wear and tear process (Lam and Zhang, 2003). In many cases, increasing in aging will be followed with reducing component performance (degradation) (Valdez-Flores and Feldman, 1989: Moustafa et al., 2004). This is a nature process of component during its lifetime. Since machine components are design based on different purposes and functions, their lifetimes also are varied. In practice, the lifetime of a component may significantly be shorter than its designed lifetime due to external factor effects.

One of the examples of external factors is environmental effect such as over heated (temperature), high humidity level, extreme dust condition, and over dosed radiation. For instance, Oyebisi (2000) discussed the effects of high temperature and humidity on electronic component. He stated that when the working temperature and humidity drastically change (increase or decrease), it affects the performance of the component due to failure. Saka (1987) reported 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 effect on the material properties of mechanical component and thus reduce the component lifetime.

Human error and inappropriate methods used during component installation are other examples of external factors that may influence to the component failure. Human error is defined as the failure to perform a specified task that result in damage to property of component (Dhillon and Liu, 2006). According to Wang and Hwang (2004), human errors can be divided into 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. 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 and repair procedure. In addition, Latorella and Prabhu (2000) presented the most common maintenance errors related to industry; they 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).

2.2.3 Failure Consequences

According to Blischke and Murthy (2003), the consequences of failure are many and varied, but most of the failure has an economic impact. In manufacturing industries, failures in production machine can create many inconveniences. It may be responsible for the major causes of machine downtime and low availability and customers' dissatisfaction, increasing maintenance time and production costs, lower product quality and delay the delivery time (Tsarouhas, 2009; Wang and Pham, 1999). In chemical or nuclear plants, failures might be very expensive (catastrophic effects) and in some cases, they are not allowed at all due to safety issues. In general, Todinov (2006) lists seven possible consequences resulting from system or component failure;

i. Lost of production time
ii. Volume of lost production
iii. Mass of harmful chemicals into the environment
iv. Lost of customers
v. Warranty payments
vi. Cost of mobilisation of emergency resources
vii. Insurance cost

Although failure cannot be totally avoidable, the risk and the effects of failure can be minimised and controlled by practicing an effective and efficient maintenance practice.

2.3 Maintenance Classification and Practices

Maintenance is defined as a set of activities or tasks used to restore an item to a state in which it can perform its designated functions (Duffuaa et al., 1999; Dhillon, 2002). Maintenance strategies can be broadly classified into Corrective Maintenance (CM) and Preventive Maintenance (PM) strategies (Duffuaa et al., 2001).

Corrective maintenance, also known as run-to-failure or reactive maintenance, is a strategy that is used to restore (repair or replace) some component to its required function after it has failed (Blanchard et al., 1995). This strategy leads to high levels of machine downtime (production loss) and maintenance (repair or replacement) costs due to unexpected failure (Tsang, 1995). An alternative to the CM strategy is the PM strategy. The concept of PM involves the performance of maintenance activities prior to the failure of component (Gertsbakh, 1977; Lofsten, 1999). One of the main objectives of PM is to reduce the failure rate or failure frequency of the component. This strategy contributes to minimising failure costs and machine downtime (production loss), and increasing product quality (Usher et al., 1998). In the industry, application of the PM strategy can be generally performed through either experience or original manufacturer (OEM) recommendations, and is based on a scientific method as shown in Figure 2.2.

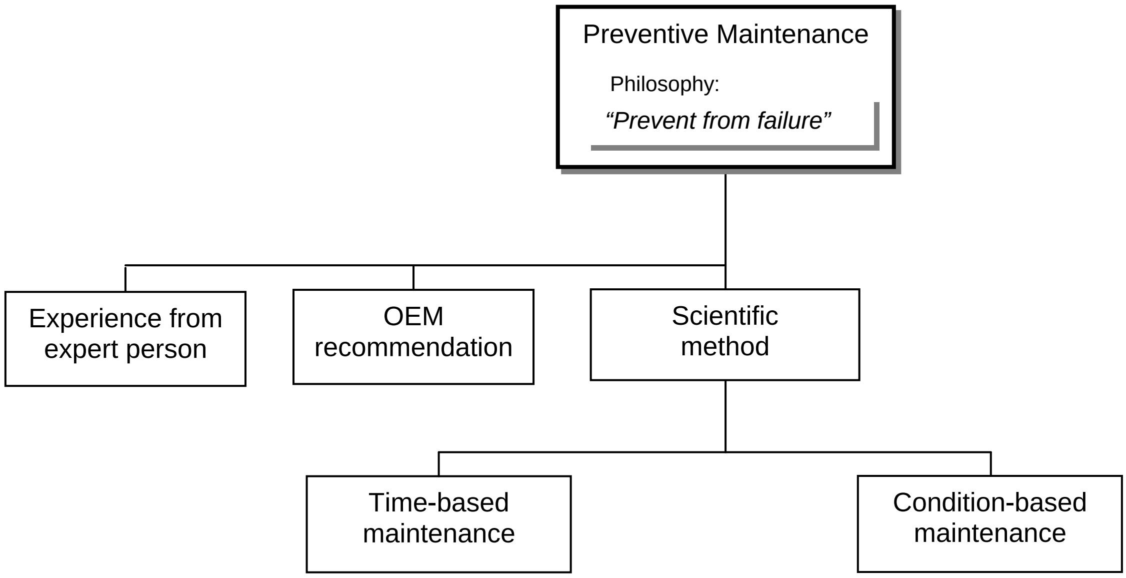

Figure 2.2: Preventive maintenance practices

2.3.1 PM based on Experience

The application of PM through experience is a conventional PM practice. In most cases, it is performed at regular time intervals, *T* (Sheu et al., 1995; Confield, 1986; Nakagawa, 1984). Through experience, no standard procedures are followed, thus knowledge from technicians and engineers for maintenance purposes is a valuable asset to the company. Technicians and engineers in this setting learn from previous mistakes and, based on their experience, are able to detect the abnormal conditions of a machine by sense. They can then decide the appropriate PM actions to apply in order to avoid machine breakdown. The main drawback of PM through experience, however, is that the company may face difficulties when the experienced person leaves the company. Moreover, such persons may not be in production lines round-the-clock to solve maintenance problems.

2.3.2 PM based on OEM Recommendation

Through OEM recommendations, PM is carried out at a fixed time, for example every 1,000 hours or every 10 days, based on recommendations. However, this PM practice is not usually applicable when attempting to minimise operation costs and maximise machine performance. Labib (2004) listed three reasons for this: First, each machine works in a different environment and would, therefore, need different PM schedules. Second, machine designers often do not experience machine failures and have less knowledge of their prevention compared to those who operate and maintain such machines. Finally, OEM companies may have hidden agendas, that is, maximising spare parts replacement through frequent PMs. This is supported by Tam et al. (2006), who stated that PM intervals based on OEM recommendations may not be optimal because actual operating conditions may be very different from those considered by the OEM. As such, actual outcomes may not satisfy company requirements.

2.3.3 PM based on Scientific Method

The application of PM based on scientific method was introduced since 1950 under operational research area. The scientific method involves specific processes and principles that employ various analytical techniques, such as statistics, mathematical programming, artificial intelligence, etc. The main advantage of PM practice based on the scientific method is that decision making is based on facts acquired through real data analysis. In the literature, PM based on the scientific method can be classified into two approaches: comprehensive-based and specific-based approaches. The comprehensive-based approach also known as maintenance concept development, which can be defined as a set of various maintenance interventions (experience-based, time-based, condition-based, etc.) and the general structure in which these interventions are foreseen (Pintelon and Wayenbergh, 1999). According to Wayenbergh and Pintelon (2002), maintenance concept development forms the framework from which installation-specific maintenance techniques are developed and is the embodiment of the way a company thinks about the role of maintenance as an operational function. Some examples of maintenance concepts are reliability-centred maintenance (RCM), business-centred maintenance, risk-based maintenance, total-productive maintenance (TPM), and the centre for industrial management maintenance concept development framework. The specific-based approach, as its name implies, is a specific maintenance approach that has unique principles for solving maintenance problems. Examples of specific-based approach are time-based maintenance (TBM) and condition-based maintenance (CBM).

- **Time-based Maintenance (TBM)**

Time-based maintenance, also known as periodic-based maintenance (Yam et al., 2001) is a traditional maintenance approach. In TBM, maintenance decisions (e.g., preventive repair times/intervals) are determined based on failure time analyses. In other words, the aging (expected lifetime), *T*, of some component is estimated based on failure time data or used-based data (Lee et al., 2006). TBM assumes that the failure behaviour (characteristic) of the component is predictable. This assumption is based on hazards or failure rate trends, known as bathtub curves, as shown in Figure 2.3.

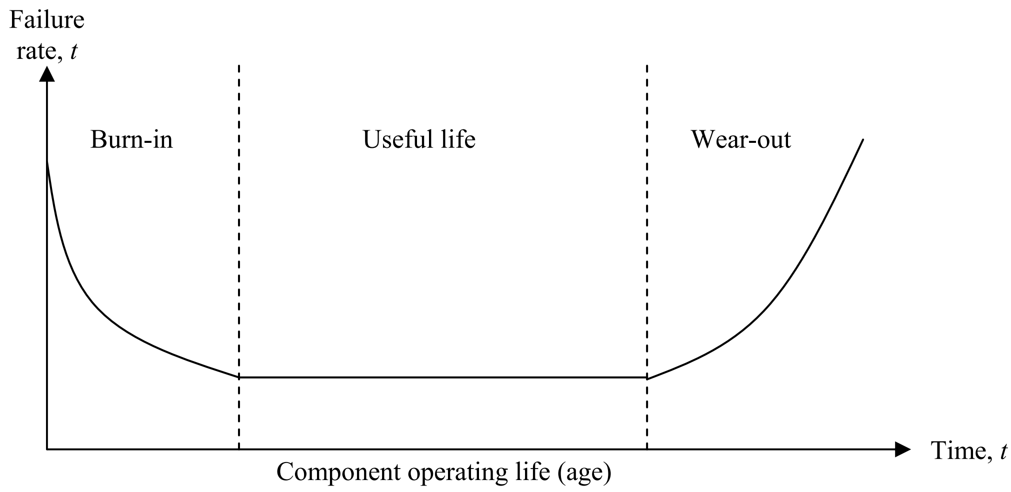

Figure 2.3: Bathtub curve [Ebeling, 1997]

As shown in Figure 2.3, failure rate trends can be divided into three phases: burn-in, useful life, and wear-out (Ebelling, 1997). The TBM approach assumes that component experience decreasing failure rates early in their life cycle (burn-in), followed by a near constant failure rate (useful life). At the end of their life cycles (wear-out), the component experiences increasing failure rates. The general process of TBM can be presented in two steps, shown in Figure 2.4.

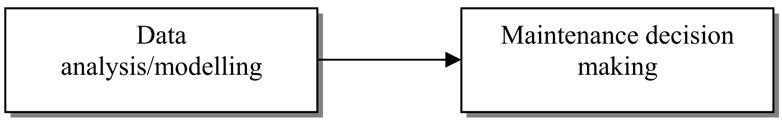

Figure 2.4: General TBM Process

The first process of TBM starts with failure data analysis/modelling. The basic purpose of this process is to statistically investigate the failure characteristics of the component based on the set of failure time data gathered. The detailed process of failure time data analysis/modelling is systematically shown in Figure 2.5.

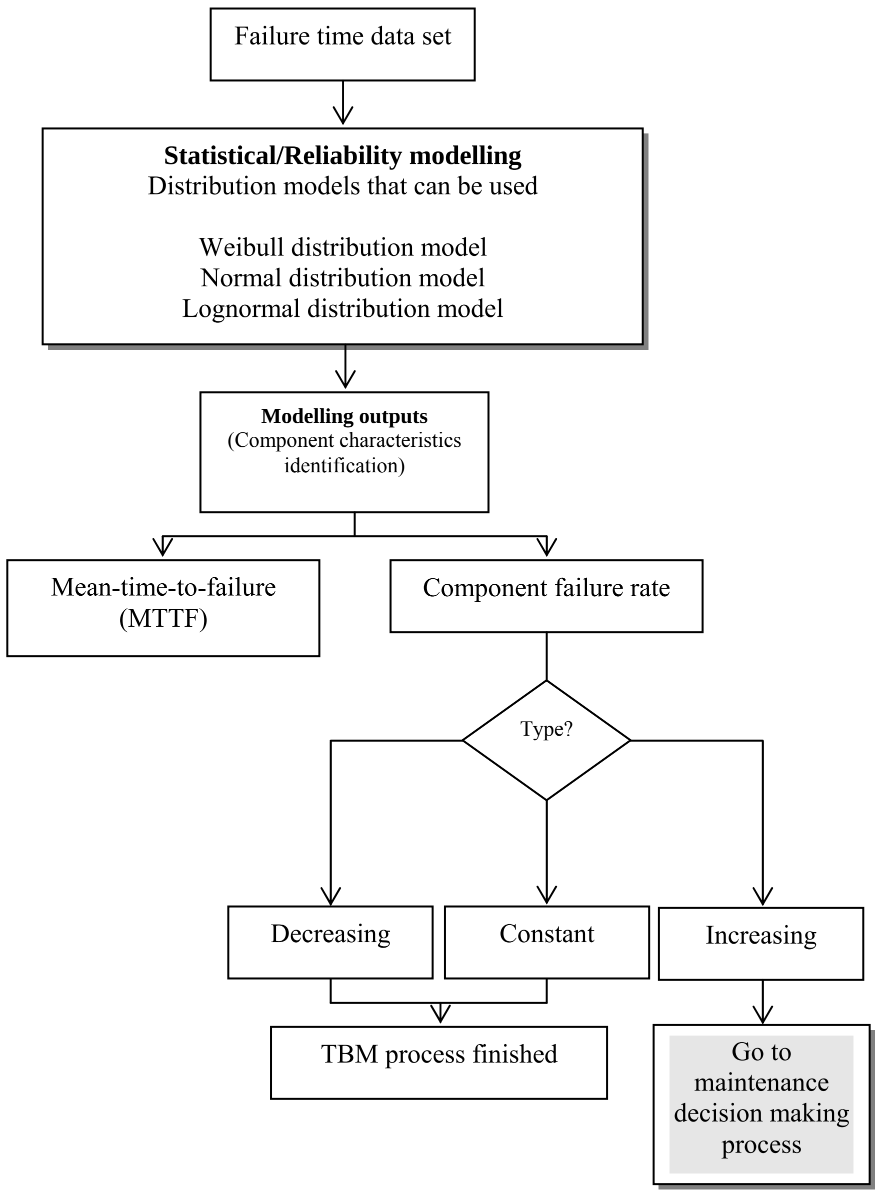

Figure 2.5: Failure data modelling process [summarised from Ebeling, 1997]

Once a set of failure time data has been gathered, it will be analysed further through statistical/reliability modelling to identify the failure characteristics of the component, including mean time to failure (*MTTF*) estimation and the trend of the component failure rate based on bathtub curve process. Statistical/reliability modelling can be carried out using various statistical tools, the most popular of which is through reliability theory using the Weibull distribution model (Ghodrati, 2005; Jóźwiak, 1997). The Weibull distribution model has been widely used to model the failures of many materials and in numerous other applications due to its ability to model various aging classes of life distributions, including increasing, decreasing, or constant failure rates (Bebbington et al., 2007). A detailed discussion of the Weibull distribution model is given in Ebeling (1997).

The Weibull distribution model is usually presented with two parameters: the scale parameter, θ, and the shape parameter, β. The scale parameter shows the lifetime (age) of the component, while the shape parameter presents the characteristics of the component lifetime, whether with a decreasing, constant, or increasing failure rate. The types of failure rates based on the Weibull distribution model can be presented by β, as shown below:

$\beta < 1$, represents a decreasing failure rate
$\beta = 1$, represents a constant failure rate
$\beta > 1$, represents an increasing failure rate

The value of the *MTTF* can then be determined using Eq. 1 below (Ebeling, 1997):

$$MTTF = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \qquad \text{-------------------------- (2.1)}$$

where $\Gamma(x)$ is the gamma function

Referring to Figure 2.5, only the component that has an increasing failure rate is considered for the next process (decision making process). This is because the optimal PM exists only if the component has an increasing failure rate distribution (wear-out stage).

The next process of TBM is the maintenance decision making process. The main objective of this process is to determine the optimal maintenance policies that aim to provide optimum system reliability or availability and safety performance at the lowest possible maintenance cost (Pham and Wang, 1996). Details of the maintenance decision making process are systematically shown in Figure 2.6.

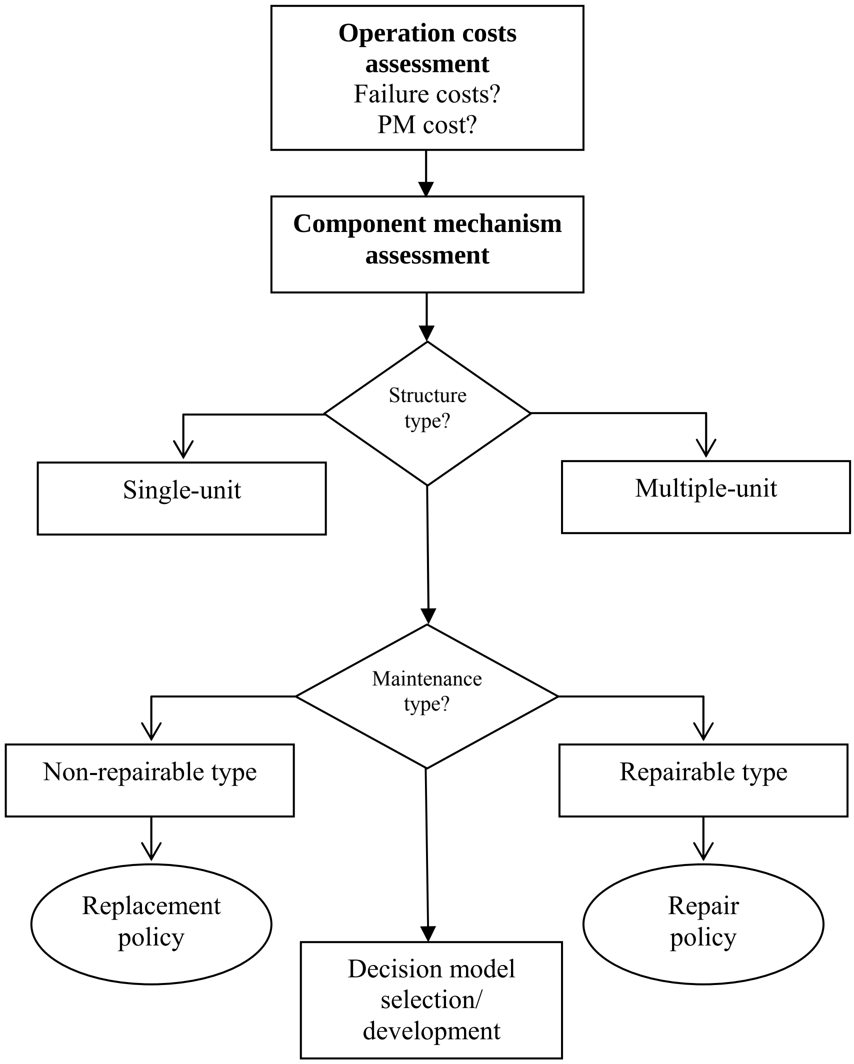

Figure 2.6: Maintenance decision making process of TBM [summarised from Dekker, 1996]

Referring to Figure 2.6, the maintenance decision making process is composed of two main assessments. The first is the operational cost assessment. The aim of this assessment is to calculate the two types of operational costs: failure cost and PM cost. These costs can be calculated as follows (Hu et al., 2009):

$$TC_{fc} = C_m + C_r + C_{dt} \qquad \text{--------------------------- (2.2)}$$

$$TC_{pm} = C_m + C_{dt} \qquad \text{--------------------------- (2.3)}$$

where

TC_{fc} = total failure cost

TC_{pm} = total PM cost

C_m = maintenance cost

C_r = product reject cost

C_{dt} = downtime cost

The next step in the maintenance decision making process is the component mechanism assessment. The aim of this assessment is to classify the structure type of the component as either non-repairable or repairable. The definitions of these structure types are as follows:

Repairable component is defined as one that can be repaired to recover its functions after each failure rather than be discarded (Crow, (1974). Meanwhile, non-repairable component is defined as the component that can not be repaired (only replace) once it failed, is discarded (as repair is physically not feasible or non-economical) (Louit et al., 2009)

After the structure of the component has been identified, the appropriate maintenance policy can be selected or developed. For non-repairable types, the replacement policy is used. One of the replacement policies is an age-dependent policy. Under this policy, a unit is always replaced at its age, *T*, or failure, whichever occurs first, with the replaced component assumed to be 'as-good-as new'. The most popular decision model under this policy in the literature is the age replacement model (ARM) (Handlarski, 1980; Aven and Jensen, 1999). The general mathematical model of ARM, which was developed by Barlow and Hunter (1960), is presented in Eq. 2.4. The main objective of this model is to determine *T* by minimising the cost function *C(T)*.

$$\min : C(T) = \frac{C_f F(T) + C_p R(T)}{\int_0^T R(t)dt} \qquad \text{-------------------------- (2.4)}$$

where

C(T) = cost function at time, *T*

T = optimum time of replacement

C_f = cost of failure replacement

C_p = cost of preventive replacement

F(T) = cumulative distribution function

R(T) = reliability function

For repairable component, a repair policy (also known as minimal repair policy) is applied. This policy addresses the appropriate times to perform repairs and replace component. The basic repair policy model was first given by Barlow and Hunter (1960), as shown in Eq. 2.5, where $g_m(t)$ is the long-run expected cost