INTEGRATION OF OVERALL EQUIPMENT EFFECTIVENESS (OEE) AND RELIABILITY FOR MEASURING MACHINE EFFECTIVENESS

by

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

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l	Failure rate
z	Failure ratio
d	Number of working days
a	Number of product processed
A*eff*	Availability effectiveness
C	Cumulative percentage
D	Ability to be detected
f(t)	Number of failure occurrences
F(t)	Probability that a failure occurs before time t
L	Total losses occurrences
LA	Availability losses
LO	Losses occurrences percentage
LP	Performance losses
l_X	Breakdown losses occurrences
l_Y	Setup and adjustment losses occurrences
l_Z	Idling and minor stoppages losses occurrences
ME	Machine effectiveness
O	Occurrences
P	Performance
p	Probability
P*eff*	Performance effectiveness
RPN	Risk priority number
S	Severity

t’	Daily production time (minutes)
t	Time
T*act*	Actual production time
T*net*	Net production time
T_{pdt}	Planned downtime
T*plan*	Planned production time
T*tc*	Theoretical cycle time
T_{updt}	Unplanned downtime
X	Breakdown losses
Y	Setup and adjustment losses
Z	Idling and minor stoppages losses

LIST OF ABBREVIATION

AMP	Asset Management Planner
APT	Assembly Process Traveller
BSC	Balanced-Score Card
CDF	Cumulative Distribution Function
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management System
CUBES	Capability Utilization Bottleneck Efficiency Systems
CWBT	Copper Wire Bonding Team
DEA	Data Envelopment Analysis
DFN	Dual Flat-Pack-No-Lead
DMR	Daily Maintenance Record
DTLS	Downtime Tracking Log Sheet
EFO	Electronic Flame Off
EOL	End of Line
EPR	Equipment Performance and Reliability
FAB	Free Air Ball
FBD	Functional Block Diagram
FMEA	Failure Mode and Effect Analysis
FOL	Front of Line
HI	Health Index
KPIs	Key Performances Indicators
MDIP	Molded Dual-In-Line Package
ME	Machine Effectiveness

MP	Machine Performance
MORT	Management Overnight and Risk Tree
MS	Manufacturing Specialist
MTBA	Mean Time Between Assist
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NEE	Net Equipment Effectiveness
NHS	National Health Service
NSOL	Non-stick on Lead
NSOP	Non-stick on Pad
OEE	Overall Equipment Effectiveness
OFE	Overall Fab Effectiveness
OLE	Overall Line Effectiveness
OMP	Overall Manufacturing Performance
OSE	Overall Section Effectiveness
PDF	Probability Density Function
PdM	Predictive Maintenance
PDT	Planned Downtime
PLCC	Plastic Leaded chip Carrier
PM	Preventive Maintenance
PMC	Post-Moulding Cure
QA	Quality Assurance
QFD	Quality Function Deployment
QFN	Quad Flat-Pack-No-Lead
QMPMS	Quantitative Model for Performance Measurement System

R&D	Research and Development
RCM	Reliability Centred Maintenance
RPN	Risk Priority Number
SGC	Silicon Graphic Crimson
SOIC	Small Outline Integrated Circuit
TPM	Total Productive Maintenance
TSOP	Thin Small Outline Package
UPDT	Unplanned Downtime
UPH	Unit Processing Hours
VSOP	Very Small Outline Package

LIST OF APPENDIXES

LIST OF PUBLICATIONS

1. Abdul Samat, H. and Kamaruddin, S. (2006). 'A Road Map towards ISO 9001:2000 Accreditation for Small and Medium Enterprises (SMEs)', *International Conference on Science and Technology: Applications in Industry and Education (2006)*, Universiti Teknologi MARA, Penang, Malaysia. [8-9 December 2006].

2. Abdul Samat, H. and Kamaruddin, S., (2008). Lean Maintenance (LM) – A New Addition to Maintenance Family, *Proceeding of International Conference on Plant Equipment and Reliability* (ICPER 2008), Sunway. [27 -28th of March 2008]

3. Abdul Samat, H. and Kamaruddin, S., (2008). Reliability in Overall Equipment Effectiveness (OEE): Its Roles and Plausibility, *Proceeding of International Conference on Plant Equipment and Reliability* (ICPER 2008), Sunway. [27 -28th of March 2008]

4. Abdul Samat, H., Kamaruddin, S. and Abd. Azid, I., (2008). Measuring Equipment Effectiveness and Reliability, *Proceeding of 8th Mechanical Engineering Research Colloquium* (MERC 2008), Nibong Tebal. [27th of August 2008]

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INTEGRASI KAEDAH OVERALL EQUIPMENT EFFECTIVENESS (OEE) DAN KEBOLEHPERCAYAAN MESIN UNTUK MENGUKUR KEBERKESANAN MESIN

ABSTRAK

Kepentingan sistem penyelenggaraan dapat dilambangkan dengan undang-undang Murphy yang mengatakan bahawa "Setiap benda akan mengalami kegagalan dalam apa jua situasi, jika diberi kesempatan". Penyelengaraan dilakukan bertujuan untuk menghapuskan kegagalan, mengurangkan masa apabila mesin rosak, meminimumkan kos pengeluaran dan meningkatkan tahap pengeluaran. Penyelengaraan adalah salah satu fungsi dalam pengurusan aset, dan ia meliputi penggunaan sumber seperti manusia, maklumat, bahan, dan modal yang tepat untuk memastikan bahawa peralatan, mesin, bangunan dan kilang diperbaiki, diganti, disesuaikan, dan diubahsuai untuk memastikan ia beroperasi pada prestasi dan masa yang ditetapkan. Oleh kerana itu penyelenggaraan perlu dilakukan secara berkesan dan prestasinya harus diukur dari masa ke masa.

Terdapat pelbagai faktor yang mempengaruhi prestasi penyelengaraan dan salah satu faktor penting adalah mesin. Mesin berkaitan langsung dengan prestasi penyelengaraan kerana ia menerima kesan penyelenggaraan dilakukan secara terus. Hipotesis yang digunakan adalah penyelengaraan yang berkesan akan menghasilkan mesin yang berkesan. Oleh kerana itu, kajian ini dilakukan untuk membangunkan model pengukuran prestasi penyelenggaraan berdasarkan keberkesanan mesin.

Dinamakan sebagai model “Equipment Performance and Reliability (EPR)”, ia dibangunkan dalam empat tahap dengan penggunaan kaedah seperti Analisis Pareto untuk pemilihan mesin dan Failure Mode and Effect Analysis (FMEA) untuk proses analisis kegagalan. Dalam kajian ini, keberkesanan mesin diukur dengan menggunakan integrasi antara Overall Equipment Effectiveness (OEE) dan prinsip

kebolehpercayaan. Hasil dari pengukuran keberkesanan mesin dalam model tersebut kemudian diinterpretasikan kepada keberkesanan penyelenggaraan berdasarkan lima peringkat Indeks Kesihatan.

Model ini dipraktikkan di sebuah syarikat semikonduktor. Hasil dari kajian kes ini mengesahkan aplikasi dan kepraktisan model EPR kerana ia membantu syarikat untuk mengukur keberkesanan penyelenggaraan mereka berdasarkan ketersediaan, tahap prestasi dan kebolehpercayaan mesin. Hubungan relatif antara OEE dan kebolehpercayaan didapati adalah penting untuk memperluaskan kemungkinan dalam meningkatkan keberkesanan penyelenggaraan.

INTEGRATION OF OVERALL EQUIPMENT EFFECTIVENESS (OEE) AND RELIABILITY METHOD FOR MEASURING MACHINE EFFECTIVENESS

ABSTRACT

The Murphy's Law that goes "Things will go wrong in any given situation, if given a chance" is best represents the importance of maintenance system. Maintenance is conducted with aims to eliminate failures, reduce machine downtime, minimize manufacturing cost and improve production rate. Maintenance is one of the functions in asset management, and it covers the proper use of resources like human, information, materials, and capital to make certain that equipment, machinery, buildings and plant are repaired, replaced, adjusted, and modified to allow it to operate at its designated performance and in specified lifetime. Therefore maintenance should be conducted effectively and its performance should be measured from time to time.

There are various factors that affecting maintenance performance where one of the significant factors is machine. Machine is related to maintenance performance because it directly received the impact of maintenance conducted. The hypothesis used is that an effective maintenance will produce an effective machine. Therefore, this research was conducted to develop a model measuring maintenance performance based on machine effectiveness.

Named as Equipment Performance and Reliability (EPR) model, it was developed in four phases with the usage of methods like Pareto Analysis for machine selection and Failure Mode and Effect Analysis (FMEA) for failure analysis processes. In this research, machine effectiveness is measured using the integration of Overall Equipment Effectiveness (OEE) and reliability principle. The

result from the measurement of machine effectiveness in the model is then interpreted into the maintenance effectiveness based on five levels of Health Index.

The model is implemented in a semiconductor company. The outcomes of this case study confirmed the application and the practicality of the EPR model as it helps the company to measure their maintenance effectiveness based on machine's availability, performance rate and reliability. The relative relations between the OEE and reliability were found important to broaden the possibility in improving maintenance effectiveness.

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. First, the theoretical foundations of this research are presented in research background and further elaborated in section discussing on maintenance performance and machine factor. Then in problem statement section, current situation in measuring maintenance performance are discussed. To give clearer information, discussion about research objectives is included in fourth section. The overview of thesis structure is prepared in the final section.

1.1 Research Background

Competition is everywhere. In manufacturing industries, not being at the forefront signifies a loss of opportunity and profit. To win the competition, companies must strive to obtain the first spot in the business. And, in trying to improve business performance, one of the ways to lead the market is by reducing waste in operation, thus offering product at low price range. Waste reduction also expands a company opportunities to broaden its market and increases its profit margin with the current resources without pricy expansion expenditure. Not only that, the company needs to maintain their business and customer loyalty by producing good quality and reliable product or system. Stepping higher on the ladder of success, some companies also aim to achieve the status of "World Class Company" (Yamashina, 2000).

"World Class Company" has many criteria to be achieved and many challenges to be faced. One of them is to have an effective maintenance activity that is for reducing cost, improving productivity and maintaining business profile (Swanson, 2001). Thus, more and more companies in part of their effort to achieve "World Class Company" have included an examination of the activities of the maintenance function.

Concise translation of the word maintenance from Oxford Dictionary is, "activities done to ensure equipment and machine is in its existing state, preserve, and ensure it to continue operating in good condition while at the same time protect it from potential damage". Figure 1.1 illustrates the types of maintenance approaches normally practised in industries. The approaches come in many modes that suit different situations and implementation stages. The basic objective of these three different modes of maintenance approaches is to avoid or to reduce unscheduled breakdown of machines during production.

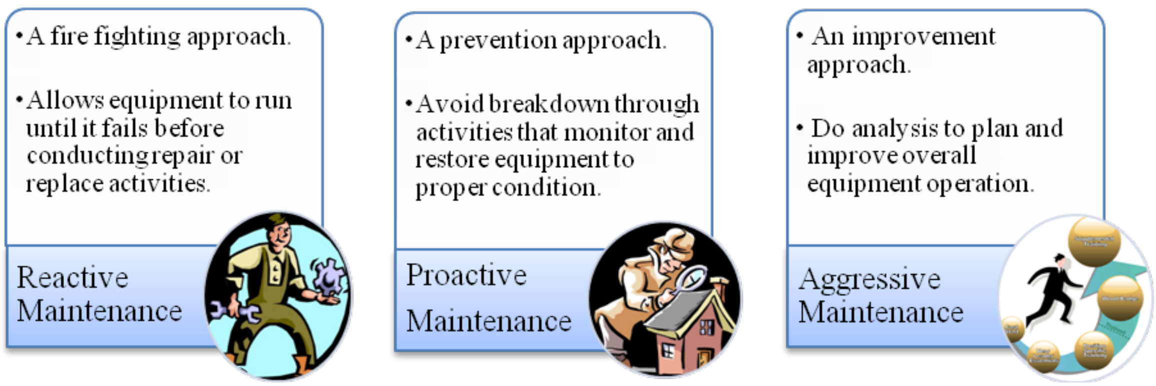

Figure 1.1: Types of maintenance approaches. *Source: Swanson (2001).*

Chan et al (2005) reported that 15% to 40% of total production cost is attributed to maintenance activities. Additionally, up to 33% of maintenance cost is spent unnecessarily (Wireman, 2003). The scenario emerges due to failure in maintenance activities such as wrong type of maintenance techniques, under-skilled workers and forged spare parts. The failures may also due to negligence in determining machines specifications and safety features during operation, which may contribute to the over utilization of the machines. This type of practice reduces the reliability of the machine and may also cause dangerous accident.

1.2 Maintenance Performance

Maintenance performance is defined as the state or condition of the action or process in conducting maintenance function when measured from time to time. Levels of maintenance effectiveness towards manufacturing operation illustrate the performance, and it is necessary to establish appropriate metrics for the purpose of measuring the maintenance performance (Chan et al, 2005). Suitable and effective maintenance performance measurement is crucial to monitor the maintenance activities and the planning for more successful improvement.

Maintenance is no longer looked as a necessary evil as known in 1950s but, as a partnership system that work as a profit contributor in manufacturing organization (Waeyenbergh & Pintelon, 2002). Thus, it is really important to monitor and improve maintenance activities from time to time in order to ensure effective operation. Maintenance performance will reflect the maintenance capabilities to ensure continuous production of quality products and at the same time reducing total operating cost (Tsang et al, 1999). It also reveals the maintenance activities effectiveness and the extent to which any investments done towards operation, such as buying new machines and repairing existing machines are profitable.

Parida (2005) has laid down seven main criteria for measuring maintenance performance which are:

1. machines or process related,
2. cost or finance related,
3. maintenance task related.
4. customer satisfaction,
5. learning, growth and innovation,
6. health, safety and environment issues, and
7. employee's satisfaction factor.

1.3 Maintenance Performance Measurement Based on Machine Factors

Out of the seven criteria, the most common and effective maintenance measurement factor practiced and widely discussed is based on machine factors. This is because maintenance failures shown from equipment malfunction have a direct impact on production capacity, cost, service quality, employee safety and customers' satisfaction (Metwalli et al, 1998). Swanson (2001) stated that effective maintenance is critical to many operations and machines as it extends the machine's life, improves its reliability and retains the machines in proper condition. Conversely, poorly maintained equipment may lead to more frequent machine failures, poor utilization of machines and delayed production schedules. Misaligned or malfunctioning machines may also result in scrap or products of questionable quality. Poor maintenance may also mean more frequent machines replacement because of shorter life which will bring to even higher operating cost.

Maintenance play major roles in ensuring machines and tools are at their best operating performance, whenever and wherever needed (Coetzee, 1999). An effective machine is one that can operate according to its specifications. A reliable machine is the machine that works without any failure, breakdown and unplanned downtime during its designated lifetime. All these can be achieved with practice of high performance maintenance activities. In order to fully utilize the assets, maintenance activities should also allow machines to work at its maximum capability as designed.

Maintenance performance measurement based on machine factor considers machine effectiveness based on machine availability, performance, product's quality rates, production rates, number of stoppages during operation and finally production downtime (Alsyouf, 2006; Parida and Kumar, 2006). There are also discussions on machine reliability relating to maintenance activities carried out on the machines (Obeyesi, 2000; Endrenyi and Anders, 2006). The issue is how effective maintenance will ensure reliable and dependable machines condition throughout its operation.

1.4 Problem Statement

Any maintenance activities conducted can only be claimed as effective if machine works as required, whenever required, during its lifetime (Alsyouf, 2006). The statement shows the relation between machine performance and reliability. The methods concerning machines effectiveness and reliability in measuring maintenance performance based on machine factor are usually done separately, despite the fact that both are related and both resulted from effective maintenance. This is because researchers only measure the machine effective during its operation with the elements like availability, performance rate and quality of product produce.

They ignore the impact of effective maintenance in ensuring high machine's reliability and longer operating time.

Commonly, Overall Equipment Effectiveness (OEE) is used to gauge machine's effectiveness during operation (Pomorski, 1997; Eldrige et al, 2005 and Dal et al, 2007), while reliability principle had been practiced to measure machine capability and dependability (Obeyesi, 2000 and Wiksten & Johansson, 2006). Unfortunately, most machine reliability is only calculated during design stage which does not portray the effectiveness of maintenance activities done. Thus, there is a need for a study to assimilate machine's reliability during operation with the maintenance carried out.

This research ventures further on this area of knowledge in order to understand the relationship between maintenance performance with machine effectiveness and reliability. The emphasis is on the development of maintenance performance measurement model by considering machine attributes and factors that influence effective maintenance activities. It is understood that performance measurement is a means of quantifying the effectiveness and efficiency of action (Neely et al., 1997). The measurement provides a means of capturing performance data which can be used to aid decision making and improvement plan. According to Tangen (2003), performance measurements are often used to increase the competitiveness and profitability of manufacturing companies through the support and encouragement of productivity improvements. Thus from the information, it can be conclude that maintenance performance measurement is the process of collecting and analyzing data on maintenance actions to determine its level of efficiency and effectiveness.

There are few implications issues related to the performance maintenance (Meeking, 1995 and Kutucuoglu et al., 2001), which are;

- The role of measurement is transformed from backward-looking record keeping to forward-looking prediction and insight,
- Measurements are used to provide feedback, build understanding and encourage intrinsic motivation, rather than as a tool for top-down management control,
- The focus is on systematic thinking, fundamental structural change and organizational learning, instead of mindless target-setting, continual fire-fighting or the rigorous of blame,
- Measurement methods become a framework for everyone to understand and align with top-level objectives of the organization, and enable them to actively and enthusiastically participate in continuous improvement.

The model will aid company especially maintenance department to gauge their maintenance system. The result from the measurement process can then be used to plan improvement action and to provide better maintenance activities in the future. Therefore, maintenance performance can be in its effective level as possible.

1.5 Research Objectives

The specific objectives of this research are:

1. To formulate and develop a model for maintenance performance measurement method based on machine factors,
2. To implement the maintenance performance measurement model in a case study company.

1.6 Thesis Outline

The thesis contains five chapters. Chapter 1 provides the overview of the current practice of maintenance in industries and the objectives of the research. Chapter 2 provides the reviews on the available literatures which encompass critical thinking, ideas and approaches of maintenance performance from researchers in maintenance area. This chapter also provides information on tools and techniques used in the industry. Chapter 3 discusses the framework development based on literature reviews in Chapter 2. The research approach together with methods to be applied in the case study company is described in this chapter. Calculation methods, data analysis approaches practiced by industries and techniques for data collection and analysis are also demonstrated in this chapter.

Subsequently, Chapter 4 describes the details on case study that been conducted in semiconductor manufacturing company in Malaysia. The semiconductor manufacturing company background and available manufacturing system in the company is discussed first to comprehend more knowledge. Extra elaborations on implementation of framework and data collection activities are put forward in the next section of the chapter. There are also the deliberations on experimental works, results and discussion as conducted in this research. Data, information and figures obtained from case study conducted can be found in this section together with discussion on research problems, obstacles and limitations faced during the research. The discussion gives extensive observation on potential gap of knowledge that is ready to be explored. Chapter 5 concludes the research work and provides the recommendations for future work in maintenance performance measurement.

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

With the understanding on how vital maintenance system really are, and how much the activities can cost as mentioned in Chapter 1, the wide area of maintenance performance measurement was reviewed in order to provide a research idea and foundation. Thus, this second chapter is structured in a way that issues signifying performance measurement are discussed first and followed by discussion about factors that affecting maintenance effectiveness. The third section reveals the theories and methods that available in the literatures in measuring the maintenance performance based on machine factor. The chapter is concluded with the literature findings.

2.1 Maintenance Issues

In the Chapter 1, maintenance has been described as a way to help company in achieving 'World Class Company" status with its profit generator function. Maintenance practices always bring a lot more than just additional cost for spare parts and outsourcing process. Actually, it can be seen as one of the major sources for cost saving process in a company. Interestingly, effective maintenance brings benefits like it helps in doing proper production scheduling and ensure longer lasting machine's lifetime in the production (Alsyouf, 2006; Parida and Kumar, 2006).

However, practitioners still puzzled by the question on how to conduct suitable and effective maintenance in the company. Having a maintenance department in the company make people only think about repair and replace activities. Both are actually only the tip of an iceberg. The bigger body of the ice submerged under the water are the issues that involved maintenance management, maintenance policies, and maintenance planning. There are also issues on human factor and maintenance performance measurement.

From the various literatures published, Gard and Deshmukh (2006) reviewed on important elements that should be considered in managing maintenance. Charles et al. (2003), Zhou and Lee (2006) and Pinjala et al. (2006) discussed on implementation and optimization of maintenance policies in a company. The other publications are by Das et al. (2007) which focus on maintenance planning while Lapa et al. (2006) proposed a model using genetic algorithm to ensure good planning. Issues on human factor in maintenance are extensively discussed by Grozdanovis (2001) and Dhillon and Liu (2006). Apart from that, there are discussions on maintenance performance measurement. Parida and Kumar (2006), Alsyouf (2006) and also Oke (2006a) examined factors that affect maintenance effectiveness as well as highlighting the importance of measurement process. The research were conducted on various methods used in performance measurement.

2.2 Maintenance Performance Measurement

Maintenance performance measurement has gained a great amount of attention and discussion from researchers and practitioners due to the understanding that what cannot be measured cannot be managed effectively (Parida and Kumar, 2006). Due to the complexity of the maintenance effectiveness, the question of how to measure maintenance performance is not easy to answer. Performance is the level to which aims and objectives are attained (Dwight, 1999). It is hard to plan, monitor, control and improve maintenance activities without any formal measure of performance. Measurement tells the status of the activities carried out and type of action to be taken there after and to indicate where those actions should be targeted (Kumar, 2006).

Therefore, management requires performance information to be able to improve their maintenance activities. The absolute value of such performance information can then be compared to a situation or a trend and, this value can be used to glean maintenance performance levels (Arts et al, 1998). This will ensure continuous improvement plan in the company. To achieve effective maintenance require suitable maintenance policies based on the company's operation, having capable and reliable maintenance technicians, and finally acquiring reliable machines, tools and spare parts for the maintenance operation. Effective maintenance is needed because large losses of profit can be attributed to downtime of machine in operation (Waeyenbergh & Pintelon, 2004). Maintenance performance measurement is also required in identifying whether maintenance is effective or not.

In Figure 2.1, Parida and Kumar (2006) revealed some of the reasons that stir the demands for maintenance performance measurement. It can be observed that, the necessity to gauge maintenance effectiveness comes from demands by every department in an organization, which also means maintenance is directly and indirectly related to all operation. Maintenance helps the maintenance department to justify the investments for their activities by measuring value created by maintenance for the company's operation. It also helps management team to revise resource allocations in the future towards better maintenance performance.

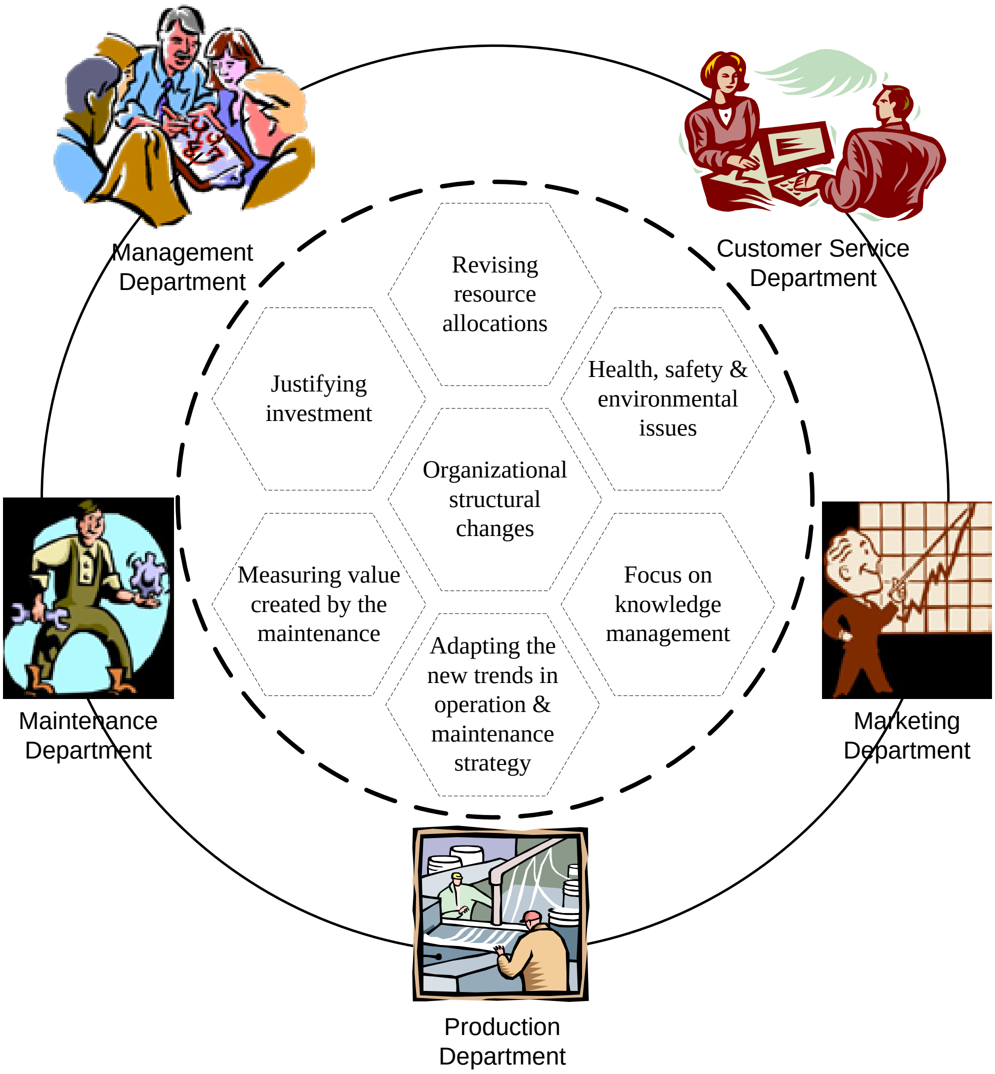

Figure 2.1: Important factors behind demands on maintenance performance measurement. *Source: Parida and Kumar (2006)*

2.3 Factors Affecting Maintenance Performance

Before venturing further on maintenance performance measurement methods, there is a need to find out factors that affect maintenance effectiveness. Since maintenance is related to many departments in an organization as shown in Figure 2.1, it is obvious that there are many factors that will affect its performance. Hence, it is really crucial to gain sufficient insight of the factors. Maintenance effectiveness can be divided into two main categories named as external and internal factors (Kumar 2006). External factors covers the issues after product was sold while, internal factors gauge maintenance activities based on its performance during the manufacturing processes. Figure 2.2 illustrates the divisions of total maintenance effectiveness together with list of common factors that are affecting it.

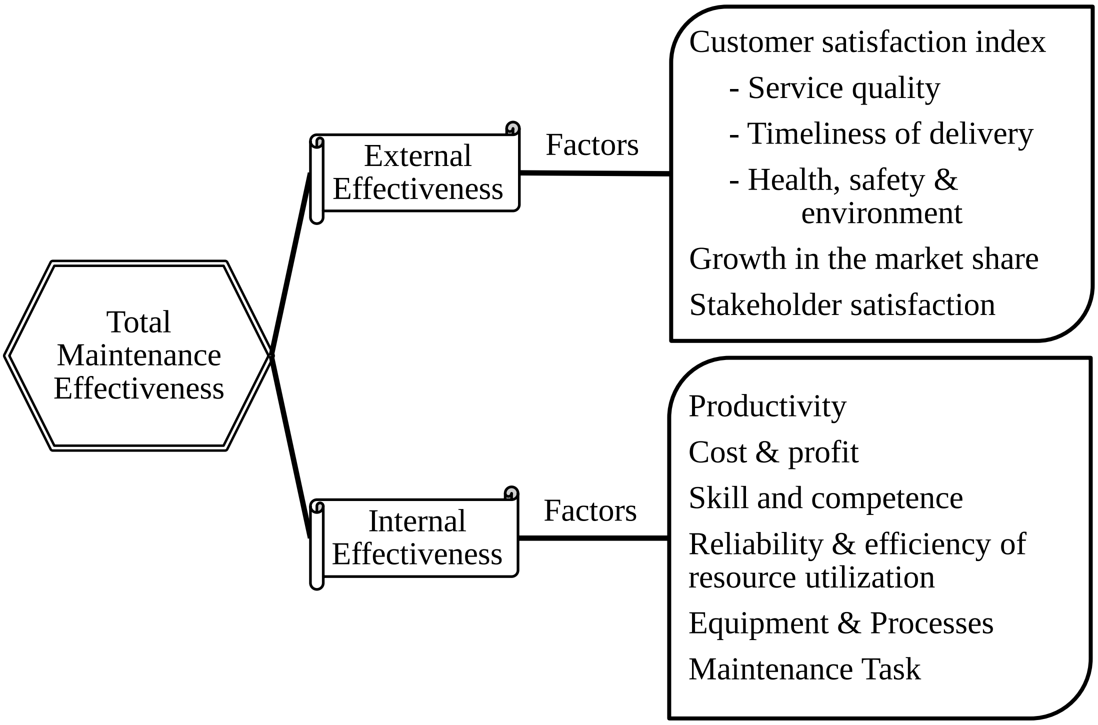

Figure 2.2: Total maintenance effectiveness based on an organizational effectiveness model. *Source: Kumar (2006)*

External effectiveness of maintenance performance is mainly affected by customer satisfaction. It can be gauged by service quality, timeliness of delivery, health, safety, and environmental issues. The factors are the long term effect of maintenance done since effective activities will ensure manufacturing of quality and reliable products. The index of maintenance effectiveness is based on growth in the market share. The growth signifies the increase of product demands in the industry (Parida and Kumar, 2006). Kennerly and Neely (2000) also agreed on external factors and put emphasis on stakeholder satisfaction to drive performance towards effective maintenance. Kumar (2006) stated that, external factors need to be measured to counter internal factors which were claimed to be inadequate. These factors are only indirectly related to maintenance performance.

The second category which is also the most crucial aspect is the internal effectiveness. The internal factors are closely and directly related to maintenance operation. Figure 2.2 shows the internal effectiveness factors are productivity, cost and profit, which are involved in the production process. With these factors, maintenance performance can be measured based on saving or expenditure for the maintenance activities. Another factor is employee's skill and competency during maintenance activities. Employee capabilities need to be measured to plan for training both in theory and practical whichever is necessary. Reliability and efficiency of resources utilization are also the considered factors in internal effectiveness. The resources for maintenance activities are tools, material and spare parts, so it should be used according to specifications at appropriate maximum capability.

For Coetzee (1999), machine and processes are the most significant factor that affects maintenance performance. This is because machine receives direct impact from maintenance activities. Thus, any misconduct during maintenance can be accurately measured by calculating machine performance and effectiveness during operation. The final factor affecting maintenance is its task efficiency. This factor considers bigger scope of maintenance system which includes the planning process. Task efficiency includes the type of techniques chosen, time allocation and also spare-part selected for maintenance activities.

2.4 Methods in Measuring Maintenance Performance

Since total maintenance effectiveness is affected indirectly by external factors and directly by internal factors. It is necessary to calculate the maintenance performance. Researchers and practitioners' emphasised on maintenance performance measurement methods because maintenance is an important process in an organization. Literatures on this area of research consist of various types of methods in measuring maintenance performance. The methods are conducted based on the various factors that affect maintenance effectiveness.

According to Oke (2006a), maintenance can be gauged in a variety of methods. Economic and technical factors are the most common measurement model followed by strategic approach. There are also practices of system auditing by doing surveys and questionnaire to collect data on maintenance effectiveness. The other approach is by doing analysis of statistical, reliability and maintainability function of machine in the operating plant. More complex approach is using mathematical model in composite formulation of maintenance performance. Finally, there is also partial maintenance productivity measurement which based on the manufacturing availability and amount of production.

Continuing the categories of maintenance measurement methods, Oke (2006b) added-up value-based approach among the previous six approaches mentioned earlier. However, this classification of measurement method is not absolute. Researchers tend to discuss maintenance performance from various factors according to their own interpretation and area of research. Aside from the literatures reviewed, there were also a few other researches that have been conducted on maintenance performance measurement method based on multi-factors.

For instance, Kutucuoglu et al. (2001) practiced the matrix of Quality Function Deployment (QFD) technique to measure maintenance effectiveness. The functions deployed are machine, task, cost, customer impact and learning and growth related issues. All functions were analyzed and structured to measure and evaluate maintenance activities. From there, the main reasons for maintenance ineffectiveness were selected and then further improved.

De Groote (1995) gauged maintenance performance based on economic and technical factor. In the literature, performance calculations include the ratio of direct maintenance cost over added or replacement value of production, and also cost of resources, maintenance personnel and spare parts over maintenance cost. These economic approaches were also gauged by calculating machine performance using OEE elements. These two factors were being practiced in the companies studied, and they preferred to gauge their maintenance performance based on cost and machine factor.

In a separate way, Arts et al. (1998) proposed a performance measurement from overall perspective that reflected a strategic, tactical and operational planning in the organization. The process is by first considering organization's aims and objectives and then comparing it with maintenance performance. For example, if the strategic planning is to operate with minimum cost possible, then the factor to be considered for maintenance performance is also how the activities can save money during operation. This holistic or overall approach is also suggested by Tsang et al. (1999) and Coetzee (1999) because it had been claimed that part solutions cannot produce the required results when used in larger managerial context.

Tsang et al., (1999) focused on direct relation between maintenance performance and organization performance in order to provide useful information for making effective decisions and shaping desirable employee behaviour. Maintenance was looked as physical asset management, thus the scope considered cover every stage in the life cycle of technical systems, specification, acquisition, planning, operation, performance evaluation, improvement, replacement and disposal. The technical systems are referred to plant, machine and facilities in the manufacturing process.

Coetzee (1999) insisted on auditing and analyzing all the critical parts of maintenance like policy, procedures, maintenance plan, maintenance information or operation systems and maintenance operation, simultaneously. The technique proposed is thus to apply a variety of techniques to a small part of the maintenance system instead of applying one technique over the total operation. These small improvements then will slowly and little by little improve the overall maintenance system.

Nevertheless, holistic maintenance performance measurement is complex because of various factors that needed to be considered. Furthermore, the calculation requires rigorous data collection and analysis in order to acquire accurate results that will portray the real situation of maintenance activities conducted. Sometimes, too many details in calculation will hinder the analysis to understand real situation behind the data and numbers.

2.5 Methods Based on Machine Factor

Machine is the main function in maintenance. Its efficiency is greatly needed especially in extreme capacity constrained operation. High availability and utilization percentages of machines will ensure maximum production output and increase the company’s profit. Tsang (1998) identified that there are some common measures of machine effectiveness based on availability, reliability and overall equipment effectiveness (OEE), measures of cost performance by calculating labour and material cost, and finally measures of process performance in example the ratio of planned and unplanned work or schedule compliance. Machine performance is commonly related to the OEE and reliability principle.

2.5.1 Overall Equipment Effectiveness (OEE) Method

First introduced by Nakajima, the father of Total Productive Maintenance (TPM) in his book (Nakajima, 1988), Overall Equipment Effectiveness (OEE) has been a powerful yardstick for tracking work progress and improvements. In many years, it can be observed that OEE has been related to TPM in all discussions (Kwon and Lee, 2004; and Tsarouhas, 2007), and it is actually a measure of the factors that determine and may influence equipment effectiveness (Williamson, 2004).

OEE was initially introduced as a method to calculate and monitor actual performance of machine relative to its capabilities under optimal operation condition. It is a function of machine availability which is connected to downtime losses, performance rate that related to speed losses, and finally quality of product produced that has to do with quality losses. OEE is a metric accumulated from multiplication of availability, performance rate, and quality rate of the machine and defined as follow (De Groote, 1995):

$$OEE = Availability \times Performance\ Rate \times Quality \qquad (2.1)$$

With,

$$Availability = \frac{Planned\ production\ time - Unplanned\ downtime}{Planned\ production\ time} \qquad (2.2)$$

$$Performance\ Rate = \frac{Actual\ production\ rate}{Planned\ production\ rate} \qquad (2.3)$$

$$Quality = \frac{Actual\ number\ of\ product - Reject\ product}{Actual\ number\ of\ product} \quad (2.4)$$

The three OEE elements are weighted as equals with each other. Nakajima suggested that the ideal values for OEE component measures are 85% (Dal et al, 2007). The percentages are dubbed the "World Class Performance" level with:

- Availability in excess of 90 percent;
- Performance rate in excess of 95 percent; and
- Quality in excess of 99 percent.

However, Ljungberg (1998) estimated OEE average to be only around 55%. Kotze (1993) also argued that an OEE less than 50% is more realistic. The different percentages are basically not critical because it depends on data collection for the OEE calculation. The important is that each measurement process should mirror pervious process so that any comparison and analysis done after that is valid. Aside from the issues, there are also a variety of OEE implementation and practice in the industry.

The measurement of OEE starts from loading time, which planned production time for the machine. So, right from the start some losses have been omitted, e.g. breaks in production schedule, precautionary resting times, and daily shop floor meetings (Ljungberg, 1998). To group the losses, Nakajima (1988) has identified Six Big Losses which affects maintenance performance. The losses are classified as breakdown losses, setup and adjustment losses, idling and minor stoppage losses, reduced speed losses, process defect losses and start up losses. The definitions of the six losses can be simplified in Table 2.1. The detail explanations about Six Big Losses can be found in Appendix A.

Table 2.1: The definitions of the Six Big Losses *Sources: (Nachaippan and Anatharaman, 2006)*

No.	Losses	Definition
1.	Breakdown	Losses due to major failures.
2.	Setup & adjustment	Stoppages losses that accompany setup and changeovers which including adjustments for correct positioning.
3.	Idling and minor stoppage	Losses that occur when the machine temporarily stops or idles due to sensor actuation or jamming of the work. The machine will then operate normally through simple measures like removal of the work and resetting.
4.	Reduced speed	Losses due to actual operating speed falling below the designed speed of the machine.
5.	Process defect	Losses due to defect and reworking of product.
6.	Start up	Losses due to product which did not follow specifications at start up of process.

In a manufacturing plant, the common maintenance problem is the first type of losses. A machine breakdown usually halts production process. The examples of breakdowns are component malfunction, machine jammed, and production stops for preventive maintenance actions. The second big losses consist of downtime caused by set up actions conducted in order to change components, correct product position or minor adjustments to achieve desired process specifications. These types of losses indicate that maintenance or component changes done on the machine are poorly carried out making the machine inefficient and unreliable.

For the third type of losses, idling and minor downtime consider the downtimes or failures that occurs in less than 5 minutes due to cleaning or simple maintenance action on the machine. Any downtime for minor adjustment and resetting which the machine will then operate normally were also included. Even though this type of downtime is considered small but with continuous occurrences will result in long downtime and immobilize the manufacturing processes. It also can reduce machine reliability by shorten its useful lifetime.

Reduced speed losses are due to the machines actual operating speed falling below or operating under the designed speed. This showed that the machine was under utilised because it was not used to the maximum capability. The speed losses are mostly related to the production planning and scheduling for the processes on the machine.

The fifth and last losses are process defect and start up losses. The process defect losses occurred when machine is operating but producing unqualified products. It can be caused by various reasons like material defect, inaccurate process setting or wrong component installed on the machine. The start up losses which also expressed as yield losses are the time when a machine start processing a new product and the early batch are considered rejected item. The concept of yield losses is a common practice in manufacturing plant to ensure the products manufactured are in good quality. Yet it is still counted as losses in OEE practice since machine is on operating mode.

There are different opinions that appear to exist within the OEE literature as to what level of availability; performance rate and quality rate that constitutes acceptable OEE performance percentages. Most publications (Steege, 1996; Leachman, 1997; da Costa and de Lima, 2002) emphasised on the availability calculation, on when should be considered planned production time. This however not a major issue in OEE principle since it is up to the practitioner to decide on OEE timeline. What is important is that the same timeline is used in every time calculating OEE so that the results can be compared to see the impact of maintenance effectiveness.

OEE is proposed as a measurement system for evaluating the effectiveness of a system as well as for establishing priorities for improvement (Eldrige et al, 2005). According to Dal et al (2000), OEE is best suited to environments of high volume process based manufacture or mass production where capacity utilisation is of a high priority, and stoppages or disruptions are expensive in terms of lost capacity. OEE has actually been implemented on bottleneck machine, due to the fact that it affect sthroughput or other critical and costly manufacturing area the most (Hansen, 2002).

Pomorski (1997) also used OEE to monitor the actual performance of a tool relative to its performance capabilities under optimal manufacturing conditions and to measure the performance of the entire manufacturing process. The author proposed a productivity metric standard based on various OEE; Production OEE, Demand OEE, Simple OEE, and Cluster Tool OEE. The variation of OEE was interpreted according to the departments where it can be implemented. This approach seemed to defy the initial intent of Nakajima.

The application of OEE is not limited towards application with TPM only. OEE was also integrated into implementation framework and computer system. Konopka and Trybula (1996) discussed OEE and cost measurement in their case study based research. They used a productivity analysis framework called the Capability Utilization Bottleneck Efficiency Systems (CUBES) to investigate data and identify then prioritize productivity efficiency with their accompanying tool capacity decreases. CUBES which also build up as a computer program acted as capacity tool that was used to enhance a very progressive TPM program (Geigling *et al*, 1997). Using OEE elements and principle, CUBES allows user to concentrate on the most problematic machine or bottleneck in operation, to effectively increase production capacity.

Jeong and Philips (2001) stated that the original definition of OEE suggested by Nakajima is not appropriate for capital-intensive industry because it does not include scheduled maintenance time for preventive maintenance and important non-scheduled time such as off-shift and holiday. Accurate estimation of machine utilization is very important in capital-intensive industry since the identification and analysis of hidden time losses are initiated from these estimates. Thus, they also conducted their research using CUBES. The framework was constructed on the total calendar time-based approach and it helps the company to plan their maintenance according to exact operation time minus their break time and holidays.

An example of OEE usage is by Chand and Shirvani (2000). The authors implemented TPM and measure it with OEE in cellular manufacturing with the goal to ensure machine can be operated to its full potential and maintained at that level. They claimed that OEE is not an exact measure of machine effectiveness as set-up, changeovers and adjustments are included. Therefore, to provide a more accurate analysis, they introduced net equipment effectiveness (NEE) that reflects the true quality and effectiveness of the machine during operation. This case study-based paper was also included with calculation of maintenance cost that can be saved up if company achieved 85% of OEE compared to 62% of OEE before TPM implementation.

Oechsner et al. (2003) in their paper discussed the transformation of OEE to Overall Fab Effectiveness (OFE). Fab is a short term for foundry in a semiconductor plant where machines were operated in a linked and complex arrangement. This situation makes it tough to calculate OEE for each machine. The solution proposed by the authors was to use OFE in order to obtain a result for the cost per product manufactured. The practiced of OFE showed the flexibility of OEE principle as well as wide scope of research conducted in the area.

Another method being used is Overall line effectiveness (OLE), an approach to measure continuous line-manufacturing system which was introduced by Nachiappan and Anantharaman (2006). With similar problem statement by Oechsner et al (2003) earlier, they tend to measure performance of product line involving machines in series. The approach is by assuming that all machines in the line working operating at the same performance, thus any problem detected is solved in the whole line.

Aimed to examine the generality of dimensions and characteristics of a comprehensive system of measuring Overall Manufacturing Performance (OMP) and the contributions of the OEE; Jonsson and Lesshammar (1999) described the OEE measure and explained how it fits into the OMP system. It was concluded that strategy, internal efficiency, improvement drives and simple and dynamic characteristics of OMP are linked to OEE. In the literature, rate of quality was considered in general because it is hard to obtain comprehensive view of the quality of the machine. They also add that a wider definition of the quality parameter would decrease the OEE simplicity. The main aim is not to get an optimum measure, but to get a simple measure that tells the production personnel where to spend their improvement resources.

2.5.2 Machine's Reliability Method

The second method in measuring maintenance performance is machine's reliability. Machine reliability is a characteristic of design, operating conditions and maintenance philosophy. Obeyesi (2000) stressed that the prime function of