

**Development of Practical Opportunistic Maintenance (OM) Policy  
Based Model for Manufacturing System**

**by**

**HASNIDA BINTI AB SAMAT**

**Thesis submitted in fulfilment of the  
requirements for the degree  
of Doctor of Philosophy**

**OCTOBER 2015**

**DEVELOPMENT OF PRACTICAL  
OPPORTUNISTIC MAINTENANCE (OM)  
POLICY BASED MODEL FOR  
MANUFACTURING SYSTEM**

**HASNIDA BINTI AB SAMAT**

**UNIVERSITI SAINS MALAYSIA  
2015**

## **ACKNOWLEDGEMENT**

IN THE NAME OF ALLAH, THE MOST GRACIOUS AND MOST MERCIFUL

In humility, thank you Allah for allowing me to complete this dissertation. The research work presented in this thesis has been carried out at the School of Mechanical Engineering, Universiti Sains Malaysia (USM). I dedicated this work to my beloved parent and siblings who always encourage and motivate me in many ways. I have been blessed with their love, inspiration, and support. It is a pleasure to acknowledge all these people.

First of all, I would like to express my deep gratitude and convey my sincere thanks to my supervisor Assoc. Prof Dr. Shahrul Kamaruddin for his thoughtful supervision, steady support, guidance, and critics throughout the course of this work. I am also thankful for his comments to improve the dissertation and the content of the research work. I also wish to thank the case study company, especially the maintenance department and its personnel, for their cooperation and discussions throughout the case study. Their comments and cooperation were crucial for the success of this research.

Special thanks to my colleagues for their fruitful ideas and comments. Everyone's assistances and encouragements help in many ways. I am also thankful for their generosity both of time and spirit. Lastly, I am indebted to every individual whom involve directly or indirectly throughout this research. Their relevant and constructive comments, and the encouragement during my research period are very much appreciated. Thank you for always being there and making this pursuit a valuable journey.

## TABLE OF CONTENTS

	<b>Page</b>
<b>ACKNOWLEDGEMENT</b>	ii
<b>TABLE OF CONTENTS</b>	iii
<b>LIST OF TABLES</b>	x
<b>LIST OF FIGURES</b>	xii
<b>LIST OF SYMBOLS</b>	xv
<b>LIST OF ABBREVIATIONS</b>	xvi
<b>ABSTRAK</b>	xviii
<b>ABSTRACT</b>	xx
<b>CHAPTER 1: INTRODUCTION</b>	
1.0 Overview	1
1.1 Maintenance System	1
1.2 Optimal Maintenance System with Opportunistic Maintenance (OM) Policy	5
1.3 Problem Statement	7
1.4 Research Aim and Objectives	9
1.5 Research Scope/Focus	10
1.6 Thesis Outline	11
<b>CHAPTER 2: LITERATURE REVIEW</b>	
2.0 Overview	13
2.1 Maintenance Approaches and Policies	13

2.2	Research Trends and Monikers for Opportunistic Maintenance (OM) Policy	22
2.3	Genealogy of Opportunistic Maintenance (OM) Policy	28
2.3.1	Age Replacement Policy (ARP)	28
2.3.2	Block Replacement Policy (BRP)	29
2.4	Principle and Concept of Opportunistic Maintenance (OM) Policy	31
2.5	Focus and Aim of Opportunistic Maintenance (OM) Policy	32
2.6	Classification of Literatures on Opportunistic Maintenance (OM) Policy	33
2.6.1	Classification from the Type of System Perspective	34
2.6.2	Classification from the Type of Research Approach Perspective	37
2.6.3	Classification from the Performance Measures Perspective	41
2.7	Application of Opportunistic Maintenance (OM) Policy in Industry	45
2.8	Optimal Maintenance System using Opportunistic Maintenance (OM) Policy	51
2.9	Literature Findings	55
2.10	Chapter Summary	60

### **CHAPTER 3: RESEARCH METHODOLOGY**

3.0	Overview	61
3.1	Review of Optimal Maintenance System and Opportunistic Maintenance (OM) Policy	61
3.2	Model Development Process	63
3.3	Model Verification and Validation	65
3.3.1	Model Verification Processes	66

3.3.2	Model Validation Processes	67
3.4	Chapter Summary	69

## **CHAPTER 4: DEVELOPMENT OF OPPORTUNISTIC PRINCIPLE TOWARDS OPTIMAL MAINTENANCE SYSTEM (OPTOMS) MODEL**

4.0	Overview	70
4.1	Focus and Motivation of OPTOMS Model	70
4.2	Phase I: Identification of Maintenance Objective Based on Company's Mission and Vision	74
4.2.1	Step 1: Mission and Vision Statement Identification	75
4.2.2	Step 2: Maintenance Objective Determination Using Check Sheet	78
4.3	Phase II: Prioritization of System/Machine	84
4.3.1	Step 1: Scheduled and Unscheduled Downtime Identification and Segregation	85
4.3.2	Step 2: Total Machine Downtime Calculation	89
4.3.3	Step 3: Critical Machine Prioritization	89
4.4	Phase III: Assessment of Preventive Maintenance (PM) Activities and Failure Analysis	91
4.4.1	Step 1: Preventive Maintenance Plan and Checklist Assessment	92
4.4.2	Step 2: Failure, Causes and Effects Analysis	94
	(a) Failure Modes Identification	98
	(b) Failure Effects Identification	98
	(c) Failure Causes Identification	98

	(d) Maintenance Action Identification	99
4.5	Phase IV: Opportunistic Maintenance (OM) Principle and Rule Selection	101
4.5.1	Step 1: Component Proximity for PM Plan Selection	101
4.5.2	Step 2: Opportunities Principle Decision	107
	(a) OM Policy Assumption	108
	(b) OM Policy Limitation	109
4.6	Phase V: Measurement and Control of Optimal Maintenance System (OMS)	110
4.6.1	Step 1: Data Collection Based on Maintenance Objective	113
	(a) Analysis of Objective 1: System Availability	114
	(b) Analysis of Objective 2: Machine/Component Reliability	116
	(c) Analysis of Objective 3: Maintenance Cost	118
4.6.2	Step 2: Means of Variance Calculation	121
4.6.3	Step 3: Standard Deviation, Upper Control Limit (UCL) and Lower Control Limit (LCL) Setting	121
4.6.4	Step 4: X-bar of Control Chart Construction	123
4.6.5	Step 5: Performance of Maintenance System Observation	124
4.7	Chapter Summary	125
 <b>CHAPTER 5: CASE STUDY</b>		
5.0	Overview	126
5.1	Case Study and Company Background	126
5.2	Verification Stage 1: Maintenance Objective Identification from Company's Mission and Vision	129

5.3	Verification Stage 2: Critical Machine Selection and Analysis of Preventive Maintenance and Failures	132
5.3.1	Critical Machine Selection	133
5.3.2	Analysis of PM Planning and Checklist	140
5.3.3	Analysis of Failures	149
	(a) Failure Modes Identification	149
	(b) Failure Effects Identification	150
	(c) Failure Causes Identification	150
	(d) Maintenance Action Conducted	151
5.4	Verification Stage 3: Optimal Maintenance System Using Opportunistic Maintenance (OM) Policy	154
5.4.1	Identification of PM activities based on Component Proximity	155
5.4.2	Observation on OM Assumptions	159
5.4.3	Observation on OM Limitations	162
5.5	Verification Stage 4: Control of Optimal Maintenance System	163
5.5.1	Data Collection for Maintenance Cost	166
5.5.2	Calculation of Means of Variance	173
5.5.3	Calculation of Standard Deviation, Upper Control Limit (UCL) and Lower Control Limit (LCL)	174
5.5.4	Construction of X-Bar	176
5.5.5	Maintenance System Observation Using Control Chart	177
5.6	Validation Process 1: OPTOMS Model in Single Component System	179
5.6.1	Critical Machine Selection	180
5.6.2	PM Activities and Failure Analysis	182



5.6.3	OM Policy Principles and Rules	189
5.6.4	Maintenance Performance Measurement	196
5.7	Validation Process 2: OPTOMS Model in Multi-Component System	201
5.7.1	Critical Machine Selection	202
5.7.2	Observation in Preventive Maintenance (PM) Planning and Failure Analysis	205
5.7.3	OM Policy Principle and Rules Application	219
5.7.4	Maintenance Performance Measurement	222
5.8	Chapter Summary	226

## **CHAPTER 6: DISCUSSION**

6.0	Overview	227
6.1	Notable Points of OPTOMS Model	227
6.1.1	Points from Concept Perspective	228
	(a) Components in a system are dependent on one another	228
	(b) The failure of a component is an opportunity for maintenance for another component	230
	(c) Optimal maintenance system with Component proximity	232
6.1.2	Points from Structure Perspective	234
	(a) Input, process and output function for each phase	235
	(b) Adoption of practical tools and methods for data analysis	237
6.2	Model Verification and Validation	239
6.2.1	Model Verification	239
6.2.2	Model Validation	242
6.3	Managerial Implication	246

6.4	Chapter Summary	249
-----	-----------------	-----

## **CHAPTER 7: RESEARCH CONCLUSION**

7.0	Overview	250
7.1	Concluding Remarks	250
7.2	Research Contributions	256
7.3	Future Work	258

<b>REFERENCES</b>		260
-------------------	--	-----

## **APPENDICES**

Appendix A	Assumptions When Applying Opportunistic Maintenance (OM) Policy
Appendix B	Machine Downtime At Cluster 3: Circuit Finishing Cluster (January – December)
Appendix C	PM Schedule For Cluster 3: Circuit Finishing (January – December)
Appendix D	Machine Downtime At Cluster 1: Back-End (January – December)
Appendix E	PM Schedule For Cluster 4: Back-End (January – December)
Appendix F	Machine Downtime At Cluster 1: Circuit Formation (January – December)
Appendix G	PM Schedule For Cluster 1: Circuit Formation (January – December)

## **LIST OF PUBLICATIONS**

## LIST OF TABLES

	<b>Title</b>	<b>Page</b>
Table 2.1	List of monikers used in publications on Opportunistic Maintenance from 1963 till 2015	24
Table 2.2	Tabulation of publications about opportunistic maintenance based on type of production system	36
Table 2.3	Research approach classifications of publications on OM	39
Table 2.4	Classification of references based on optimal criteria's used	43
Table 4.1	Features of mission and vision statement	78
Table 4.2	Check Sheet to identify maintenance objective	83
Table 4.3	Difference between scheduled and unscheduled downtime	86
Table 4.4	Form for daily downtime tracking system	88
Table 4.5	Downtime collection form	89
Table 4.6	Example of PM checklist	94
Table 4.7	Example of FMEA checklist for failure of capillary screw	100
Table 4.8	Terms and definitions in FBD ( <i>Source: Benjamin and Fabrycky, 2006</i> )	106
Table 5.1	Check Sheet for Identification of maintenance objective based on company's mission and vision	131
Table 5.2	The unscheduled downtime recorded by the machines in the Circuit Finishing cluster (Jan 11-Dec 11)	135
Table 5.3	Scheduled and unscheduled downtime collection for Cluster 3 – Circuit Finishing in January until December 2011	138
Table 5.4	PM Schedule for OKUNO machine (No. 186 and Equipment No. 8039)	142
Table 5.5	PM checklist for Auto Electrolytic Copper Plating (OKUNO) Machine	143
Table 5.6	PM checklist for Auto Electrolytic Copper Plating (OKUNO) Machine	144
Table 5.7	Daily Maintenance Checklist for the OKUNO machine in Cluster 3	146
Table 5.8	FMEA worksheet for failures on the OKUNO machine	152
Table 5.9	List of assumptions and observations in Company A	160

	<b>Title</b>	<b>Page</b>
Table 5.10	List of limitations and observations in Company A	162
Table 5.11	Unscheduled downtime record for 3 in 1 Gold Line Machine for one year	169
Table 5.12	Frequencies and costs of scheduled and unscheduled downtime for 3-in-1 Gold Line machine	173
Table 5.13	A sample of PM checklist for Hitachi # 1, # 2 and #3	183
Table 5.14	FMEA worksheet for failures of the HMS machine	186
Table 5.15	Unscheduled downtime for Hitachi machines for a year	192
Table 5.16	Values of MTBF and reliability at Hitachi #1 machine	198
Table 5.17	Weekly and monthly PM checklist for HMS (etching and stripping) machine	208
Table 5.18	PM checklist for HMS (developing) machine	208
Table 5.19	Daily PM checklist for HMS (Etching) machine	210
Table 5.20	Weekly PM checklist for HMS (Etching) machine	211
Table 5.21	Unscheduled downtime for HMS machines in a year	215
Table 5.22	FMEA worksheet for failures on the HMS machines	217
Table 5.23	Production time, downtime and availability at HMS machine	223

## LIST OF FIGURES

	<b>Title</b>	<b>Page</b>
Figure 1.1	Characteristics of optimal maintenance system	6
Figure 2.1	Types of maintenance approaches	14
Figure 2.2	Classification of maintenance strategies and policies in publication by Khazraei & Deuse (2011)	20
Figure 2.3	Prospective maintenance approach	21
Figure 2.4	Number of publications on opportunistic maintenance from 1963 to 2015	23
Figure 2.5	Percentage of publications based on system type in OM research	35
Figure 2.6	Percentage of publications based on research approaches in OM research	38
Figure 2.7	Percentage of publications based on various optimal criteria's in OM research	42
Figure 2.8	Elements in conceptual analysis of OM policy	56
Figure 2.9	Three groups of literatures classification	57
Figure 2.10	Four types of research paper	58
Figure 3.1	The five phases of OPTOMS model	63
Figure 3.2	The four stages in model verification process	66
Figure 3.3	Focuses and objectives in validation process	68
Figure 4.1	Concepts of OM policy	71
Figure 4.2	The flow of OPTOMS model	73
Figure 4.3	Relation between corporate strategy, vision, mission and objective with maintenance strategic plan (Source: Al-Turki, 2011)	75
Figure 4.4	Characteristics of a company's mission and vision	77
Figure 4.5	Transformation of corporate mission and vision into maintenance objective	79
Figure 4.6	Three main optimal measures for maintenance and its elements	82
Figure 4.7	Stacked bar chart for both scheduled and unscheduled downtime	90

	<b>Title</b>	<b>Page</b>
Figure 4.8	Basic FMEA process flow	96
Figure 4.9	Opportunistic zone in OM policy ( <i>Source: Koochaki et al., 2012</i> )	102
Figure 4.10	Opportunistic Maintenance (OM) policy ( <i>Source: Pham and Wang, 2000</i> )	102
Figure 4.11	Basic Functional Block Diagram (FBD). ( <i>Source: Benjamin and Fabrycky, 2006</i> )	105
Figure 4.12	First indenture FBD. ( <i>Source: Benjamin and Fabrycky, 2006</i> )	106
Figure 4.13	Second indenture FBD. ( <i>Source: Benjamin and Fabrycky, 2006</i> )	107
Figure 4.14	Steps in developing Control Chart for maintenance system's performance measurement	113
Figure 4.15	Maintenance objectives and its performance measurement factor	114
Figure 4.16	Direct and indirect cost when conducting maintenance	120
Figure 4.17	Example of X-bar chart in Control Chart	124
Figure 5.1	The processes for FPC manufacturing in Company A	128
Figure 5.2	Overall flow of circuit board manufacturing processes divided into four clusters	129
Figure 5.3	Unscheduled downtime frequency of machines at Cluster 3 from January until December	135
Figure 5.4	Unscheduled downtime duration of machines at Cluster 3 from January until December	136
Figure 5.5	Stacked bar chart for scheduled and unscheduled downtime	139
Figure 5.6	List of components in OKUNO and periods of its checked during PM	147
Figure 5.7	FBD of components and subcomponents at the OKUNO machine	158
Figure 5.8	Timeline of scheduled downtime or PM activities in 2011 for 3-in 1-Gold Line machine for the whole year	168
Figure 5.9	Timeline of unscheduled downtime dates for 3 in 1 Gold Line machine for the whole year	171
Figure 5.10	Control Chart for maintenance cost in 3-in-1 Gold Line machine	177

	<b>Title</b>	<b>Page</b>
Figure 5.11	Total machine downtime at Drilling Department for 12 months period	181
Figure 5.12	Scheduled downtime for weekly, monthly and yearly PM schedules for Hitachi machine	184
Figure 5.13	List of components mentioned in PM checklist and FMEA form	189
Figure 5.14	FBD of critical components in Hitachi #2 machine	191
Figure 5.15	Unscheduled machine downtime at Hitachi #1, #2 and #3 for January until December	193
Figure 5.16	The Bathtub Curve. Sources: (Dhillon, 1999)	194
Figure 5.17	Control chart of reliability of Hitachi #1 machine when failures occur	200
Figure 5.18	Total unscheduled downtime in a 12 months period at all four clusters in Company A	202
Figure 5.19	Total unscheduled downtime on the machines in Wet-process from January until December	204
Figure 5.20	HMS machines in Wet-process in Cluster 1: Circuit Formation	206
Figure 5.21	Daily, weekly, monthly and yearly PM activities scheduled for HMS machine	213
Figure 5.22	Timeline of unscheduled downtime at HMS machines	215
Figure 5.23	Lists of components mentioned in PM checklist and FMEA form	220
Figure 5.24	The FBD of critical and sub-components in HMS machines	221
Figure 5.25	Control chart for machine availability at the HMS machine	225
Figure 6.1	Three notable concepts from OM policy in OPTOMS model	233
Figure 6.2	Input, processes and output in OPTOMS model	235
Figure 6.3	Two types of system for model validation processes	243

## LIST OF SYMBOLS

$\delta$	Number of working days
$C_c$	Cost of CM task conducted.
$C_p$	Cost of PM task conducted
$n_c$	Number of CM task conducted
$n_p$	Number of PM task conducted
$\mu$	Means of Variance
$C$	Maintenance Cost
$f$	Failure
$n$	Number of measurements conducted
$p$	Probability
$T$	Time failure of the machine (component)
$t$	Time
$T_{act}$	Actual production time
$T_{pdt}$	Planned downtime
$T_{plan}$	Planned production time
$T_{updt}$	Unplanned downtime
$X_i$	individual measurements
$\sigma$	Standard Deviation

## LIST OF ABBREVIATIONS



ARP	Age Replacement Policy
BRP	Block Replacement Policy
CBM	Condition Based Maintenance
CDF	Cumulative Distribution Function
CL	Centre Line
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management System
DDTS	Daily Downtime Tracking System
FBD	Functional Block Diagram
FMEA	Failure Mode and Effect Analysis
LCL	Lower Control Limit
MORT	Management Overnight and Risk Tree
MTBF	Mean Time Between Failures
OEMs	Original Equipment Manufacturers
OM	Opportunistic Maintenance
OMISSYS	Opportunistic Model-based Diagnosis System
OMS	Optimal Maintenance System
OPTOMS	Opportunistic Principle towards Optimal Maintenance System
PCB	Printed Circuit Board
PdM	Predictive Maintenance
PDT	Planned Downtime
PM	Preventive Maintenance
RCM	Reliability Centred Maintenance
RPN	Risk Priority Number

SMT	Surface-Mount Technology
SPC	Statistical Process Control
TPM	Total Productive Maintenance
UCL	Upper Control Limit
UPDT	Unplanned Downtime
WIP	Work In Progress

# **PEMBANGUNAN MODEL YANG PRAKTIKAL BERDASARKAN POLISI PENYENGGARAAN OPORTUNIS UNTUK SISTEM PEMBUATAN**

## **ABSTRAK**

Penyenggaraan dijalankan untuk memastikan bahawa semua peralatan di dalam sebuah syarikat dibaiki, diganti, diselaraskan dan diubah suai mengikut keperluan pengeluaran. Sistem penyenggaraan yang berkesan dan dioptimumkan amat diperlukan di dalam sistem pembuatan pada hari ini. Dengan kemajuan teknologi dan kerumitan sistem, terdapat satu pendekatan baru yang dipanggil penyenggaraan prospek di mana polisi ini adalah 'penyenggaraan oportunis' (OM). OM boleh ditakrifkan sebagai aktiviti penyenggaraan yang dijalankan untuk membaiki komponen yang rosak dan pada masa yang sama menggunakan peluang yang ada untuk membaiki / menggantikan komponen lain di dalam sistem dengan tujuan untuk mengelakkan kegagalan pada masa hadapan dan mengurangkan bilangan masa henti mesin. Ia adalah gabungan penyenggaraan membetul (CM) yang digunakan apabila sebarang kegagalan berlaku, dengan penyenggaraan cegahan (PM) –pendekatan penyenggaraan yang dirancang dan dijadualkan untuk mencegah kegagalan berlaku. Apa-apa pemberhentian mesin kerana kegagalan adalah 'peluang' untuk menjalankan PM. Walau bagaimanapun, cabaran untuk mencapai sistem penyenggaraan yang optimum menggunakan dasar OM adalah untuk mencari keseimbangan yang optimum antara kos penyenggaraan dan umur komponen umur mesin dan ciri-ciri kebolehpercayaan. Tahun demi tahun, penyelidikan yang telah diterbitkan berkisar tentang seluruh teori konsep dan analisis berangka polisi tetapi kekurangan model yang realistik dan praktikal untuk penggunaan. Fokus kajian ini adalah menjurus ke arah isu-isu penggunaan OM dalam mencapai sistem penyenggaraan yang optimum. Berdasarkan pengenalan gagasan prinsip, konsep dan

ciri-ciri dasar OM, sebuah model membuat keputusan telah dibangunkan. Dengan akronim sebagai OPTOMS untuk Opportunistic Policy towards Optimal Maintenance System, model ini dibangunkan dalam lima fasa dengan penggunaan Check Sheet dan Stacked-Bar Chart untuk fasa pemilihan mesin, Failure Mode and Effect Analysis (FMEA) untuk analisis kegagalan dan Control Chart untuk fasa pengukuran prestasi. Di dalam model ini, prinsip OM dikaji dan dibangunkan menjadi set peraturan dengan beberapa batasan dan andaian untuk disesuaikan dengan dasar ke dalam persekitaran praktikal. Butiran perbincangan disediakan untuk membuat OM dasar dengan sebaik mungkin dalam mencapai sistem penyenggaraan yang optimum. Model ini disemak dan disahkan di sebuah syarikat semikonduktor. Hasil kajian kes ini mengesahkan penggunaan dan amali model OPTOMS sebagai sistem sokongan keputusan dalam mengguna pakai dasar OM. Model yang dibangunkan ini membantu syarikat dalam perancangan dan penjadualan aktiviti penyenggaraan bagi mengurangkan kos dan masa henti mesin serta meningkatkan kebolehsediaan dan keboleharapan mesin sehingga 20%.

# **DEVELOPMENT OF PRACTICAL OPPORTUNISTIC MAINTENANCE (OM) POLICY BASED MODEL FOR MANUFACTURING SYSTEM**

## **ABSTRACT**

Maintenance is conducted to ensure that all equipment in a company are repaired, replaced, adjusted and modified according to production requirements. Effective and optimized maintenance system are highly acquired in today's manufacturing system. With the advancement of technologies and complexity of systems, there is a new maintenance approach called prospective maintenance where the policy is 'opportunistic maintenance' (OM). OM can be defined as maintenance activities that are conducted to repair a component and at the same time opportunistically repair/replace other components in the system with the aim to avoid future failures and reduce the number of machine downtime. It is the combination of corrective maintenance (CM) which is applied when any failure occurred, with preventive maintenance (PM) -a planned and scheduled maintenance approach to prevent failure to happen. Any machine stoppage due to failure is the 'opportunity' to conduct PM. However, the challenge to achieve optimal maintenance system using OM policy is to find a balanced trade-off between maintenance cost and component or machine age and reliability features. Throughout the years, literatures that had been published lingers around conceptual theory and numerical analysis of the policy yet in the realistic and practical model for the application is lacking. The focus of this research is directed towards the issues of OM application in achieving optimal maintenance system. Based on conceptual identification of principle, concept and characteristics of OM policy, a decision making model was developed. With the acronyms of OPTOMS for Opportunistic Policy towards Optimal Maintenance System, the model was developed in five phases with the usage of Check Sheet and

Stacked-Bar Chart for machine selection phase, Failure Mode and Effect Analysis (FMEA) for failure analysis and Control Chart for performance measurement phase. In this model, OM principle are studied and developed into a set of rules with some limitations and assumptions to suit the policy into practical environment. Detail discussions were provided to make OM as a practical policy in achieving optimal maintenance system. The model is validated and verified in a semiconductor company. The outcomes of this case study confirmed the application and practicality of the OPTOMS model as a decision support system in applying OM policy. The developed model helps the company to plan and to schedule maintenance activities in reducing cost and machine downtime as well as increasing up to 20% of its machine availability and reliability.

# **CHAPTER 1**

## **INTRODUCTION**

### **1.0 Overview**

The first chapter is written and structured in six sections as to provide the general idea of what, why, where, who and how this research has been conducted. The first section gives an overview of maintenance system as the research field and issues that commonly arise. The second section introduces the theoretical principle of Opportunistic Maintenance (OM) as an effective and optimal maintenance policy. Then, the third section highlighted some issues in OM policy as the problem statement studied in this research. Subsequently, the fourth section deals with the research motivation under the aims and objectives section. The fifth section includes the research focus and limitations. Finally, to show the overall structure, section six highlights the contents of each chapter of this thesis.

### **1.1 Maintenance System**

The concise translation of the word maintenance from British Standard BS 3811:1993 “Glossary of Terms in Terotechnology” is, “the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function” (Maintenance Management, 2015). Maintenance is conducted to ensure that all equipment in the company is repaired, replaced, adjusted and modified according to production requirements. This way, the whole manufacturing processes are guaranteed to have an effective and efficient operation (Arts et al., 1998; Parida and Kumar, 2006).

In recent years, maintenance is commonly viewed as a value-adding activity instead of as 'necessary evil' for expenses like in the past (Ben-Daya and Duffua, 1995; Al-Turki, 2011). Even though maintenance system is not related directly to the processes in product manufacturing, Alsyouf (2007) presented the scenario of an effective maintenance system with the result of less unplanned stoppages, better product quality, less production stoppages, etc. The author argued that the manufacturing cost will definitely be reduced and the company's profit will increase. The good product quality image due to higher customer satisfaction, then will lead to an increase of a product's price. At the end, the company will experience the increase in their productivity and profit.

The maintenance role in today's manufacturing system is also becoming more important as companies start to adopt the system as one of its profit generating elements (Waeyenbergh and Pintelon, 2002; Sharma et al., 2011). The measured performance of maintenance system in a company will signify the current business condition of the organization to determine its successful direction (Kutucuoglu et al, 2001). However, based on the research conducted by Mobley (1990), cited by Chan et al. (2005), 15 to 40% of total production cost is spent for maintenance activities. On the other hand, Bevilacqua and Braglia, (2000) stated that maintenance cost can reach 15-70% of production costs, varying according to the type of industry. Consequently, further research by Wireman (2003) showed that up to 33% of this maintenance cost is actually wasted or spent unnecessarily. These percentages show a lot of improvements could be carried out in achieving effective and optimized maintenance system.

Effective maintenance is imperative as large losses of profit can be attributed to machine breakdown and downtime during operation (Waeyenbergh and Pintelon,