Optimisation Oriented Lean Six Sigma Development for Maintenance Management in Service Sector

A thesis submitted for the degree of Doctor of Philosophy

by

Barrak Hamdan Alsubaie

College of Engineering, Design and Physical Sciences
Brunel University London

February 2016

Abstract

This research deals with the optimization of preventive maintenance (PM) and process improvement for maintenance management in service sector. To stay competitive and sustain long-term profitability, process improvement methodologies have become strategically important for maintenance management in recent years. These include well-known approaches such as Total Quality Management (TQM), Business Process Reengineering (BPR), Six Sigma, Lean and Lean Six Sigma (LSS). The adoption of LSS and PM optimisation in the maintenance services sector, however, is still at an early stage. There has been very limited research in this topic reported in the literature. This research has explored the LSS and PM optimisation through case studies in vehicle fleet maintenance.

This research has made contributions to knowledge in the quality management and, in particular, the process improvement methodology and service quality for the vehicle maintenance service sector, but potentially also in a broader context. The main contribution is the establishment and demonstration of a sound methodology and model to integrate LSS and PM optimisation in the vehicle fleet maintenance. The model also provides guidelines for further development of a practical process improvement framework. The proposed model is therefore considered as a basis for further empirical work relating to the process improvement in the services context. Further, this study has developed a total cost model to optimise the PM activities based on both the PM maintenance cost and the quality loss cost. There have been two parallel developments for determining the optimum PM interval, one based on the maintenance cost without considering the quality loss, and the other based on the quality loss without considering the maintenance cost. A novel approach combining the maintenance cost and quality loss has been developed. Moreover, the total productive maintenance (TPM) implementation in the service process and the integration with the LSS/PM optimisation has enhanced the theory and practice of continual improvement in maintenance.

The implementation of the integrated model of LSS and PM optimisation through case studies in vehicle fleet maintenance has provided an impetus for establishing best practices within the organisation under study. The implementation of this model has also increased the future performance of the organisation. It has enabled the maintenance management based on a strong customer-supplier relationship by satisfying customer requirements. The proper utilisation of the resources and the application of LSS tools and techniques will upgrade the company procedures and reduce the maintenance non-conformities, with the key process parameters continually improved and ultimately optimized.

Acknowledgment

I would like to thank all those who have helped me to accomplish this research. My highest gratitude goes to the Ministry of Defence in Saudi Arabia for giving me the opportunity to pursue my PhD. I am also greatly indebted and thankful to my supervisor, Dr Qing Ping Yang who had extended me all valuable directions, guidance and encouragement. Also, I am grateful for the encouragement, invaluable comments, and support that I have received from Dr Joe Au during my PhD. Special thank goes to my family, colleagues and friends for their support and cooperation.

Declaration

I declare that I have read and understood the requirement for dissertation submission in the Projects & Dissertation Guide, including the section on plagiarism and I confirm that:

1. The work is original.

2. The work is my own.

3. I have previously submitted a draft which was commented on by my supervisor.

4. The work conforms to the style and layout specified in the guide.

5. The literature review is included.

6. The work is sufficiently and properly referenced throughout the document.

7. Units, figures and diagrams are clear, accurate and appropriate.

8. I understand that the English has to be acceptable.

9. I enclosed a copy of the dissertation.

Disclaimer

This disclaimer is intended to remove any liability to the university or the author on any applications of this research methods or ideas. The use of these will be on the user own risk. The ideas and methods introduced, developed or suggested in this research are the opinion of the author and do not represent the thought and opinion of the university or its members. This also is intended to remove any liability on the faculty members who have contributed in this research in any form.

Table of Contents

List of tables

List of figures

List of abbreviations

AD: Anderson-Darling

CI: Continuous Improvement

CM: Corrective Maintenance

CTQ: Critical to Quality characteristics

CUSUM: Cumulative Sum chart

DMAIC: Define, Measure, Analyse, Improve and Control

EDF: Empirical Distribution Function

FMEA: Failure Mode and Effect Analysis

GOF: Goodness-of-fit

JIT: Just In Time

LSS: Lean Six Sigma

LTB: Larger-The-Better

MC: Monte Carlo simulation

MCS: Measuring Customer Satisfaction

ME: Method of Moments

ML: Method of Maximum Likelihood

MSD: Mean-Squared Deviation

MTBF: Mean Time between Failures

MTTF: Mean Time to Failure

MTTR: Mean Time to Repair

NC: Nonconforming

NTB: Nominal-The-Best

OEE: Overall Equipment Effectiveness

PCA: Process Capability Analysis

PCIs: Process Capability Indices

PDCA: Plan, Do, Check, and Act

PM: Preventive Maintenance

QLF: Quality Loss Function

QMO: Quantitative Maintenance Optimization

RCM: Reliability-Centered Maintenance

SIPOC: Supplier-Input-Process-Output-Customer

SMED: Single Minute Exchange of Sies

STB: Smaller-The-Better

TC: Total Cost

TPM: Total Productive Maintenance

TQM: Total Quality Management

VSM: Value Stream Mapping

1. Introduction

1.1. Introduction

Equipment maintenance management is the process of keeping and restoring the performance of the equipment. This process involves decision making, planning, organisation, coordination, supervision and control. As an established goal and responsibility, it is related to the effective integration of resources, including the planning, organisation, coordination and management behaviours and activities to effectively integrate human, material, time, information and the other equipment maintenance management elements. Zhang et al. (2013) argue that with the increasing complexity of engineering equipment, maintenance is an effective and essential work to ensure the normal operation of these systems. According to Chu et al. (1998) and Mobley (2002), the maintenance cost generally reaches up to 15% of the total manufacturing cost, and 60% of the maintenance cost is caused by the sudden downtime. Even in the United States (US), manufacturing plants have to pay $200 billion annually for equipment maintenance, and the indirect loss from the production equipment downtime is greater (Chu et al., 1998 and Mobley, 2002).

In military, vehicle fleet maintenance has high requirements in terms of speed, quality and cost reduction. On the other hand, some shortcomings in the quality management system influence and restrict the quality and efficiency of equipment maintenance and cause high costs. A study confirms that the implementation of current maintenance management systems has not reached the expected level of success (e.g., maintenance schedules are not implemented on time, and priorities are difficult to identify) (Aldairi, Khan and Munive-Hernandez, 2015). This situation is caused by the lack of maintenance management skills and execution experience, which produces negative effects on facility performance (Aldairi, Khan and Munive-Hernandez, 2015). Therefore, equipment maintenance management should adjust to new situations and tasks, keep pace with the age, actively explore the characteristics of the scientific management rules, and encourage the innovation and development of equipment management.

1.2. Problem Statement

Maintenance management refers to the process of scheduling and allocating resources to the maintenance activities (repair, replacement and preventive maintenance [PM]) linked to a fleet of equipment (Cassady et al., 1998). The leading objectives of the maintenance function in any organisation are to maximise asset performance and optimise maintenance resources. The organisation under study has applied the PM policy to prevent vehicle failures and component deteriorations; they have a strict procedures and training programmes to keep high maintenance efficiency. With these applications, the organisation has been facing a cost increase due to excessive PM activities and at the same time low customer satisfactions due to the variability of the product in hand of the customers. Generally, in the Kingdom of Saudi Arabia (KSA) military, vehicle fleet maintenance management has achieved significant progress, but some problems remain. Primarily, maintenance planning is poor, and maintenance efficiency is not high. Second, some individual service units cannot strictly carry on operations according to the system and programme implementation. Third, some maintenance workshops' repair cycle is too long, and the maintenance quality issues lack effective supervision. Fourth, corrective maintenance (CM) cost is very expensive, hence to keep high level of reliability and availability preventive maintenance is done frequently which a raise the maintenance cost. These problems are serious, and they cannot raise the level and sustainable development of equipment maintenance management. Thus, how to adapt to the needs and improve the equipment maintenance management ability have become crucial tasks. Indeed, the enormous waste of resources and poor quality results from the failure to apply maintenance strategies. Excessive repair or inspection will definitely lead to an increase in maintenance budget commitments and a drop in quality performance, for instance, due to the waste in the maintenance area (Milana et al., 2014). These issues indicate that maintenance processes have nonvalue-adding steps that need continuous improvement (CI).

1.3. Significance of this Research

Maintenance is vital in any service/industrial organizations as it could prevent unexpected breakdown of equipment's that may result in unexpected cost associated with productivity and quality of services or products. Maintenance is very expensive; therefore an effective maintenance strategies and optimal maintenance schedule are required to reduce the overall maintenance budget cost without reducing the maintenance itself and neglecting the serviceability level of the equipment's/machines. In general, a significantly larger amount of money gets spent in operating and maintaining the system during the lifecycle of a vehicle fleet maintenance system than acquiring it. Hence, efficient systems are critically important, including inventory management, modifications and maintenance activities, for containing the lifecycle costs of vehicle fleet maintenance systems and for maintaining the highest level of military readiness.

Companies, in last three decades, recognised that if they wanted to manage maintenance adequately, it would be necessary to include it in the general scheme of the organisation and to manage it in interaction with other functions (Pintelon and Gelders, 1992). Once this is achieved, maintenance could receive the significance that it deserves and be developed as one more function of the organisation, which generates "products" to satisfy users, fulfilling or contributing to the achievement of specific goals of the organisation. The challenge of "designing" the ideal model to drive maintenance activities according to Uday et al. (2009) has become a research topic and a major question for attaining effectiveness and efficiency in maintenance management and achieving enterprise objectives. In the historic development of maintenance, various authors have proposed what they consider the best practices, steps, sequences of activities or models to manage this function. Department of maintenance is facing ever-increasing military expenses to maintain military readiness with aging vehicle fleet systems. Hence, the Department is keenly interested in providing a model of practical guidelines for the maintenance providers in the service sector to improve the service process.

1.4. Research Aim

This research aims to develop a model that integrates LSS and PM optimisation and provide an implementation structure for establishing an operation for maintenance organisation that is effective at improving performance. The LSS and PM optimisation model presents not only the process improvement but also the techniques to manage and enhance maintenance effectiveness and efficiency.

1.5. Research Objectives

The research objectives are as follows:

(1) Identify the need for the total cost (TC) model for service and the model optimisation and simulation application.

(2) Identify the importance of the integrated LSS and PM optimisation model for maintenance process in service organisations.

(3) Develop a mathematical model and a formulation of the optimisation models to optimise the maintenance activities based on the total maintenance cost, including:

- quality loss function development,
- TC model development and model optimisation, and
- model simulation.

(4) Develop a model for integrating LSS and PM optimisation in maintenance in the service industry.

(5) Validate the model by using a case study.

1.6. Methodology

To achieve the research aims and objectives, the following methodology is employed:

(1) Review the published literature.

(2) Develop a mathematical model to optimise the maintenance activities based on the PM maintenance cost and the quality loss cost.

- Develop a multi-characteristic quality optimisation in service, using the Taguchi quality loss function.
- Perform a simulation study. Computer-based simulation software will be used to test the resulting optimisation for layout effectiveness, identification of operational issues and optimum utilisation of resources.

(3) Develop an innovative model to support the implementation of the LSS and PM optimisation.

(4) Validate the model with a field study. The model will be tested in a real environment for its integrity, ability to be implemented and effectiveness in improving operation performance.

1.7. Thesis Structure

This thesis is divided into seven chapters. Chapter 2 gives a comprehensive review of the literature on maintenance optimisation, process improvement and LSS. Chapter 3 covers the research methodology. It discusses the issues related to the research design, the rationale for choosing the case study technique, and the set of research questions about the aims and objectives of this study. Chapter 4 introduces a mathematical model to optimise PM activities. Computer-based simulation software is used to test the resulting optimisation. Chapter 5 explains the integration of the LSS and PM optimisation model. Chapter 6 presents a case study to validate the model. Finally, Chapter 7 provides the conclusions and a summary of suggestions for future research.

2. Literature Review

This chapter will review the relevant literature to provide the foundations of the research. The first section presents a review of some used statistical models in modern reliability engineering. Also, the quality and reliability concept and application of Taguchi loss function in service sector to improve variability are presented. A complete review of various optimisation models related to PM, as well as some key works that utilise simulation and optimisation are also reviewed and discussed. This chapter also covers process improvements and LSS. Finally, integrated LSS and optimisation methods are reviewed.

2.1. Statistical Modelling

Statistical modelling can be used to describe, analyse and estimate the probability associated with failure or the product life. This subsection presents the basic definitions and concepts in statistical analysis and then discusses the commonly used probability distribution analyses. Reliability analysis is also briefly discussed.

2.1.1. Probability Distributions

The normal, log-normal and Weibull distributions are the most important statistical distributions used (Fatemi et al., 2001).

2.1.1.1. Normal Distribution

The normal distribution is often used to describe the dimensions of parts made by automatic equipment, natural physical and biological phenomena, and certain types of life data (Nelson, 1982). Figure 2.1 shows the normal probability density, which is symmetrical about the mean.

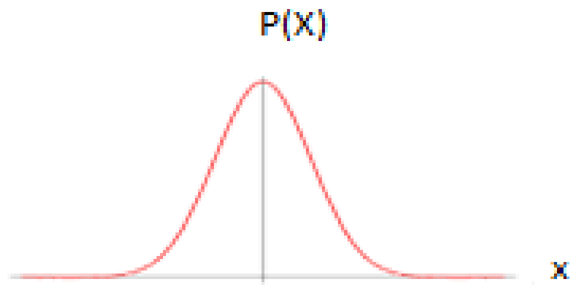


Figure 2.1 Normal probability density functions

The normal probability density function is

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)},$$

Where μ is the mean (any value), and σ is the standard deviation (positive value).

2.1.1.2. Log-normal Distribution

The log-normal distribution is regularly used for economic data and certain types of life data, for example, metal fatigue and electrical insulation life. There is a relation between log-normal and normal distributions (Nelson, 1982). Figure 2.2 shows the Log-normal probability density.

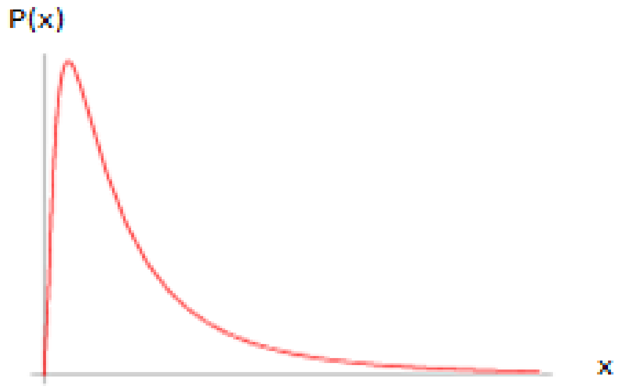


Figure 2.2 Log-normal probability density functions

The log-normal probability density function is

$$P(x) = \left\{\frac{0.4343}{(2\pi^2)x\sigma}\right\} exp\left\{\frac{-[log(x) - \mu]^2}{2\sigma^2}\right\}, \qquad x \geq 0,$$

Where $0.4343 = 1/\ln(10)$.

2.1.1.3. Weibull Distribution

The most commonly used model in modern reliability engineering is the Weibull distribution (Tabikh and Khattab, 2011), named after Waloddi Weibull (1951). It is used in statistical analysis due to its flexibility and ability to handle a small sample size in order to evaluate the lifetime of a system component. The Weibull analysis is the classic reliability analysis, with an exceptional impact on the automobile industry. Since the Weibull and log-normal distributions tend to be better in representing the measurement of product life, these are called the lifetime distributions (Tabikh and Khattab, 2011). There are two- and three-parameter Weibull distribution functions.

The Weibull probability density function is

$$f(x) = \left(\beta/\theta^{\beta}\right)x^{\beta-1}exp\left[-(x/\theta)^{\beta}\right],$$

where θ = scale parameter, also called the characteristic life, since it is always $100 * (1 - e^{-1}) = 63.2\%$ and has the same units as x, and β = shape parameter (or slope), which gives the measure of the shape of the distribution. The reduced density function, called a two-parameter Weibull distribution, is used in probabilistic fracture mechanics and fatigue.

As a result of its flexibility, the Weibull distribution is often used in the field of life data analysis. It can mimic the behaviour of other statistical distributions, such as the normal and the exponential.

- If the failure rate decreases over time, then $\beta < 1$.
- If the failure rate is constant over time, then $\beta = 1$.
- If the failure rate increases over time, then $\beta > 1$.

An understanding of the failure rate may provide insights into what is causing the failures:

- A decreasing failure rate would suggest "infant mortality".
- A constant failure rate suggests that items are failing from random events.
- An increasing failure rate suggests "wear out"; parts are more likely to fail as time goes on.

The Weibull density function can take lots of different shapes. Figure 2.3 shows the density functions (Pascovici, 2008) for the five parts of the engine that are more likely to fail, as follows: combustor, life limited parts (LLP), high pressure compressor (HPC), general breakdowns and high pressure turbine (HPT).

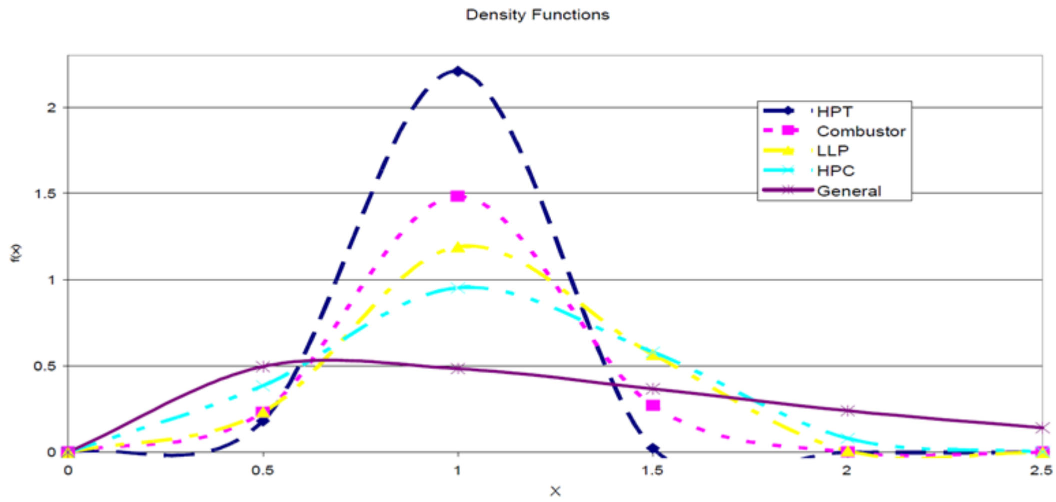


Figure 2.3 Probability density function for five components of the engine

- Parameter estimation methods

According to Dodson (1994), the four most commonly used methods to estimate Weibull parameters are as follows:

- Maximum likelihood estimation

Maximum likelihood estimation (MLE) is one of the most widely used statistics method to estimate Weibull's parameters, based on maximising the value that maximises the probability of the data. Let $X1, X2, \ldots\ldots Xn$ be independent random variables that are the representations of the probability density function $f(x)$.

The likelihood function is maximised by a natural logarithm to simplify the calculations.

- Moment estimation

The moment estimation method is used in estimation parameters by matching the moment of the sample to the moment defined by the distribution. In the case of Weibull's two parameters, the first and second moments for the sample data would be mean and variance, which are equal to:

$$\mu = \theta\Gamma\left(1 + \frac{1}{\beta}\right)$$

and

$$\sigma^2 = \theta^2\Gamma\left[\Gamma\left(1 + \frac{1}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)\right].$$

- Probability and hazard plotting

Both probability and hazard plotting are graphical methods used to estimate the Weibull parameters. The cumulative distributions are linearized by a logarithmic transformation. The median rank is used in the probability approach. Furthermore, a manual approach would require special papers (a special type of worksheet), but due to the high-technology computers, linearisation could easily be done.

2.1.2. Reliability Data Analysis

Reliability engineers analyse the product life data to determine the probability and capability of parts, components and systems to perform their required functions for desired periods of time without failure, in specified environments.

Life data are measures of the lifetimes of products in the marketplace, such as the length of time that the product operated effectively or operated before it failed. These data can be measured in hours, miles, cycles-to-failure, stress cycles or any other unit by which the life or exposure of a product can be measured. There are different types of life data, and because each type provides special information about the life of the product, the analysis method varies, depending on the data type (Nelson, 2005).

Nelson (2005) identifies two types of data:

(1) Complete data – This term means that the value of each sample unit is observed (or known).

(2) Censored data – There are three subtypes, as follows:
   - Right censored (suspended) data refer to the units that have not yet failed when the life data are analysed.
   - Interval censored data reflect uncertainty about the accurate times when the units failed within an interval.
   - In left censored data, a failure time is only identified as being before a certain time.

2.1.2.1. Test Data

Life testing of materials or components that exhibit high reliability requires a long time to obtain data when tested under the conditions of use. In such cases, to reduce test time and test cost, as well as to gain a better understanding of the products' failure modes and their life characteristics, reliability practitioners have applied methods to force these products to fail more quickly than they would under normal-use conditions by applying accelerated life testing.

2.1.2.2. Field Data

Analysis of field failure data is essential in reliability performance studies of automobile components since it captures the actual usage profiles and the combined environmental exposures that are difficult to simulate in the laboratory. Field data are often only available from the maintenance data of automotive companies in the service sector. In fact, maintenance data are a major source of information on the performance of the product in use.

The time and/or mileage during which the maintenance will repair all failures that occur in the vehicle is called the maintenance period. Typically, all the repairs performed throughout the maintenance period at authorised dealerships are recorded in their respective maintenance databases. Field failure data that are extracted from automotive databases are considered complete data, from a statistical perspective.

2.2. Quality and Reliability

Condra (1993) (cited in Meeker and Escobar, 2003) state that “Reliability is quality over time.’’ This indicates that good quality is necessary but not sufficient! One of the major contrasts between quality and reliability is that reliability can be assessed directly only after a product has been in the field for some time; and hence a prediction of accurate reliability presents a number of technical challenges.

2.2.1. Effect of Variability

According to Kackar (1985) variation in a product's performance during its life span is an important aspect of product quality. Deming (1982, p. 20) quotes Lloyd S. Nelson stating that “The central problem of management in all its aspects, including planning, procurement, manufacturing, research, sales, personnel, accounting and law, is to understand better the meaning of variation, and to extract the information contained in variation”. Deming (2000, p. 202) further remarks that “improvement nearly always means reduction of variation" and he includes "knowledge about variation" as one cornerstone in his system of profound knowledge composed of appreciation for a system, knowledge of variation, theory of knowledge and psychology.

The relationships between quality and reliability are illustrated in Figures 2.4 through 2.7. Figure 2.4 reflects the barely acceptable three-sigma quality (Under the assumption of normality, this Three Sigma quality level translates to a process yield of 99.73%) of a particular product characteristic. Although the customers whose purchased product is near the centre of the distribution may be happy with the product's performance, other customers whose purchased product is closer to the specification limits are not fully pleased. As illustrated in Figure 2.5, there will be drift over time caused by wear, chemical change or other degradation, moving more and more customers towards or outside the specification limits and causing serious reliability problems.

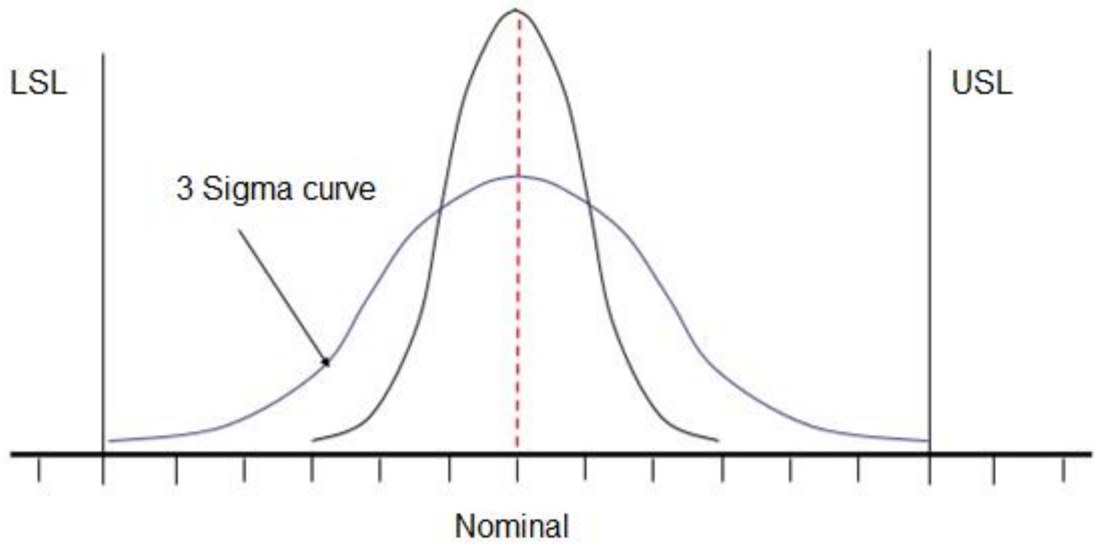


Figure 2.4 Three-sigma quality characteristic

where LSL and USL are the lower and upper specification limits, respectively.

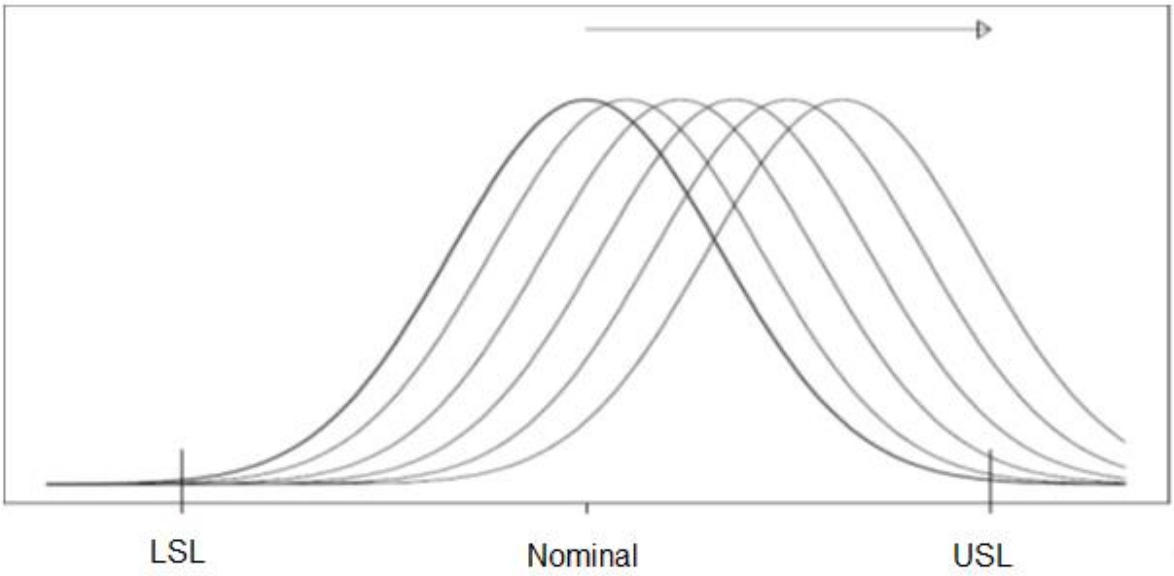


Figure 2.5 Drifting three-sigma quality characteristic

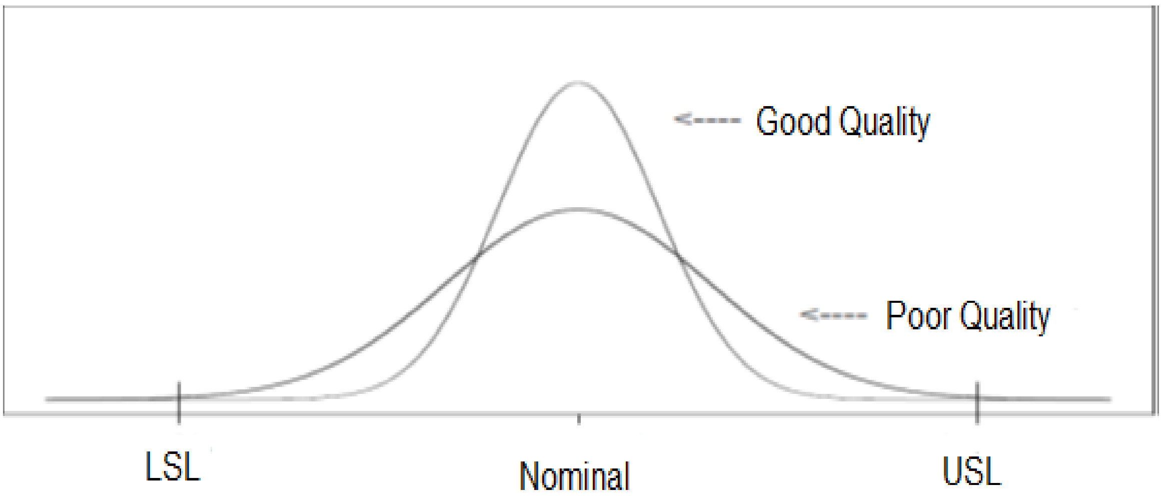


Figure 2.6 Good quality and bad quality

Figure 2.6 shows good quality and poor quality. The point of Figures 2.5 and 2.6 is that it is insufficient for the quality to be within the specification limits. A small variability means that more customers have products close to the target, which are more likely to stay within the specification limits over time, providing higher reliability. As illustrated in Figure 2.7, with good quality, the products will continue to have good performance quality over time or high reliability even with the expected drift over time.

According to Meeker and Escobar (2003), it is often said that variability is the enemy of quality. Variability is also the enemy of reliability. The reduction of input variability and the reduction in the transmission of input variability to the customers' perceivable variability are important goals for engineering design. Based on ideas from statistically designed experiments, Taguchi, (1986) has suggested a methodology that can be used to improve product or process designs by reducing the transmission of variability, called robust design.

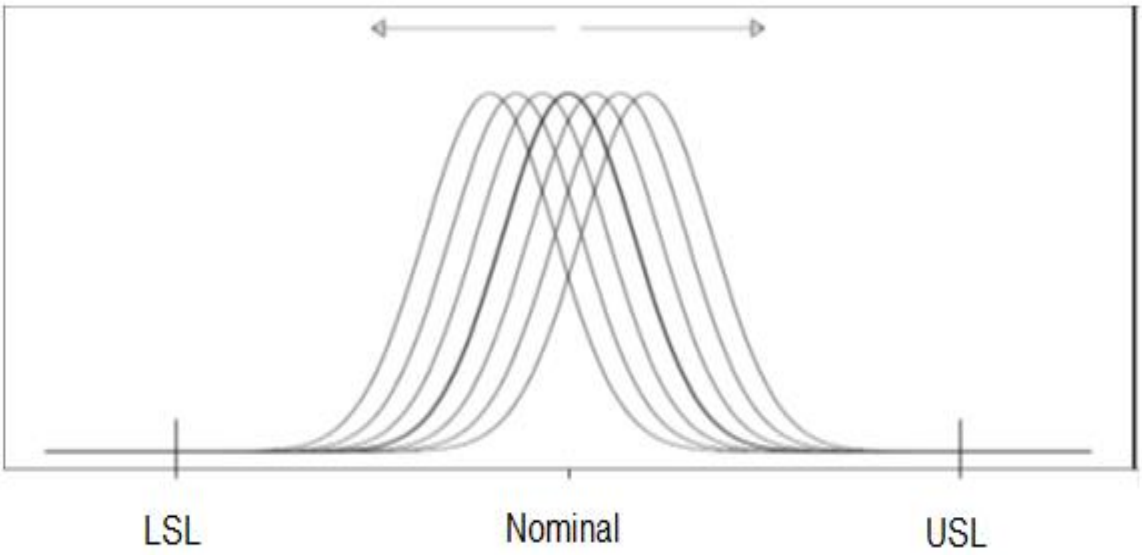


Figure 2.7 Drifting six-sigma quality characteristic

2.2.2. Robust Design for Improved Reliability

Meeker and Escobar (2003) state that robust design is an important, widely known (at least among statisticians working on quality) but still under-used concept in quality and reliability. They define robustness as the ability of a product or a process under various operating and environmental conditions (including long-term wear or other degradation) to effectively perform its intended function. An operational/technical idea of robustness has been derived from Taguchi's important engineering ideas. Using the quality loss function and the confidence of product performance, the product quality is commonly defined and addressed by assessing its reliability (or probability of failure).

2.2.3. Exploring and utilizing transfer functions

Transfer functions are an important concept in identifying control factor settings that yield robust products. Transfer function is defined as the relation between the response and the control factors and noise factors. It may be possible to make the response less sensitive to noise factors (Z) by using suitable non-linear relationships between the response (y) and the control factors (X). Box and Fung (1994) has stated that the transfer function may be known when dealing with relatively well-known physical phenomena. In other cases, when the transfer function is unknown, it may be necessary to make use of simulation and/or physical experimentation to estimate the transfer function.

In this research, the Taguchi loss function can be applied to improve product or process designs by reducing the transmission of variability, using the statistical tools that are developed to control and improve service quality. As shown in Figure 2.8, various environmental noises in service and product use lead to variability in process or product variables (X variables), which in turn causes variability in the quality characteristics (Y variables) that are important to the customer.

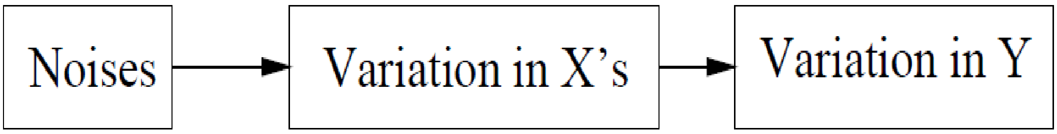


Figure 2.8 Causes of variation in a quality characteristic Y

In terms of probability distributions, these are illustrated with linear transfer functions in Figure 2.9. Note the interaction between X1 and X2 in their relationship with Y. Suppose that X1 is a variable that may be difficult or impossible to control in the operation of the product or process. X2 is a "design" variable that can be chosen by the product/process designers. There are basically two ways to reduce the variability in Y:

- Reduce the variability in the X variables by controlling the maintenance plan more carefully.
- Reduce the transmission of variance through the transfer function.

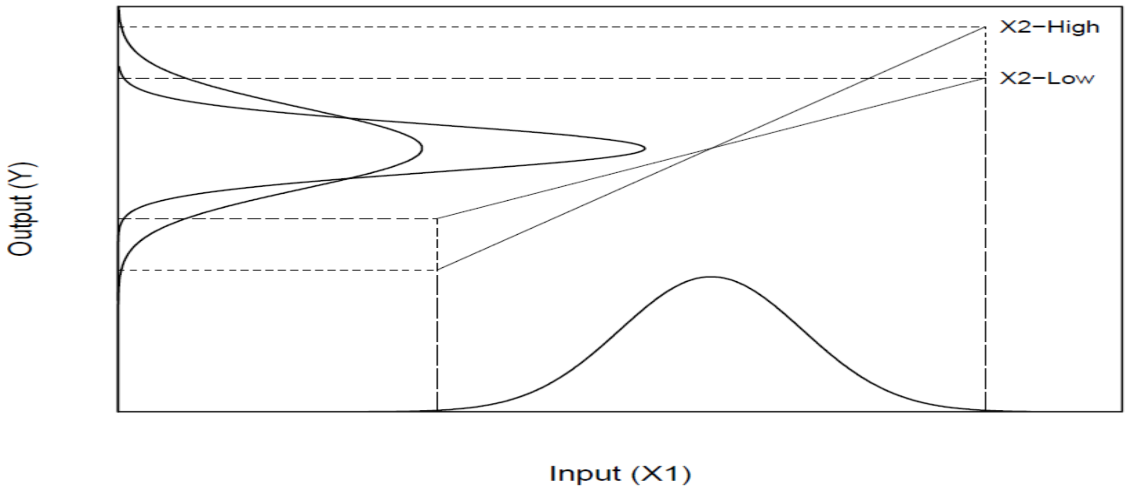


Figure 2.9 Variability transmissions from an input to an output

The former alternative, commonly known as Tolerance Design, is often impossible or unreasonably expensive. However, Figure 2.9 suggests that choosing the lower level of X2 reduces the effect of the X1 variability on the variability of output Y. Exploiting the interaction between a variable (X1) and a design variable (X2) may make it possible to reduce the variability in Y by making relatively inexpensive changes to the level of X2. The suggested new approaches (using the Taguchi loss function) provide a framework that will allow engineers to identify design variables and settings that will lead to a more robust and reliable product.

2.2.4. Process Variance Estimation

Organisations should always consider the source and amount of variability (Senvar and Tozan, 2010). To satisfy customer requirements, organisations must improve product quality by reducing variance in the processes. Less variation of the system provides better quality. In this regard, the variability of critical-to-quality (CTQ) characteristics is a measure of the outputs' uniformity. If the variation is large, the numbers of nonconforming products are large as well. Nonconformance (NC) is the failure of meeting specification limits, in which the specifications are the desired measurements for a quality characteristic.

Specifically, process capability deals with the uniformity of the process. At this point, variability can be assumed in two ways; one is the inherent variability of a CTQ characteristic at a specified time, and the other is the variability of a CTQ characteristic over time. It should be considered that a process capability study frequently measures the functional parameters or CTQ characteristics of a product. It does not measure the process itself (Montgomery, 2009). Process capability compares the inherent variability in a process with the specifications that are determined along with the customer requirements. In other words, process capability is the proportion of the actual process spread to the allowable process spread, which is measured by six process standard deviation units. Process capability compares the output of a process that is in an in-control state to the specification limits by using process capability indices (PCIs).

2.2.4.1. Process Capability Analysis

Statistical process control (SPC) charts serve three purposes (Sauers, 1999). The first purpose is to ensure that the process is in statistical control. The second purpose is to provide alarms when the process shows out-of-control signals. Finally, SPC charts also provide the prerequisite information for process capability analysis (PCA). Typically, $\overline{X} - R$ and $\overline{X} - S$ control charts are the two most commonly used ones. After the process is in statistical control, PCA can be conducted to further examine if the process is capable of producing high-quality products. According to Montgomery (2009), PCA includes statistical techniques that are useful all the way through the product cycle. He states that PCA is often used in development activities prior to the manufacturing process, the quantification of process variability, the analysis of this variability relative to specifications, and the elimination or reduction of the process variability.

As a fundamental technique in any quality and process improvement effort, PCA is claimed to improve processes, products or services to achieve higher levels of customer satisfaction (Senvar and Tozan, 2010). The process capability can be frequently estimated by PCA (Senvar and Tozan, 2010). This estimation can be in the form of a distribution that has the parameters of shape, centre (mean) and spread (standard deviation). For PCA, the following techniques can be used:

- Histograms are defined in statistics as graphical displays of frequencies. In the quality applications, histograms are well known as one of the seven basic tools of quality control.

- Probability plots are useful in estimating the process capability. Moreover, they can be used to determine a distribution's parameters (shape, centre and spread).
- Control charts are valuable for establishing a baseline of the process capability or the process performance. They can be used as monitoring devices to show the effects of changes in the process on process performance.

2.2.4.2. Process Capability Indices

Several statistical methods can be used to measure the capability of a process. The commonly used measures of performance are the PCIs, which relate the natural tolerance limits of a process to the specification limits (English and Taylor, 1993). In practice, $C_{p_k}$and C_p are some of the widely used PCIs.

The PCI C_p is frequently used to express the process capability in a simple quantitative way in an industrial environment. When the parameters are known, that is, when process standard deviation σ is known, PCI C_p is computed as follows:

$$C_p = \frac{USL - LSL}{6\sigma},$$

Where LSL and USL are the lower and upper specification limits, respectively.

For one-sided specifications, C_{pk} is defined as a one-sided PCI for the specification limit nearest the process mean. When the parameters are known, that is, when process mean μ and process standard deviation σ are known, PCI C_{pk} is computed as follows:

$$C_{pk} = \frac{\min(USL - \mu, \mu - LSL)}{3\sigma}.$$

In reality, it is often impossible to know the parameters. Therefore, it is suitable to replace sample mean $\overline{x}$ and sample standard deviation s to estimate process mean μ and process standard deviation σ, respectively. The formula used for estimating C_{pk} is given below:

$$C_{pk} = \frac{\min(USL - \overline{x}, \overline{x} - LSL)}{3s}.$$

Table 2.1 shows the C_p and C_{pk} differences as defined by Montgomery (2009).

Table 2.1 Differences between C_p and C_{pk}

C_p	C_{pk}
• Measurement of the potential capability in the process • Does not consider where the process mean is located relative to the specification limits • Does not deal with the case of a process with the mean that is not centred between the specification limits	• Measurement of the actual capability in the process • Takes process centring into account • Deals with the case of a process with mean μ that is not centred between the specifications limits

2.2.4.3. Taguchi Loss Function

The ability of a process to satisfy customers in terms of specification limits can be examined by PCA. However, it can be more suitable to investigate the costs associated with process variation. Therefore, the Taguchi quadratic loss function can be used to examine the costs. In other words, the Taguchi loss function is generally ideal for modelling the expected costs. The Taguchi quadratic loss function is based on a product's quality characteristics that deviate from the target value. The Taguchi loss function is shown below:

$$L(y) = k(y - m)^2,$$

where L symbolises the loss function, k is constant, Y is the observed value of the quality characteristic, and m is the target value of the quality characteristic.

Taguchi's philosophy highlights the need for low variability around the target as the small deviations from the target result in a loss of quality. As a result, the most capable process produces its product at the target (Senvar and Tozan, 2010).

Actually, PCIs are based on expected loss. Quality improvement efforts deal with reducing variances and discriminating against them as much as possible. For this purpose, there is the increasing importance of clustering around the target rather than conforming to the specification limits, which makes the Taguchi loss function an alternative to PCIs (Senvar and Tozan, 2010).

Taguchi and Wu (1979) argue that every deviation from the target value is a loss to society. In line with this point of view, Kackar (1985) says that "the smaller the performance variation about the target value, the better the quality". This is in contrast with the traditional view on variation that basically implicates that customers are equally satisfied within tolerance limits. Taguchi proposed the quadratic loss function as a general perception of performance variation and as a technique to determine appropriate tolerances. The ideas behind the quadratic loss function concerns identifying the losses that are incurred if the previously defined product characteristic deviates from its target performance.

Box, Bisgaard and Fung (1988) argue that “in more complex examples the loss function idea is less useful because of the difficulty of characterizing and balancing real economic losses”. Although in many cases it might be troublesome and expensive to actually estimate the loss function, it is useful as a mental model to make designers better aware of the consequences of variation. This view is supported by Deming (2000), who argues that “the most important use of a loss function is to help us to change from a world of specifications to continual reduction of variation through improved processes”.

2.2.5. Taguchi Loss Function Applications and Obstacles in Service

Taguchi’s methods of robust design have occasionally been employed in manufacturing settings. It seems that there are virtually limited studies that use Taguchi’s methods to optimise a service-based process. Kumar, Motwani and Otero (1996) have used Taguchi’s robust design principles to improve the response-time performance of an information group operation. They have demonstrated that Taguchi’s methods, previously employed to improve manufacturing processes, can also be applied to upgrade service processes. Taner and Antony (2006) have applied Taguchi’s methods to healthcare. They conclude that the Taguchi loss function can help improve the quality management and measurement of outcomes in healthcare in terms of costs. Kumar, Motwani and Otero (1996) have claimed that this limitation can be partly traced to Taguchi’s original intention to use his robust design to optimise engineering processes. However, as the total quality management (TQM) movement has increasingly taken root in the US and elsewhere, there has been an ever-increasing quest for cost-effective methods that eliminate waste while improving quality. Kumar, Motwani and Otero (1996) clarify that as expected, this quest for higher quality at a lower cost has extended beyond the manufacturing and engineering realms to all business areas, including service and government. In response, organisations are developing new quality tools that improve productivity, quality and flexibility simultaneously (Kumar, Motwani and Otero, 1996). This present research serves this effort by extending the applicability of Taguchi's methods to process optimisation, from manufacturing to a service site. This research aims to establish that an unusually cost-effective tool (previously applied to optimise product specifications and process parameters in manufacturing settings) can be employed, with the same effectiveness, to optimise the factors that influence the maintenance process in service organisations.

Moving away from Taguchi's original intent to apply his methods to manufacturing settings, Kumar, Motwani and Otero (1996) believe that, in service, there are other reasons why Taguchi's methods have not been commonly employed. First, it is very difficult to measure the performance of a service process precisely. This causes problems in applying Taguchi's methods, which in reality depend on the accurate measurement of variations of “quantifiable” parameters of a process. Second, the service process outcome is fundamentally much more diverse in quality than that of its manufacturing counterpart. This is because of the performance of service mainly depends on the behaviour of the humans involved in delivering it. High variation in quality makes it difficult to make real judgements about the process performance since Taguchi's methods depend on only a small part of the total information pertaining to variations. Lastly, compared with their manufacturing counterparts, the service processes generally have more associated “noise” factors. Taguchi, (1986) defines the control factors as those that can be controlled, while the noise factors are difficult, expensive or impossible to control. He argues that since such methods (Taguchi's methods) are well equipped to deal with noise factors the last one is not a limitation. However, regardless of a well-grounded optimisation of controllable factors, the presence of too many noise factors may seriously limit the potential for improving process performances. He concludes that despite these aspects of a service process that actually limit his methods' applicability to it, by appropriately identifying a “quantitative” measure of performance, his concepts of robust designs can be employed to optimise service performance.

2.3. Maintenance Optimisation

In all sectors of manufacturing and service organisations, the importance of maintenance functions and maintenance management has substantially increased. This is due to the continuous expansion in the capital inventory, the requirements for the functioning of systems and the outsourcing of maintenance. Maintenance management is gaining importance, and support from science is needed to improve it. Dekker (1996) and Dekker and Scarf (1998) stated that maintenance management could have benefited from the advent of a large area in operations research, called maintenance optimisation.

In the early 1960s, researchers such as Barlow, Proschan, Jorgenson, McCall, Radner and Hunter started the interest in the development and implementation of maintenance optimisation (Dekker, 1996; Sandve and Aven, 1999). The well-known models originating from that period are the so-called age and block replacement models (Dekker, 1996; Sandve and Aven, 1999). Vasili, Hong and Ismail (2011) argue that for the age-type models, the timing of the maintenance action depends on the age of the system; however, in the block-type models, the timing of the maintenance action is known in advance, depending on neither the age nor the state of the system. According to Sandve and Aven (1999), a maintenance optimisation model is a mathematical (stochastic) one that aims to quantify costs (in a broad sense) and to find the optimum balance between the maintenance cost, on one side, and the associated cost (benefit), on the other. There has been extensive literature on the models for maintenance optimisation (e.g., Vasili, Hong and Ismail, 2011).

The optimisation process can utilise different methods. It can be developed by adding features and conditions that make the maintenance policy more realistic e.g. by taking into account the working conditions, safety issues and perfect and imperfect actions. According to the way they describe and represent natural variability and uncertainty in parameter, model and scenario, maintenance optimisation models are generally classified. The use of deterministic methods does not provide information about potential risks, which results in non-optimal maintenance planning for process plants. However, using the probability distributions, probabilistic models describe and represent natural variability and uncertainty in different cases (Vasili, Hong and Ismail, 2011).

In military logistics two types of maintenance are performed: corrective and preventive maintenance. While corrective maintenance (CM) is repairing equipment when it fails, preventive maintenance (PM) is servicing equipment on regular basis, for example, an interval of operating time. CM involves much uncertainty. It is not easy to predict because the failure of equipment follows stochastic processes. PM, performed according to the operating level of equipment, is relatively easy to forecast like changing engine oil of a car. Two maintenance practices have trade-off relationship such that investment on PM tends to reduce corrective maintenance to a certain level. In this research the application of PM using a predetermined interval will be apply rather than using condition based. Therefore, in the following section, PM optimisation models for the PM predetermined policies are reviewed.

2.4. PM Optimisation Model

According to Vasili, Hong and Ismail (2011), among the different types of maintenance policies, PM is widely applied in large systems, such as production, transport and so on. They state that PM consists of a set of management, administrative and technical actions to reduce the components' ages in order to improve the availability and reliability of a system (i.e., reduction of probability failure or of the degradation level of a system's components). Depending on their effects on a component's age, these actions can be characterised as follows: the component becomes "as good as new"; the component's age is reduced, or the state of the component is slightly affected, only to ensure its necessary operating conditions; and the component appears to be "as bad as the old". Moghaddam and Usher (2011) explain that "preventive maintenance" is a broad term that encompasses a set of activities aimed at improving the overall reliability and availability of a system. All types of systems, from conveyors and cars to overhead cranes, have manufacturer-prescribed maintenance schedules that aim to reduce the risk of system failure (Moghaddam and Usher, 2011). Generally, PM activities comprise inspection, cleaning, lubrication, adjustment, alignment and/or replacement of sub-components that wear out. Moghaddam and Usher (2011) claim that PM involves a basic trade-off between the costs of conducting maintenance/replacement activities and the costs saved by reducing the overall rate of occurrence of system failures. To minimise the overall cost of system operation, PM schedule designers must weigh these individual costs. Subject to some sort of budget constraint, they may also be interested in maximising the system reliability. For the objective functions, other criteria such as availability and demand satisfaction might be considered.

In service organisations, all costs incurred in the machine life cycle can be divided into two categories – maintenance cost and quality loss. Therefore, a balance between maintenance cost and quality loss should be arrived at in the maintenance design for quality improvement and cost reduction. Naidu (2008) reports that generally, although the maintenance cost is lower, loose reliability indicates that the variability of the product characteristic will be high, resulting in poor quality and high-quality loss. On the other hand, tight reliability indicates that the variability of the product characteristic will be less, resulting in very good quality and reducing quality loss but increasing the maintenance cost. Recently, studies have begun to focus on the optimisation of PM policies. Traditionally, optimal PM intervention schedules have been obtained by using models that involve minimisation of the costs incurred in relation to maintenance activities. Considering both PM and quality loss costs, in the following subsections, several models for the optimisation of PM policies are reviewed, and hence, the first contribution of the research is clarified.

2.4.1. PM Cost Optimisation Models

The PM cost model has been widely used in manufacturing and production systems. For example, Charles et al. (2003) present a PM optimisation model to minimise the total maintenance costs in a production system. They consider the total productive maintenance, corrective maintenance and PM actions, along with production operations, as well as the related associated costs. Adzakpa, Adjallah and Yalaoui (2004) present an application of the combination of maintenance scheduling and job assignment in distribution systems. They have developed an optimisation model that considers the TC of maintenance actions as the objective function, availability in a given time window, precedence over consecutive standby jobs and their emergency as the constraints of the model.

Another excellent study that may be applicable to vehicle fleet maintenance is that of Das, Lashkari and Sengupta (2007), who have developed three PM models for maintenance planning in a cellular manufacturing environment. One is the cost-based model that determines the optimum PM interval by minimising the sum of the system failure repair costs and the PM costs. Another is the reliability-based model that determines a common PM interval, subject to an acceptable level of machine failure probability. The third is the combined, multi-objective model that determines the PM interval by taking into account both the costs and the machine reliability. Das, Lashkari and Sengupta (2007) have mentioned that the basic cost-based approach to maintenance planning was developed by Jardine (1973) and was subsequently extended and refined by others (Sherwin, 1997; Talukder and Knapp, 2002). This approach estimates the optimal interval between preventive replacements of equipment, subject to breakdowns, and may be applied to PM and overhaul – assuming that the overhaul restores the equipment to the as-good-as-new condition and that the failure repair between PM actions makes it possible to operate the machine up to the next interval (i.e., it results in the as-bad-as-the-old condition).

The PM cost model has been widely applied in the service sector. For example, Jayabalan and Chaudhuri (1992) present two different PM models for maintaining bus engines in a public transit network, based on minimisation of the TC over a finite planning horizon. They have constructed the models based on the concept of mean time to failure (MTTF) of the engines and have assumed the upper bound for the failure rates. The first model is based on different Weibull failure functions between PM activities, and the second assumes that each PM action reduces the effective age of the system. Pongpech and Murthy (2006) present an optimisation model that minimises the total maintenance costs and penalty costs for used equipment under lease. They have assumed the Weibull distribution as the failure function for the equipment, have developed a four-parameter model and have applied a four-stage algorithm to solve it.

2.4.2. PM and Quality Cost Model

The production process is usually considered as following a deteriorating scheme where the in-control period follows a general probability distribution with an increasing hazard rate. Ben-Daya and Duffuaa (1995) has pointed out the possibility of integration between PM and quality control in two ways. In the first approach, proper maintenance is expected to increase the time between the failures of the machine. The second method is based on Taguchi's (1986) approach to quality, where a quadratic function called the Taguchi loss function is defined. This function measures the deviation of product quality characteristics. The economic design of control charts and the optimisation of PM policies are two research areas that have recently received increasing attention in the quality and reliability literature.

A growing number of researchers have recognised the strong relationships among product quality, process quality and equipment maintenance. Reviews of this research have been provided by Hadidi, Al-Turki and Rahim (2011) and Pandey, Kulkarni and Vrat (2010, 2012). More recently, Shrivastava, Kulkarni and Vrat (2015) present an integrated model that can be used to minimise the expected TC of process failures, inspection, sampling and corrective maintenance/preventive maintenance (CM/PM) actions by jointly optimising maintenance and quality control chart parameters for a cumulative sum (CUSUM) chart.

Taguchi, Elsayed and Hsiang (1989) discuss the effect of maintenance on quality and present some models based on Taguchi's online quality control approach. The basic idea is to perform PM when the amount of deviation in the product characteristic used to measure quality reaches a given threshold. Therefore, it is possible to reduce the deviation from the target and consequently enhance quality by performing PM. Pandey, Kulkarni and Vrat (2012) have developed an integrated model, using the Taguchi loss function for the joint optimisation of the PM interval and the quality control policy of the process, subject to machine failures and quality shifts.

2.4.3. Gaps in Related Research

In the service sector, the performance of the system strongly depends on the breakdown-free operation of equipment. The performance can be improved if these breakdowns can be minimised in a cost-effective manner. The customer satisfaction due to process variation minimisation is also an important issue in the service process. Maintenance and quality control play important roles in achieving this goal. An appropriate PM policy not only reduces the probability of machine failure but also improves the machine's performance in terms of lower costs and higher quality. Similarly, an appropriately designed quality control chart may help in identifying any abnormal behaviour of the process, thereby helping initiate a restoration action. However, both PM and quality control add costs in terms of downtime, repair/replacement, sampling, inspection and so on. Traditionally, these two activities have been optimised independently in the service industry. However, researchers have shown that a relationship exists between equipment maintenance and process quality (Pandey, Kulkarni and Vrat, 2010), and joint consideration of these two shop-floor policies may be more cost-effective in improving the system's performance. Ben-Daya and Duffuaa (1995) state that models that determine the PM schedule, which minimises the quality loss function, can also be developed as extensions and alternatives to the idea proposed by Taguchi, Elsayed and Hsiang (1989). The above-mentioned gaps are addressed in Chapter 4.

2.5. Simulation and Optimisation

Analytics has been defined as "the scientific process of transforming data into insight for making better decisions" (Better, Glover and Kochenberger, 2015). Many organisations are using analytics to make better decisions and reduce risks. To develop more powerful solution methods for many settings where traditional methods fall short, analytics includes well-established methods such as mathematical optimisation, simulation, probability theory and statistics, as well as newer techniques that take elements from traditional methods and modify and/or combine them into robust frameworks. A crucial example of a robust framework is simulation optimisation. As its name suggests, this method combines simulation and optimisation to tackle complex situations where risk and uncertainty do not behave according to certain simplifying assumptions.

Taken individually, each method is critical but limited in scope (Better, Glover and Kochenberger, 2015). Optimisation by itself provides an excellent method to select the best element (in terms of some system performance criteria) from a set of available options, in the absence of uncertainty. In contrast, to better understand the uncertainty in the system's performance, simulation is a tool that allows building a representation of a complex system.

Researchers can develop a powerful framework by combining these two methods, which takes advantage of each one's strong point, so they have at their disposal a technique that allows them to select the best element from a set of choices and simultaneously take account of the uncertainty in the system (Better, Glover and Kochenberger, 2015).

2.5.1. Monte Carlo Simulation

Monte Carlo (MC) simulation is a method used for example by financial companies to simulate and realise the risks related to various investments. The leading advantage of this method is that the normality assumption is no longer a requirement; in fact, the power of the method is that researchers can use statistical techniques to analyse an asset's historical data and forecast its future behaviour by simulating the probable outcomes. This provides freedom from strict assumptions about the probability distribution of the assets. The following steps are typically performed for the MC simulation of any process (Raychaudhuri, 2008).

2.5.1.1. Static Model Generation

A deterministic model that closely resembles the real scenario is the first step of every MC simulation.

2.5.1.2. Input Distribution Identification

Researchers enhance the risk components of the deterministic model when they are satisfied with it. Since the risks originate from the stochastic nature of the input variables, they try to classify the underlying distributions, if any, that govern the input variables. To identify the input distributions for the simulation model, frequently called distribution fitting, there are standard statistical techniques. Numerical methods are used to fit the data to one theoretical discrete or continuous distribution when there are existing historical data for a particular input parameter. For a given set of data, fitting routines provide a way to find the most suitable probability distribution. Distribution fitting is essentially the same as finding the parameters of a distribution that would generate the given data in question; hence, each probability distribution can be uniquely identified by its parameter set. There are limited standard procedures for fitting data to distributions, which are briefly discussed in the following subsections.

(1) Methods for distribution fitting

There are three methods for distribution fitting:

- method of maximum likelihood (ML),
- method of moments and
- Nonlinear optimisation.

(2) Goodness-of-fit statistics

Goodness-of-fit (GOF) statistics are statistical measures that define the correctness of fitting a dataset to a distribution. Other than visual indications through graphs, such as p-p plots or q-q plots, these are mostly used by various software to automate the decision of choosing the best-fitting distribution.

It has two methods:

- chi-square test and
- Empirical Distribution Function (EDF) Statistics.

2.5.1.3. Random Variable Generation

For the input variables, once the underlying distributions are identified, a set of random numbers (also called random varieties or random samples) is produced from these distributions.

2.5.1.4. Analysis and Decision Making

After a sample of output values is collected from the simulation, statistical analysis of these values is carried out.

2.5.2. Monte Carlo Simulation Software

Many options are available for using MC simulations in computers (Raychaudhuri, 2008). A researcher can use any high-level programming language, such as C, C++, Java or one of the. NET programming languages presented by Microsoft, to develop a computer program for generating uniform random numbers, generating random numbers for specific distributions and output analysis. To facilitate the development of the MC simulation code a number of software libraries are also available in most of these high-level programming languages. Some stand-alone software packages can be used for MC simulations (Raychaudhuri, 2008). These are general-purpose simulation software packages, which can be used to model an industry-specific problem, generate random numbers and perform output analysis.

The MC simulations can also be performed by using add-ins to popular spreadsheet software, such as Microsoft Excel. Using this software, a researcher typically starts by developing a deterministic model for the problem and then defines the distributions for the input variables that contain uncertainty. These add-ins to the software are capable of generating charts and graphs of the output parameters for further analysis.

2.6. Process Improvement

Process improvement, also referred to as continuous improvement (CI), is described as a philosophy that, simply stated, involves "improvement initiatives that increase successes and reduce failures" (Deming, 1982).

Process improvement is also defined as "the act of consistently improving process efficiency by targeting waste, variation and poor quality to improve output and make the most out of available resources" (Shamou and Arunachalam, 2008).

2.6.1. Successful Implementation of Process Improvement

To formulate the requirements to be fulfilled by the processes, the development of a quality management system (QMS) should be supported by the use of standards (Pfeifer, Reissiger and Canales, 2004). The most popular and globally known QMS standards are those of the ISO 9000 family. Originally published in 1987, the ISO 9000 family of standards was revised in 1994 and again in December 2000. The revised ISO 9000:2000 is based on eight quality management principles, as follows:

(1) customer focus,
(2) leadership,
(3) involvement of people,
(4) process approach,
(5) system approach to management,
(6) continual improvement,
(7) factual approach to decision making and
(8) mutually beneficial supplier relationships (ISO, 2008).

2.6.2. Need for Process Improvement

According to Deming (1982), process improvement is essential for meeting customers' varying needs. Due to the intense global competition, companies have become more interested in process improvement, which is needed for four main reasons (Misterek, Anderson and Dooley, 1990):

(1) To withstand the competitive market – With higher quality and a shorter delivery lead time, manufacturers should be aware that their rivals are trying to deliver the same products to the customers at lower costs.
(2) To improve quality – It is important to include all activities performed during a product's life, from its creation up to and after it reaches the customer (e.g., product development, supply chain, manufacturing, delivery, service and customer support).
(3) To satisfy customers – Due to higher living standards and education and the Internet, customers' taste for quality has improved. Customers are seeking innovative, tailored, accessory-supported products and products that surprise and delight them.
(4) To ensure the company's flexibility to changes in the market and uncertainty.

2.6.3. Need for Process Improvement in Service Context

The service sector has some obvious disadvantages in the equipment maintenance process, including the following:

(1) During the maintenance process, there is a lack of monitoring, analysis and improvement measures.
(2) In the maintenance quality management process, the methods are simple, the means are backward, and inspection personnel make decisions by guesswork and intuition rather than based on data.
(3) The modern quality management theory is generally not applied in the quality management system. Consequently, the management system is lax, the management is not standardised, responsibilities are unclear, and it is difficult to investigate problems.

2.6.4. Types of Process Improvement Tools

The second wave of improvement tools, which started in the late 1970s and early 1980s, had a wider scope for improvement (Nicholas, 1998). It upgraded the whole manufacturing operation instead of the individual process on the shop floor; therefore, it took the form of programmes that proposed to improve the entire process, from receiving customer orders to delivering products. The following are some examples of these tools:

- total quality management (TQM),
- lean or just-in-time (JIT) manufacturing,
- Six Sigma,
- process re-engineering.

2.6.5. Six Sigma

Six Sigma is a systematic methodology aimed at operational excellence through continuous process improvements. Six Sigma is defined as “a well-established approach that seeks to identify and eliminate defects, mistakes or failures in business processes or systems by focusing on those process performance characteristics that are of critical importance to customers” (Antony, 2008). In the process, Six Sigma has the power to reduce defects and variations and also increase the bottom line and more. According to Jiju Antony et al. (2015), by following the define, measure, analyse, improve, control (DMAIC) steps, which comprise the most common method in Six Sigma, plus some tools and techniques that can be used under DMAIC, Six Sigma is the best solution to company problems with an unknown root cause. Some of these tools and techniques are the Pareto analysis, cause-and-effect diagrams and root cause analysis, among others.

According to Pophaley and Vyas (2015), in the literature, the era from 1986 to 1990, which focused on the elimination of defects, improvement of product and service quality, cost reduction and continuous process improvement, has been referred to as the first generation of Six Sigma. In the second generation in the 1990s, Six Sigma became a business-centric system of management, shifting its focus from product quality to business quality. In the third generation after 2000, many new developments took place, such as the integration of lean manufacturing techniques and Six Sigma, termed as Lean Six Sigma (LSS), and so on. During this time, an integration of maintenance with Six Sigma had also been proposed.

Artiba et al. (2008) report that deploying the concept of Six Sigma into equipment reliability/maintenance applications has lately emerged since this methodology has traditionally been limited to manufacturing and administrative processes. Arifin and Nehzati (2012) state that the review of recent works shows that Six Sigma is appropriate for the maintenance management concept, considering different aspects, such as statistical evaluation. Thomas, Barton and Byard's (2008) Six Sigma maintenance model combines current business management techniques with total productive maintenance (TPM) strategies and offers practising maintenance managers and engineers a strategic framework for increasing productive efficiency and output. Employing a standard operational framework for implementing both approaches is viewed as a clear and necessary step for companies to achieve concurrent benefits from the TPM and Six Sigma strategies (Thomas, Barton and Byard, 2008). Recently, Pophaley and Vyas' (2015) inspection of the gap between plant maintenance practices and the Six Sigma approach has led them to suggest that there is a broad scope in the recommendation of Six Sigma for the maintenance theory. They conclude that for the automobile industry to reach its goals, the maintenance department must implement the Six Sigma programme to change how traditional practices are employed at work for continual improvement of the maintenance function.

2.6.5.1. Six Sigma and Process Capability Relationship

According to Montgomery (2009), to have a reliable estimate of process capability, the process should be stable or be in statistical control. Senvar and Tozan (2010) have stated that the Six Sigma technical elaboration can be achieved through the use of the normal distribution and PCIs. Generally, Six Sigma employed C_p as it was accepted as a standard quality measure. To achieve the predictive performances, Six Sigma was developed to solve the complexity of products and to observe their failures. In a process capability study, such as the Six Sigma methodology, the number of standard deviations between the process mean and the nearest specification limits is given in sigma units. The process sigma level can be used to express its capability, which means how well it performs with respect to the specification limits. In statistics terminology, sigma represents the variation in the process mean. The Six Sigma methodology application provides a reduction in variance and an augmentation in the process capability and process performance at the same time. Important improvements in process capability and process performance can be achieved after a successful implementation of the Six Sigma methodology, which is accepted as a rigorous concept of quality control with this feature.

Six Sigma process can be interpreted in terms of process capability as stated above, which is associated with process variation by using PCI, such as C_{p_k}. Currently, most of the manufacturers are required to produce a product with a specified C_{p_k} value. Organisations are under pressure to keep up with the world-class competition, so they need to meet or exceed this specified C_{p_k} value or quality level. It should be noted that C_{p_k} values are related to how much variation there is in the product or process with respect to the requirements/specifications, as shown in Table 2.2. A higher value of C_{p_k} indicates a better process.

Table 2.2 Process capability ($\mathrm{C_{p_k}}$) implications

Process	C_{p_k}	specification range		Parts Per Million (Ppm) defective
		Long term sigma level	Short term sigma level	
Less capable	1	1.5	3	66,807
Capable	1.33	2.5	4	6210
Very capable	1.67	3.5	5	233
Six Sigma	2	4.5	6	3.4

2.6.5.2. Statistical interpretation of Six Sigma

In Six Sigma process, as its name implies, there are six standard deviations between the process mean and specification limits, when the process is centered. The objective of using Six Sigma approach is to reduce process variation, and thereby defects. The six sigma metric uses DPMO, which is the abbreviation for defects per million opportunities. Here, opportunities represent the number of potential chances within a unit for a defect to occur.

$$DPMO = \frac{total\ number\ of\ defects}{number\ of\ units\ x\ number\ of\ opportunuties}$$

Six Sigma represents a quality level of at most 3.4 dpmo in the long term. Unavoidable assignable causes lead processes to shift 1.5 standard deviations from process mean toward either specification limit that would provide the maximum of 3.4 defects per million. That means Six Sigma measure of process capability allows process mean to shift by up to 1.5 sigma over the long term basis. For Six Sigma process, 3.4 dpmo value is the area under the normal curve beyond 6-1.5= 4.5 sigma. Same logic is valid for three sigma process, that is, 66,807 dpmo value is the area under the normal curve beyond 3-1.5=1.5 sigma (Antony et al., 2005).

For a process that has a lower quality level than Six Sigma, the success rate will decrease significantly when the process shifts. In this point of view, if an organization is operating at Six Sigma level, it is defined as having less than 3.4 dpmo. This corresponds to a success rate of 99.9997%. On the other hand, if an organization is operating at three sigma level, it is defined as having 66,807 dpmo. This corresponds to a success rate of 93% (McClusky, 2000). Therefore, three sigma level cannot be regarded as having good quality performance as it is not good enough for many products or processes that attempt to avoid quality problems in the long run. In general conclusion, Six Sigma is represented by 3.4 defective parts per million (Harry, 1998). This means it is about improving the process capability for all CTQs from all processes in the organization. The goal in a Six Sigma organization is to achieve defect levels of less than 3.4 ppm for every process in the organization and for every CTQ characteristic produced by those processes.

2.6.6. Lean

Lean is a powerful methodology in reducing waste and nonvalue-adding activities in business processes, and it resolves visible problems in an efficient manner. Lean is defined as a “dynamic process of change, driven by a set of principles and best practices aimed at continuous improvement” (Womack et al., 1990, cited in Albliwi et al., 2015). Lean methods are not just a tool for improvement but are also a complete paradigm for corporate management, creating the greatest value for customers and using the smallest investment possible (Cheng and Chang, 2012).

Bokrantz, Ylipää and Skoogh (2014) have conducted a questionnaire survey to map how Lean principles and engineering tools are useful in a maintenance context in the Swedish industry. Their results specify a gap between applying Lean in production and maintenance, as well as the minimal use of valuable engineering tools. They report that applying a variety of Lean tools in a maintenance context can have such effects as reduced over-maintenance, general waste reduction in maintenance activities, and a 10–20% reduction in inventory cost without losing reliability. They also state that there is synergy in the integration of TPM and Reliability-Centred Maintenance (RCM).

Baluch, Abdullah and Mohtar (2012) report that although the core of Lean principles is a commitment to CI and customer satisfaction by striving for perfection and elimination of waste, Lean is best known for its tools, such as 5S (sort, set in order, shine, standardise and sustain), Standardized Work, Kaizen, Poka-yoke and Value Stream Mapping (VSM). These are most commonly applied in the production environment in the direction of targets such as reduced lead time or cost, but they can also be employed for maintenance operations. Examples include Standardized Work for maintenance operators, using signals to initiate corrective maintenance and using VSM to identify and eliminate waste in maintenance operations (Bokrantz, Ylipää and Skoogh, 2014).

Arifin and Nehzati (2012) state that both Lean and TPM are coming together on their way to the common goal of specifying areas of hidden wastes and have evolved in parallel from their early concepts. Additionally, both are approaches that extend all over the company and cover a wide spectrum of techniques. They have both accomplished significant results by delivering practical solutions to different business concerns. Despite the different origins of these approaches, their respective progress can be determined by clarifying wasteful behaviours and practices. The TPM strategy acts as a link between Lean thinking and maintenance towards efficiency improvement and waste reduction. According to Raouf and Ben-Daya (1995), the TPM application within the Lean strategy allows a company to develop advanced techniques in maintenance analysis and to become more "technical" in its approach to problem solving in maintenance.

2.6.7. Total Productive Maintenance

Total productive maintenance (TPM) is a programme that employs an approach for maintaining a plant and its equipment at their optimum level of operational efficiency. The TPM approach mainly links to the Lean concept, targets waste reduction (caused by poorly maintained machinery) and provides value-added inputs by way of certifying that the machinery remains in productive operation for longer periods of time (Ahuja and Khamba, 2008). Maintenance techniques and systems are designed to facilitate their processes, which is achieved through machine redesign and modifications.

The effective adaptation and implementation of strategic TPM initiatives in manufacturing organisations constitute a strategic approach to improve the performance of maintenance activities (Ahuja and Khamba, 2008). The TPM programme brings maintenance into focus as a crucial part of the business. The TPM creativity is targeted to enhance the competitiveness of organisations. It involves a powerful structured approach to change the mindset of employees, thereby making a visible change in the work culture of an organisation. Ahuja and Khamba (2008) state that TPM seeks to engage all levels and functions in an organisation to maximise the overall effectiveness of production equipment. As a result of reducing mistakes and accidents, this method further tunes up existing processes and equipment. Shirose and Guide (1995) claim that TPM demonstrates world-class manufacturing (WCM) creativity that seeks to improve the effectiveness of manufacturing equipment. While maintenance departments are the traditional centre of PM programmes, to ensure an effective equipment operation, TPM aims to involve workers from all departments and levels, from the plant floor to senior executives (Shirose and Guide, 1995).

Nakajima (1989), a major contributor to TPM, defines it as an innovative approach to maintenance through day-to-day activities that improves equipment effectiveness, eliminates breakdowns and supports autonomous maintenance by operators, including the total workforce. Chaneski (2002) states that TPM is a maintenance management programme with the objective of reducing equipment downtime. Nevertheless, TPM is not a maintenance-specific policy; it is a culture, a philosophy and a new attitude on the road to maintenance.

According to Ahuja and Khamba (2008), the pillars or elements of TPM are its basic practices. Its whole edifice is built and stands on eight pillars. Through its unique eight-pillar methodology, TPM paves the way for excellent planning, organising, monitoring and guiding practices. The TPM initiatives, as proposed and promoted by the Japan Institute of Plant Maintenance (JIPM), involve an eight-pillar implementation plan that extensively increases labour productivity through controlled maintenance, lower maintenance costs and reduced production stoppages and downtimes. The main TPM initiatives, classified into eight pillars or activities to accomplish the manufacturing performance improvements, are autonomous maintenance; focused maintenance; planned maintenance; quality maintenance; education and training; office TPM; development management; and safety, health and environment (Ahuja and Khamba, 2008). Figure 2.10 shows the JIPM's eight-pillar TPM implementation plan.

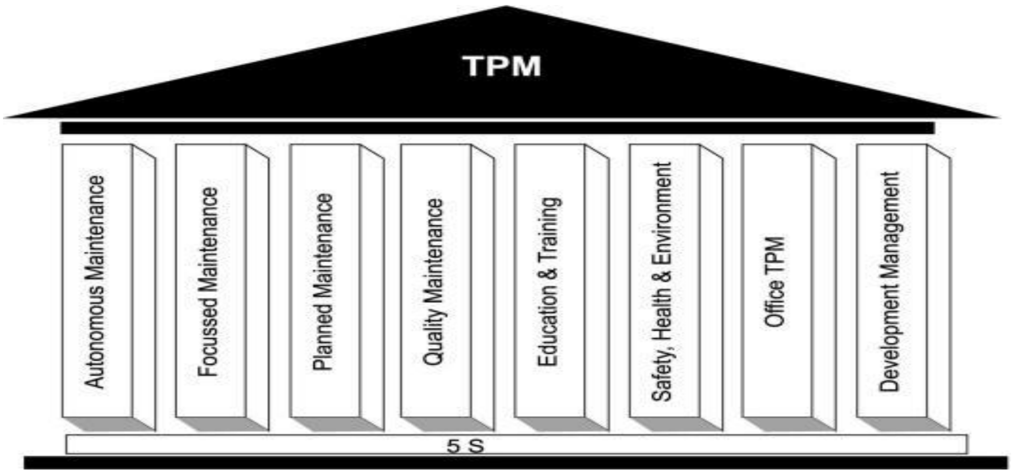


Figure 2.10 Eight-pillar approach for TPM implementation as suggested by JIPM (Ahuja and Khamba, 2008)

Chan et al. (2005) specify that from a generic perspective, TPM can be defined in terms of overall equipment effectiveness (OEE), which in turn can be considered a combination of operation maintenance, equipment management and available resources. They state that the OEE is the core metric for measuring the success of the TPM implementation programme. Thus, the goal of TPM is to increase the OEE (Waeyenbergh and Pintelon, 2002).

According to Nakajima (1988), OEE measurement is an effective way of analysing the efficiency of a single machine or an integrated system. It is calculated by obtaining the product of the availability of the equipment, the performance efficiency of the process, and the rate of quality products, expressed as follows:

$$OEE \ = \ A \ x \ PE \ x \ Q,$$

where A is the availability of the machine. Availability can be expressed as the ratio of actual operating time to loading time:

$$\mathrm{A} = \frac{\text{loading time}}{\text{loading time} - \text{downtime}}$$

where loading time is the planned time available per day (or month) for production operations, and downtime is the total time during which the system is not operating because of equipment failures, setup/adjustment requirements, exchange of dies and other fixtures, and so on.

The performance efficiency (PE) is calculated as

$$\text{performance efficiency} = \frac{\text{design cycle time} - \text{output}}{\text{operating time}}$$

where the design cycle time is in a unit of production, such as parts per hour, the output is the total output for a given time period, and the operating time is the availability value from previous formula.

Finally, Q refers to the quality rate, which is the percentage of the good parts out of the total produced, sometimes called the "yield".

Referring to Ahuja and Khamba (2008), TPM has the standards of 90% availability, 95% performance efficiency and 99% rate of quality. They claim that an overall 85% benchmark OEE is perceived as world-class performance.

2.6.8. Lean Six Sigma

Lean Six Sigma (LSS) has become the most popular business strategy for CI in the manufacturing and service sectors, in addition to the public sector (Albliwi et al., 2014). This powerful CI methodology is a combination and synergy between Lean thinking and Six Sigma. Snee (2010) defines LSS as “a business strategy and methodology that increases process performance, resulting in enhanced customer satisfaction and improved bottom line results”. It applies the tools and procedures of both Lean manufacturing and Six Sigma.

As stated earlier, LSS combines Lean methods and Six Sigma, using specific DMAIC processes to provide companies with better speed and lower variance in increasing customer satisfaction (George, 2002). The first phase in DMAIC is defining project objectives and customer needs. The second phase entails measuring errors and process performance, as well as quantifying problems. The third phase involves analysing the data and finding the causes of defects. The fourth phase is improving, which means eliminating the causes of defects and reducing errors. The final phase includes controlling the process and maintaining performance, thus improving performance.

According to Antony (2015), LSS as a methodology is not a standardised procedure, so it can be used in different sectors. A variety of methods is also used to apply the LSS, according to the literature. Moreover, LSS has been applied by several sectors and industries (Antony, 2015). Although most of the LSS examples come from the manufacturing industry, Psychogios and Tsironis (2012) mention a few instances of the application of LSS in the service industry, both public and private. There is evidence of the effective implementation of LSS in military organisations, such as the US Army. There are cases of healthcare services and local government organisations that have applied LSS.

Apte Uday and Kang, (2006) has reported that the LSS methodology was developed in the private sector. To the extent the competitive environment it is necessary that the LSS methodology be suitably modified in its implementation in the military, the organizational culture and the nature of operational challenges are considerably different in private sector firms than in the Department of Defense. They have stated that while the organizational culture and the nature of operational challenges are important and must be carefully analysed by military planners, the benefits of reduced lifecycle costs and improved readiness that can be realized from implementing Lean Six Sigma are simply too great. They conclude that implementing

Lean Six Sigma in the military is a strategically important logistics initiative and recommend that it be undertaken under full steam.

2.7. Importance of LSS in Equipment Maintenance Process

The implementation of current maintenance management systems has not reached the expected level of success (e.g., maintenance schedules are not implemented on time, and priorities are difficult to identify) (Aldairi, Khan and Munive-Hernandez, 2015). The underlying reason is the lack of maintenance management skills and execution experience, which leads to poor impacts and negative effects on performance (Aldairi, Khan and Munive-Hernandez, 2015). Unnecessary repair or inspection will definitely increase maintenance budget commitments and decrease quality performance, as described by Milana, Khan and Munive (2014) regarding the waste in the maintenance area. These issues indicate that maintenance processes have nonvalue-adding steps that need CI.

Wang, Wang and Xu (2012) have reported that LSS can be applied to the quality management of equipment maintenance to correct the deficiencies and the inefficiency in the equipment maintenance process. They conclude that the LSS implementation in equipment maintenance should uphold the CI philosophy and constantly renovate the management concept to enhance equipment maintenance capability. Conversely, the deployment of LSS in maintenance in the service sector is still far behind. From the practitioners' standpoint, there might be several reasons for this lag, including the complex organisational structure, the multifaceted organisational objectives and the practical fact that waste and rework are not as visible in maintenance as in manufacturing, where scrap material and queuing have a physical manifestation.

2.8. Need for Integrated Model of LSS and Maintenance Process Optimisation

According to Dhillon (2006), maintenance takes up 60–75% of a large system's or a product's life cycle costs. This automatically poses a challenge to the maintenance management in validating asset performance and allocating the required funds. One of the main reasons behind the weaknesses in maintenance management systems is the lack of experience, which results in imprecise information obtained for decision making, thus losing control of priorities (Aldairi, Khan and Munive-Hernandez, 2015). The performance of the maintenance operations management should be analysed and reviewed constantly to achieve high service quality (Aldairi, Khan and Munive-Hernandez, 2015). However, in maintaining a consistently high performance level, the traditional approach leads to over-exhaustion of resources. Thus, a newer strategy is required to address these problems.

Moreover, equipment maintenance has high requirements in terms of speed, quality and cost reduction. However, some shortcomings in the quality management system affect and restrict the quality and efficiency of equipment maintenance and cause high costs. Maintenance management is gaining importance, and support from science is needed to improve it. Maintenance management could have benefited from the advent of a large area in operations research, called maintenance optimisation. Hammer (2002) argues that various improvement initiatives should be positioned in the larger context of process management, consistent with Zhao, Ye and Gao's (2012) suggestion that LSS be introduced to the process optimisation system to accomplish the aim of CI for the equipment maintenance process. This gives a reason to develop a management system that can integrate LSS as an advanced quality philosophy and process optimisation for vehicle fleet maintenance to support the decision-making process. Therefore, this research introduces the LSS framework (the most advanced process optimisation method) into the process optimisation model to build an integrated methodology for the vehicle fleet maintenance process.

2.9. Chapter Summary

In this chapter, recent works pertaining to the methods of PM optimisation and process improvement that use LSS frameworks have been reviewed. They have been categorised as PM optimisation models, LSS, and integrated LSS framework and optimisation methodology. Two parallel developments for determining the PM optimum interval have been found, one based on the maintenance cost without considering the quality loss, and the other one based on the quality loss without considering the maintenance cost. Not much work has been done in integrating the LSS framework and optimisation methodology in service organisations. Hence, this study proposes to develop PM models that deal with these two costs (maintenance and quality loss). It also aims to build an integrated model to combine LSS and the optimisation methodology. These are the contributions of this research, which are applied to a real system.

3. Methodology

The research methodology refers to how research is done scientifically. Various steps that are considered in the research process are emphasises to obtain insights or a solution to a given problem. The aim is to guide the implementation of correct procedures to solve the problem.

3.1. Literature Review

In the first stages of this project, a literature review was conducted to find the theory that would be applicable to the research. The literature about both LSS and optimisation was studied, especially the works involving the application of LSS and optimisation in the service industry and operations. The integration of LSS and optimisation into a single strategy was also investigated since it was decided that the project would contain elements of both approaches.

3.2. Mathematical Model Development

Fleet maintenance management refers to the process of scheduling and allocating resources to the maintenance activities (repair, replacement and PM) associated with a fleet of equipment. The true impact of mathematical modelling has not been realised in maintenance applications, and the benefits of coordinating maintenance efforts across an entire fleet have not been fully investigated. For these reasons, the new opportunity for significant gains in service organisations is the application of mathematical modelling techniques to develop comprehensive maintenance plans for fleets of equipment. The mathematical model of process optimisation for equipment maintenance includes three steps, as shown in Figure 3.1.

(1) The first step is to develop the mathematical model.

The link between maintenance and quality, although not completely missing, is not adequately addressed in the literature. Although the link has been identified by TPM, there are no adequate models relating quality and maintenance. The literature review shows that the developments for determining the optimum maintenance activity in the service industry have been based on the maintenance cost without considering the quality loss. Ben-Daya and Duffuaa (1995) point out the possibility of integration between PM and quality control, based on Taguchi’s (1986) approach to quality, where a quadratic function called the Taguchi loss function is defined. According to Ben-Daya and Duffuaa (1995), the models that determine the PM schedule that minimises the quality loss function can also be developed as extensions and alternatives to the idea proposed by Taguchi, Elsayed and Hsiang (1989). Therefore, this research bridges this gap by providing a mathematical model to determine the optimum maintenance activity by combining the PM cost and the quality loss cost.

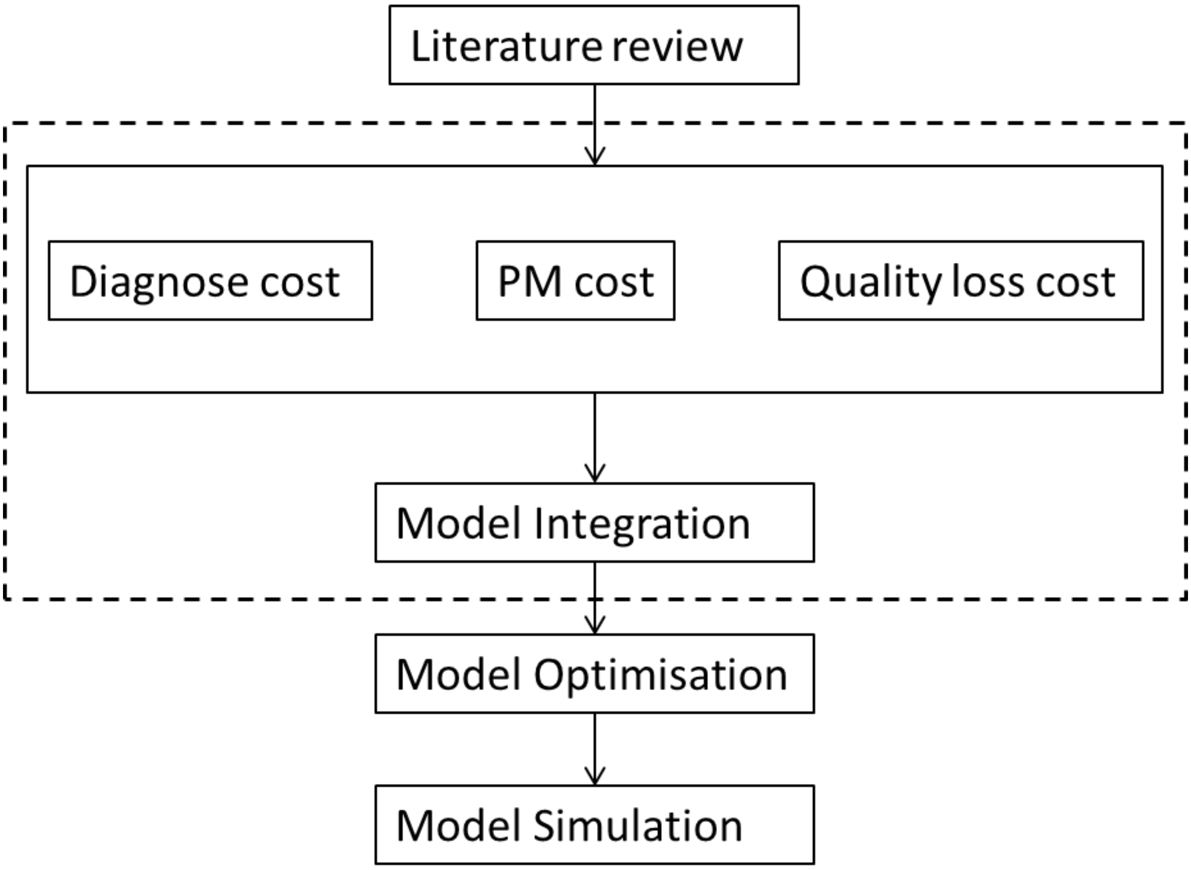


Figure 3.1 Equipment maintenance process optimisation model

In this step, an integrated TC model is developed for the joint determination of the PM activity cost and the quality loss cost. The total expected cost of the model consists of diagnosis cost, PM cost and quality loss cost. The literature on the present mathematical models for the PM cost is reviewed to identify the best model that will be used to determine the PM cost in vehicle fleet maintenance in service organisations. As an extension and an alternative to the idea proposed by Taguchi, Elsayed and Hsiang (1989), the classical form of the Taguchi loss function will be used to determine the quality loss cost by reducing variability and staying closer to the target value for the multi-quality characteristic in vehicle fleet maintenance.

(2) The second step is to determine the process optimisation.

This step is done by applying a numerical solution, using Matlab. The problem is to determine the values of the decision variables n and tmp, which define the inspection interval and the PM interval, respectively, and minimise the expected TC.

(3) The last step is to improve decisions under conditions of uncertainty.

The following steps are typically performed for the MC simulation of a physical process (Raychaudhuri, 2008).

- Static model generation: In this step, the most likely value of the input parameters is used. The mathematical relationships that use the values of the input variables are applied and transformed into the desired output.
- Input distribution identification: The risk components are added to the model in this step. This step needs historical data for the input variables. Also, to identify the input distributions for the simulation model, frequently called distribution fitting, there are standard statistical techniques as mentioned in literature.
- Random variable generation: This step is the core of the MC simulation. After identified the fundamental distributions for the input variables, a set of random numbers (also called random variates or random samples) is generated from these distributions. To provide one set of output values a one set of random numbers will be used in the deterministic model, consisting of one value for each of the input variables. This process is repeated to generate more sets of random numbers, one for each input distribution, and collect different sets of possible output values.
- Analysis and decision making: Statistical analysis is performed after a sample of output values is collected from the simulation. This step provides researchers with statistical confidence for the decisions that they might make after running the simulation.

3.3. Integrating LSS and PM Optimisation in Vehicle Fleet Maintenance in Service Organisations

Services represent a major portion of the economies of the world's most industrialised nations, and they have experienced significant growth over the past several decades. Even in less developed countries, the service sector still accounts for a substantial part of their economies (Su, Chiang and Chang, 2006). The service industries not only have grown in size; along the way, they have also absorbed all the jobs shed by traditional industries, such as agriculture, mining and manufacturing. By the mid-1990s, the service industries employed nearly 80% of the workforce in the US (Su, Chiang and Chang, 2006).

In service applications, the revenue growth potential of improving the speed and quality of service often overshadows the cost reduction opportunities (George and George, 2003). However, services are frequently criticised for being delivered at a slow pace due to excessive waste in the service processes, leading to the inflated cost of services and the deterioration of service quality. Moreover, one of the characteristics of service is heterogeneity, which refers to variations in the level of customer service, resulting in poor service quality and customer dissatisfaction (Su, Chiang and Chang, 2006). These issues represent a huge opportunity to improve the service quality by increasing the speed of service delivery and reducing the variations in the service level.

Figure 3.2 represents the conceptual model for the research topic as it relates to the integration of LSS and optimisation as an improvement methodology that is expected to yield positive organisational performance.

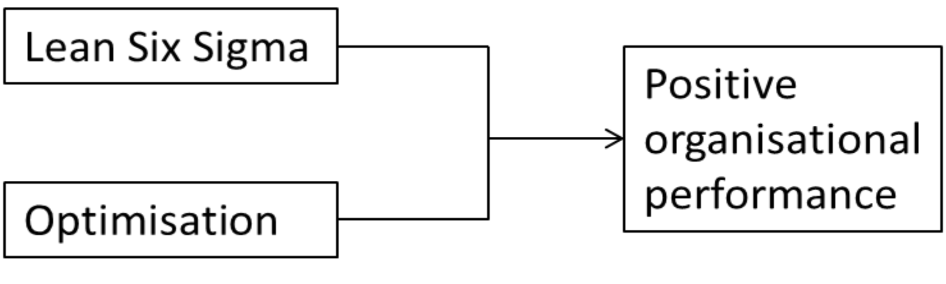


Figure 3.2 Lean Six Sigma and optimisation

Maintenance management is gaining importance, and support from science is needed to improve it. In theory, maintenance management could have benefited from the advent of a large area in operations research, called maintenance optimisation. On the other hand, LSS is a fusion of Lean efficiency engineering and Six Sigma quality control. Lean improvements focus on process speed and waste removal, while Six Sigma concentrates on the elimination of process defects and the reduction of process variability. Therefore, it is necessary to conduct an in-depth study of the concept of the integration between LSS and optimisation methods, analysing the problems in the quality management of equipment maintenance and taking effective measures to improve the level of quality.

In the actual process optimisation of equipment maintenance, a method based on the business process model and simulation, business process optimisation software and other methods should all be introduced into the LSS process optimisation system to create a more powerful toolbox and ultimately accomplish the general aim of CI for the equipment maintenance process (Zhao, Ye and Gao, 2012). Based on this view, this research introduces the LSS framework (the most advanced process optimisation method) into the process optimisation model to build an integrated methodology in service organisations. This integration is applied by using the following steps:

3.3.1. LSS Framework

The primary research framework for this step is the DMAIC cycle of Six Sigma. This has been chosen since the researchers gained an understanding of the framework from previous projects and considered it highly suitable for executing these types of improvement projects. Using the DMAIC cycle, the following procedure has been applied:

3.3.1.1. Definition Phase

The define phase is divided into three elements:

(1) Significance of the problem. The LSS requires that the situation under analysis be proven as significant cost wise, with solid facts. The objective of this step is to prioritise the costly problems.

(2) Scoping of the problem. The LSS suggests limiting the problem to a manageable yet significant size.
(3) Baseline performance. The LSS requires an initial baseline performance analysis to gauge the recommended improvements when implemented at a later stage.

3.3.1.2. Measurement Phase

The following items should be considered during the measurement phase of the LSS methodology:

(1) Ensure the adequacy of the measurement system. The LSS requires that the data used for the analysis be verified for accuracy.
(2) Determine the current performance of the service process (process yield, defects per million opportunities (DPMO), short-term and long-term capability and OEE).
(3) Decide what to measure (a CTQ characteristic) and how to measure it.
(4) For a specific CTQ characteristic, the sigma level can be calculated. Hence, the sigma level of a process can be used to express its capability, which means how well it performs with respect to specifications.
(5) Identify the strengths and weaknesses, and determine the gaps for improvement.

3.3.1.3. Analysis Phase

(1) To ascertain the root cause(s) of a high level of machinery failure, an analysis using the cause-and-effect diagram is carried out, and the reasons are identified during a brainstorming session by the LSS team.
(2) Next, the team creates failure modes and effects and conducts a criticality analysis on each of the areas identified from the failure routes on the cause-and-effect diagram. This phase includes the estimation of the Weibull parameters, following a four-step procedure:
    - Define the scope.
    - Collect the data.
    - Plot the data.
    - Estimate the parameters.

The first step is to precisely define the time origin for the analysis. For vehicle components, the time origin is marked by the installation of the components in the vehicle. The passage of time is measured in months of operation, and failure is a component's inability to perform according to the specifications.

The next step is to obtain the data on each component in the analysis. Each observation is identified as either a failure or censored; the latter term refers to engines that have not failed prior to the conclusion of the sampling period.

The third step is to plot the failure data to verify that they conform to a Weibull distribution. Computing the plotting positions for the failures involves approximating the true values of the Weibull cumulative distribution function. Nelson (1982) presents a variety of methods for computing both probability and hazard plotting positions. Regardless of the technique employed, the data must be plotted. Only the failures are plotted although the censored data define the relative plotting position. The plotted points should lie in a relatively straight line if the data conform to a Weibull distribution.

Fourth, once this requirement has been satisfied, the Weibull parameters may be estimated. The two generally accepted methods are ordinary least squares regression and MLE.

3.3.1.4. Improvement Phase

Suggested improvements can be applied in this step, based on the analysis results. This step also discusses the implementation of TPM in the case study.

3.3.1.5. Control Phase

Once the process is verified as having improved, continuing this improvement is very important. Even well-planned maintenance processes still depend on shifts and drifts. Without close monitoring and control methods, problems can remain undetected till they become serious.

3.3.2. Optimisation Method

Using the mathematical model proposed in Chapter 4, this step is applied to improve the maintenance plan and decrease the TC. The previous step with the DMAIC process is used to obtain the model input data. Then the steps in the mathematical model development section are followed to obtain the model optimisation results and to improve the decisions under conditions of uncertainty.

3.3.3 Advantages of Systematic Integration of Both Approaches

The following are the benefits of systematically integrating both approaches:

(1) an effective process to identify the most relevant improvement areas,
(2) the assurance of a conforming project and process objectives and thus the sustainability of LSS projects,
(3) the choice of the most capable project participants and minimisation of the qualification effort,
(4) the fulfilment of all organisational requirements designed for conducting projects by using standard procedures and measures,
(5) increased availability of project experiences through well-structured documentation facilities,
(6) making decisions that are determined by customer satisfaction,
(7) data-driven decision-making and scientific-based changes,
(8) quality improvement based on decreasing variations and
(9) a highly structured, company-wide approach towards education and training.

3.4. Integrated Approach Validation through Application of a Case Study in the Maintenance Process of a Service Organisation

The LSS and optimisation can improve the efficiency of processes, upgrade the quality of service delivery to customers and reduce the costs of providing these services. The author validates the LSS framework and optimisation method by applying it to the processes in vehicle fleet maintenance. This demonstrates how the tools and problem-solving approach of LSS can be used to streamline the processes and reduce their completion time. The author assumes that LSS can be similarly applied to other maintenance processes in service organisations. Based on the LSS framework and optimisation, a real case study is used to validate this proposed new approach.

The LSS problem-solving approach known as DMAIC, along with optimisation tools, are used to improve the processes. A successful implementation will be measured by the reduction of the total PM cost, the reduction of the PM activities, and customer satisfaction. No quantitative or qualitative measures of process or quality characteristics existed prior to the LSS and optimisation implementation for any of the maintenance processes, but these are developed within the case study.

3.5. Methodology Summary

Figure 3.3 summarises the framework methodology. It identifies the activities performed during the research.

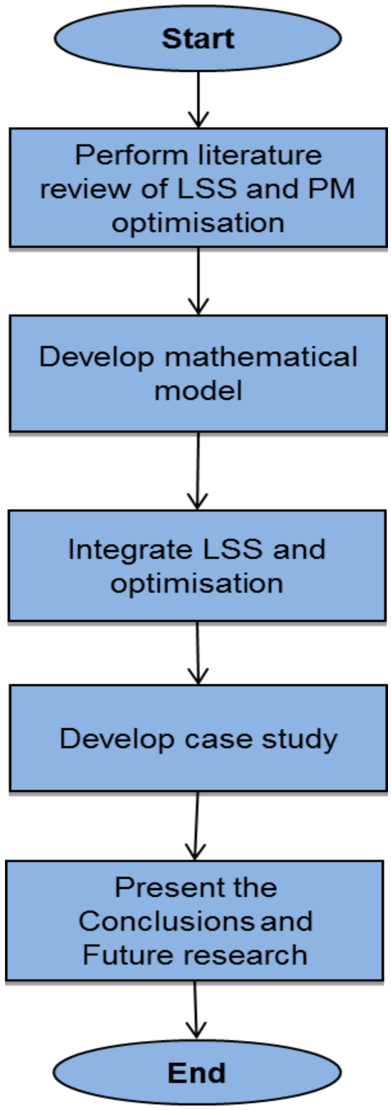


Figure 3.3 Methodology flow chart

4. Development of the Mathematical Model to Optimise PM Activities in Service Organisations

This chapter presents a PM, total cost-optimisation approach to bring both quality and reliability issues simultaneously in a single objective function. The proposed approach determines the optimal maintenance interval and minimises the combined PM maintenance and quality loss costs. It ensures a reliable, robust and concurrently cost-effective product design by satisfying all the desired quality characteristics.

4.1. Introduction

Throughout the years, there has been tremendous pressure on manufacturing and service organisations to be competitive and provide timely delivery of quality products. Any loss of production in many heavily automated and capital-intensive industries, which are due to equipment unavailability, intensely reduces company profits. This new environment has forced managers and engineers to optimise all sectors involved in their organisations.

Preventive maintenance involves repair, replacement and maintenance of equipment and products before their failures to avoid unexpected breakdowns during their use. The objective of PM is to minimise the downtime of equipment. However, excessive PM results in unnecessary costs. Therefore, an optimal PM schedule minimises the TC of repair and the downtime of equipment.

Preventive maintenance, as it affects the online quality control system, may involve two areas of application (Taguchi, Elsayed and Hsiang 1989). The first is the quality control of the characteristics of the products or equipment. The second is the reduction of the expected failures of the machine during the operation. A machine may fail by its inability to meet the quality requirements. A machine failure may also be its sudden breakdown during the operation. The failure of either type can be reduced by employing a PM schedule (Taguchi, Elsayed and Hsiang, 1989). However, both will add costs in terms of downtime and repair/replacement.

Traditionally, these two activities have been optimised independently (Pandey, Kulkarni and Vrat, 2012). However, researchers have shown that a relationship exists between maintenance and quality (Pandey, Kulkarni and Vrat, 2010), and joint consideration of these two shop-floor policies may be more cost-effective in improving the system performance. Recent literature indicates that such joint consideration has started receiving attention from the research community. Naidu (2008) reports that generally, loose reliability (less frequency of maintenance) indicates that the variability of the product characteristic will be high, resulting in poor quality and high-quality loss. On the other hand, tight reliability (increased frequency of diagnosis) indicates that the variability of the product characteristic will be less, resulting in very good quality and reducing quality loss but increasing the PM cost, as shown in Figure 4.1. Hence, the TC that consists of quality loss and PM cost is applied to find the most economical and efficient way of determining the maintenance intervals.

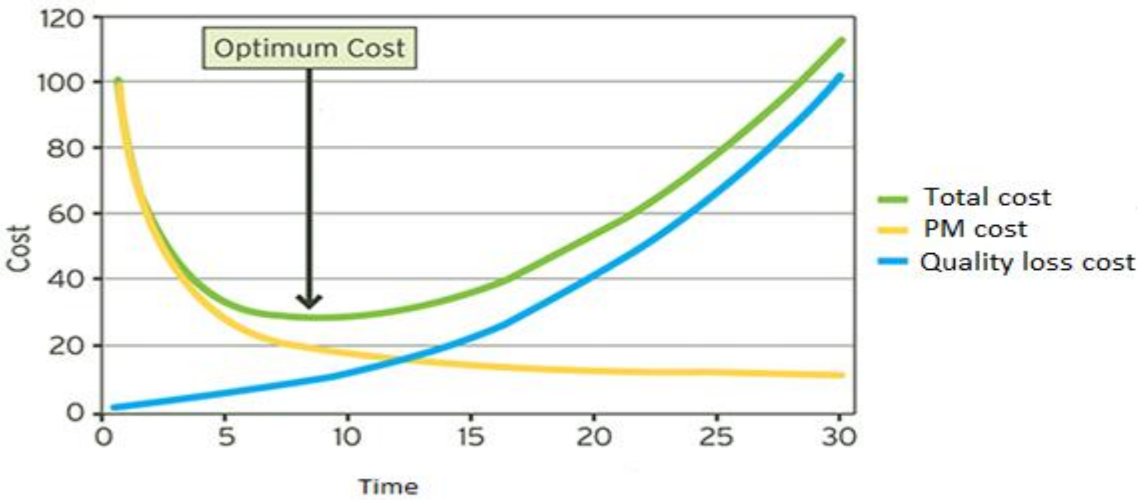


Figure 4.1 Optimal costs

4.2. Mathematical Model Development

A mathematical model is named deterministic if all parameter values are assumed to be known with certainty; it is called probabilistic if it involves quantities that are known only as probable (Rardin, 1998). The PM methods can be classified as either deterministic or probabilistic (Taguchi, Elsayed and Hsiang, 1989). Deterministic problems are those in which the timing and outcome of a maintenance action are assumed to be known with certainty. Probabilistic problems are those where the timing and outcome of the maintenance rely on probability. In the simplest situation, the machine may be good or bad. The probability describing the operating status of the machine may be obtained by using a random variable whose distribution may be termed the machine failure distribution.

The failure distribution of a machine plays a major role in deciding on its optimal PM schedules (Taguchi, Elsayed and Hsiang, 1989). Vasili, Hong and Ismail (2011) also claim that the use of deterministic methods does not provide information about potential risks, which results in non-optimal maintenance planning for process plants. However, probabilistic models use probability distributions to describe and represent the natural variability and uncertainty in different cases.

Therefore, this chapter focuses on the development of an integrated probabilistic model that can be used to minimise the expected TC of a PM action by jointly optimising both types of application.

4.2.1. Assumptions and Notations

The following assumptions and notations are made in the model development. Table 4.1 shows the notation used in the model development.

Table 4.1 Notations

y	Quality performance of the considered quality characteristic		
$TC_M\ (tpm)$	PM cost as a function of maintenance interval		
TC	Total cost as a function of maintenance interval 'tpm'		
n	Checking interval (to check the amount of deviation)		
k	Cost coefficient of quality loss function		
A	Value of the loss at which PM should be performed		
z	Number of machines	Co	PM fixed cost
tpm	Maintenance interval	$CPRM_j$	PM average cost of machine j
m	Target value	cf_j	Repair cost of machine j
μ	Process mean	σ^2	Mean squared deviation
σ_m^2	Measurement error	Γ	Gamma function
L	Quality loss function	F_0	Failure probability control limit
C_{meas}	Measurement cost	PM	Preventive maintenance
β	Shape parameter	θ	Scale parameter

Before setting up the model, assume the following hypotheses:

(1) During the period of PM, breakdown maintenance will be performed after the equipment breakdown. This activity cannot change the system failure rate.

(2) The not-working time after the equipment breakdown can be ignored.

(3) The quality characteristic of the product is maintained very close to its target value; hence, the reworked components will not have any quality loss.

4.2.2. PM Total Cost Model

In this chapter, the PM TC model is developed for large-scale systems, such as the vehicle fleet maintenance system. Vehicle components are subject to deterioration over time; therefore, periodic diagnoses are needed in conjunction with the PM schedule. Moreover, variability is one of the root causes of poor product performance and results from variations due to degradation, which lead to variations in the actual expected values of the quality characteristic. Therefore, the variability in quality characteristics must be considered in the PM TC model. Figure 4.2 shows the PM applications and the development process for the PM TC model.

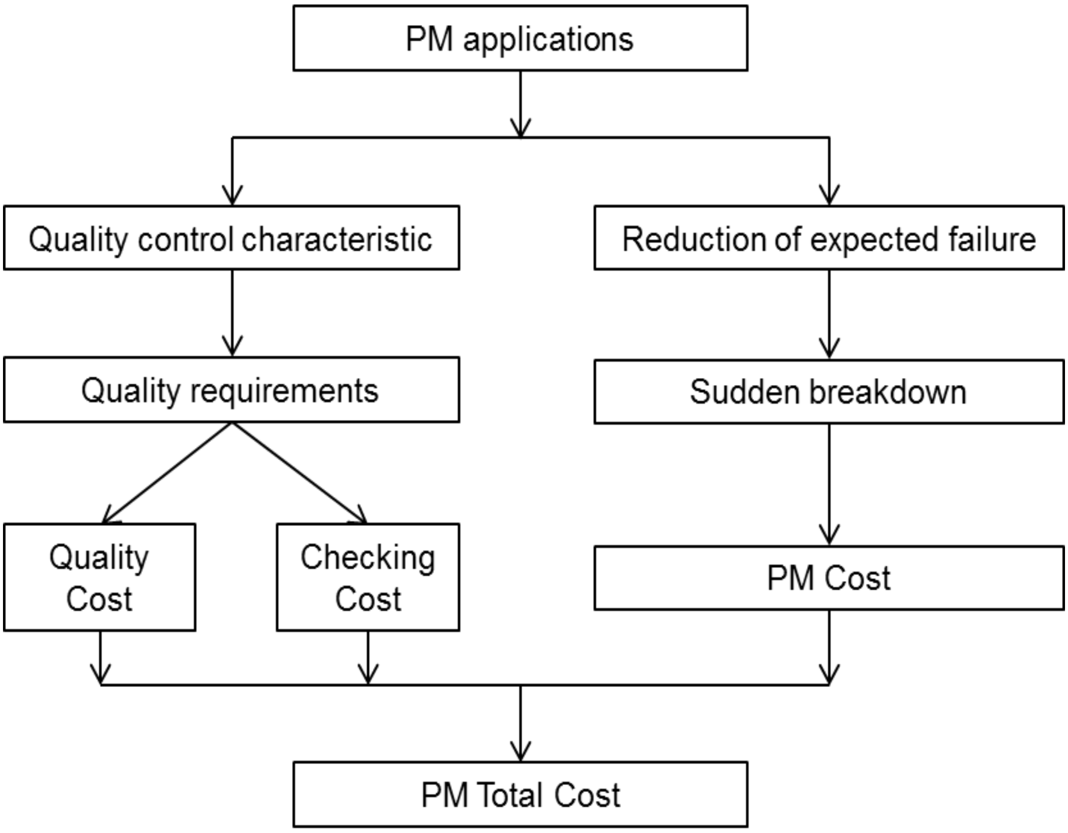


Figure 4.2 PM applications and development process for PM TC model

The TC model considers the following costs and losses as the yardsticks for the evaluation of the PM system cost:

$$Total\ Cost\ (TC) = \text{Diagnosis cost} + \text{preventive maintenance cost} + \text{loss cost} \qquad (1)$$

4.2.2.1. Diagnosis Cost

The diagnosis cost includes the investment and expenditure required per equipment to inspect and diagnose the defects, if any, during the operation process.
The cost associated with the diagnosis, which is, carrying out measurements from time to time, is:

$$= \frac{C_{meas}}{n} \qquad (2)$$

4.2.2.2. PM Cost

The PM cost consists of the investment and expenditure required per equipment to correct the process by making periodic adjustments.

It can be concluded that the cost approach provided by Das, Lashkari and Sengupta (2007) is applicable for use in maintenance plans for vehicle fleet maintenance in service organisations due to the similarity between the machines used for cellular manufacturing systems and the vehicle components' system. Therefore, this model (cost-based approach) is considered for the PM cost in this chapter. Das, Lashkari and Sengupta (2007) mentioned that the basic cost-based approach to maintenance planning was developed by Jardine (1973) and subsequently extended and refined by others (Sherwin, 1997; Talukder and Knapp, 2002). It estimates the optimal interval between preventive replacements of the equipment subject to breakdowns and may be applied to PM and overhaul, assuming that the overhaul returns the equipment to the as-good-as-new condition and that the failure repair between PM actions makes it possible to operate the machine up to the next interval (i.e., it results in as bad-as-the-old condition).

Using the approach suggested by Das, Lashkari and Sengupta (2007) and defining tpm as the PM interval for a cost-based approach, the cost of adjustment, when necessary, (PM cost) per unit time for a group of m machines may be represented by:

$$\frac{TC_M(tpm)}{tpm} = \frac{\left(Co + \sum_{j=1}^{z} CPRM_j\right) + \sum_{j=1}^{z} cf_j H_j(tpm)}{tpm} \tag{3}$$

The first expression $\left(Co + \sum_{j=1}^{z} CPRM_j\right)$ computes the PM cost during the interval tpm, where Co is the fixed cost of carrying out the PM, and $CPRM_j$ is the estimated average maintenance cost to return machine j to the as-bad-as-the-old condition. The second expression, $\sum_{j=1}^{m} cf_j H_j(tpm)$, is the failure repair cost during the interval tpm, where cf_j is the average cost of a failure repair on machine j, and $H_j(tpm)$ is the average number of failures of machine j during the interval tpm. Sherwin (1997) and Talukder and Knapp (2002) (cited in Das, Lashkari and Sengupta, 2007) state that assuming the machine failure times are Weibull distributed, $H_j(tpm)$ is computed as:

$$H_j(tpm) = \left(\frac{tpm}{\theta_j}\right)^{\beta_j},$$

where β is the shape parameter, and θ is the scale parameter. Replacing $H_j(tpm)$ in Eq. (3), the total maintenance cost per unit time is:

$$\frac{TC_M(tpm)}{tpm} = \frac{\left(Co + \sum_{j=1}^{z} CPRM_j\right) + \sum_{j=1}^{z} cf_j (\frac{tpm}{\theta_j})^{\beta_j}}{tpm} \tag{4}$$

4.2.2.3. Quality Loss Cost

The product/equipment performance variations require a quality evaluation. One of the quality evaluation systems is based on the concept of quality cost. Quality cost is the loss to the customer that is incurred when the product/equipment performance deviates from the customer-desired level (Taguchi, 1986).

The loss may be estimated by the quality loss function. The quality loss function is a way to quantify the quality cost in monetary terms when a product or its production process deviates from the customer-desired value of one or more key characteristics. Despite some researchers' attempts to construct many types of quality loss functions, there is general consensus that the quadratic loss function may be a better approximation for the measurement of customer dissatisfaction with the product quality (Taguchi and Rafanelli, 1994). Taguchi's loss function approximates loss based on two reasons: (1) the variation (represented by the standard deviation) in performance from the mean and (2) the mean performance away from the target, represented by the distance between them.

A. Bathtub curve

The bathtub curve is the most basic model used in reliability engineering to model various failure rates during the lifetime of a product or a machine. Machines or systems with these hazard rate functions experience three distinct periods, as shown in Figure 4.3. They experience decreasing failure rates early in their life cycle (burn-in period), followed by a nearly constant failure rate (useful life) period and then by an increasing failure rate during the wear-out period.

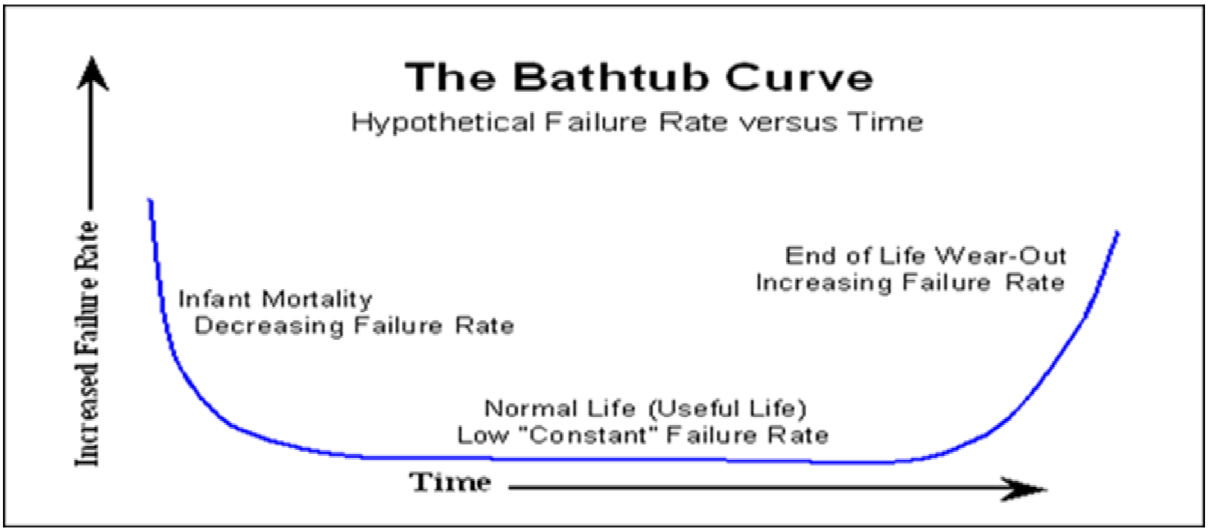


Figure 4.3 The bathtub curve (hazard rate function over machine life)

The machine reliability analysis for the burn-in and wear-out periods may be denoted by using the Weibull distribution and the exponential distribution. During the useful life period, failures are random, and this is the only region where exponential distribution is valid. The burn-in period is quite short and is spent as a test-run period, with the goal of removing various defects developed during the manufacturing of the machines (poor quality control for components, poor workmanship, defective parts, cracks during assembly, etc.). The wear-out periods for machines are due to aging, friction, cyclical loading and fatigue. The wear-out period's effect on production machines can be reduced by PM, modification and parts replacement.

Das (2006) stated that exponential distribution has been demonstrated to provide good approximations of machine failure distribution when the failure rate is constant and as such, is widely used in the literature. However, the Weibull distribution approach is considerably more versatile than the exponential distribution and can be expected to fit many different failure patterns. In reliability analysis, it has the advantage of adjusting distribution parameters to address increasing, decreasing and constant failure distributions.
The Weibull reliability function for machine *j* is defined as:

$$R_j(t) = exp\left[-\left(t/\theta_j\right)\right]^{\beta_j}, \tag{5}$$

where t is the time period for the part time under consideration,
θ_j is the characteristic life for machine *j*,
β_j is the shape factor for the machine,
β_j> is used to consider the increasing failure rate,
β_j<1 is used to consider the decreasing failure rate analysis, and
when $\beta_j = 1$, the exponential reliability function results, with mean life β_j = 1/*λ*.

The shape factor value can be evaluated by studying and analysing the failure data for the type of machine/components under consideration. In this research, the Weibull distribution is used to analyse an increasing machine failure rate.

The mean time between failures ($MTBF$) and the mean time to repair ($MTTR$) data can be obtained from the maintenance files of service organisations. It is assumed here that the $MTBF$ data for all the machines under consideration are known. According to the Weibull failure model:

$$\mathrm{MTBF} = \theta\Gamma\left(1 + {}^{1}/_{\beta}\right)$$

The $MTTF$ can be considered equal to the $MTBF$ for a repairable system when complete samples (failures) are analysed for the estimation of the $MTTF$ (Das, 2006). For this study, it is also assumed that the $MTTF$ equals the $MTBF$.

Expressing θ in terms of $MTBF$ and β:

$$\theta_j = \frac{MTBF_j}{\Gamma\left(1 + {}^{1}\!/_{\beta_j}\right)}, \tag{6}$$

where Γ is the gamma function.

In the service industry, the components fail randomly, which is reflected by the failure rate. There are three patterns of failures for repairable items, which can change with time. The failure rate (hazard rate) may be decreasing, increasing or constant, as displayed in Figure 4.3. Vehicle components are subject to deterioration over time; in turn, the failure rate increase (represented by the Taguchi loss function) for the customer-desired level has the smaller-the-better (STB) characteristic. The larger-the-better (LTB) and nominal-the-best (NTB) cases have both been clearly shown to affect the mean-squared deviation (MSD) and in turn, quality loss. In this chapter, only the STB quality is considered as it is the most commonly used in deterioration and mechanical parts.

The preceding sections have just started the discussion on the idea of failure probability and the problem associated with the target of the failure probability. The next section explains the importance of the quadratic loss function in quality engineering. Then, it is deliberated whether a target value of the failure probability is needed. In the theory section, relevant formulas are derived.

B. Quadratic quality loss function and probability distribution

A robust design is achieved by applying a three-step decision-making process:

(1) Define the objective.

(2) Define the feasible options.

(3) Select the feasible option that best achieves the objective.

The best criterion to measure a robust design is the failure probability. Maximum robustness means minimum quality loss and maximum customer satisfaction. The failure probability distribution recognises and measures the deviation from the smaller value and integrates the information into one metric. It is important to define the measure of the quality loss and then incorporate the same into the design.

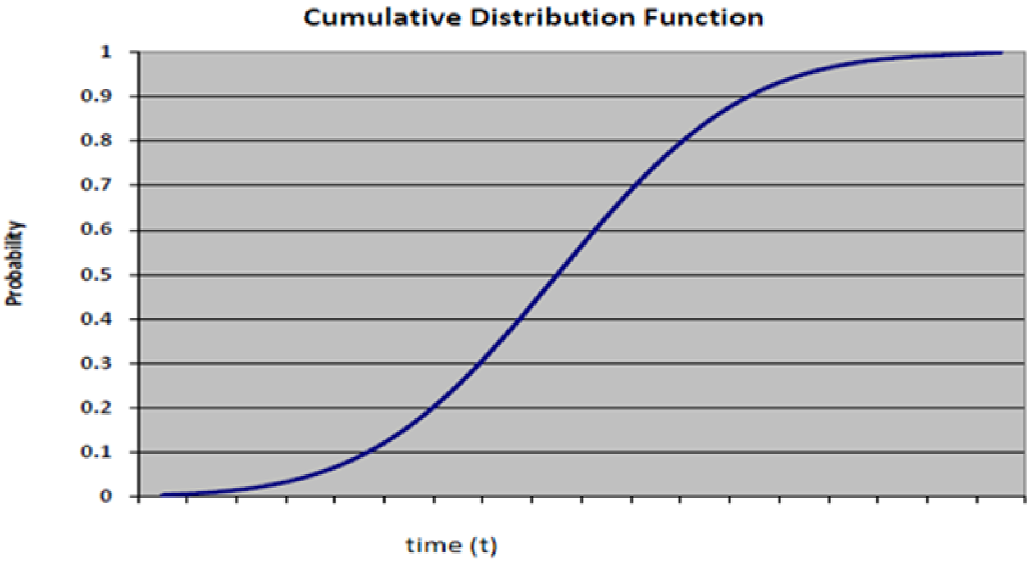


Figure 4.4 Cumulative distribution function (Nelson, 2005).

Some performance characteristics exist, and it is essential to distinguish among these when evaluating quality. Therefore, a failure probability distribution is needed for each performance characteristic. Cumulative distribution function shown in Figure 4.4. The small value is the best performance characteristic value for a given parameter. The STB should be used whenever possible because this allows the two-step optimisation. The failure distribution measures the deviation from the smaller value, allowing for subsequent adjustment.

The objective for achieving a robust design is to have the lowest failure probability (i.e., the smallest standard deviation or variation). In any process, trials on several units of equipment are conducted; whose key objective is customer satisfaction. Optimum performance is achieved when variation is low, and the mean of the performance is close to the target. After understanding the customer's expectations, it is necessary to learn about the tools required to address these parameters.

From the customer's standpoint, there is no difference among products, whether their specifications are just within or just beyond the specification limits. Taguchi, (1986) developed his quality loss function to convert customer satisfaction into a monetary value so that a manufacturer could estimate the loss to the company as a result of customer dissatisfaction.

The idea is to deliver a performance near the target (customer preference), which maximises the customer satisfaction value. Depending on the quality characteristics, this satisfaction level can be of three types – LTB, STB or NTB. When it is desirable to deliver a performance near the target, the case is termed as STB. In the cases of NTB and LTB, these values need to be higher than and away from a certain threshold value.

It is important to understand the relationship between the performance that is away from the target and quality loss. Products with smaller variations have smaller quality loss. The quality loss function essentially translates the qualitative terms, which affect the consumer, into quantitative terms, such as monetary values. Depending on the situation, the quality loss function takes one form:

- STB – The smaller value is best because it is what satisfies the customer's need. The characteristic value that is away from the target is undesirable.

C. Theory

Assuming that m is the customer-desired point, the quadratic loss function (L) is defined as Eq. (7) (see also Figure 4.5):

$$L(y) = k(y - m)^2, \quad (7)$$

where k is a positive loss coefficient based on estimated losses at a given specification limit, and y is the quality performance of the considered quality characteristic. Hence, the well-known expected quality cost based on the quadratic loss function is:

$$E[L] = k[(\mu - m)^2 + \sigma^2], \quad (8)$$

where μ and σ are the mean and standard deviation, respectively, of the quality performance of the considered quality characteristic.

By setting $m = \mu = 0$ for the STB approach, Eq. (9) is obtained, which can be expressed as:

$$E[L] = k\sigma^2 \tag{9}$$

Based on the behaviour of the failure rate increase and assuming that the failures follow a Weibull distribution, the loss function model can now be proposed.

Gradual drifts from the mean value in repair items are usually in one direction, and then the time taken to reach the control limit is directly proportional to the square distance from the target value. If the characteristic value of the part starts out at the small value zero and changes by following a Weibull distribution, at the end, it will deviate by $F(t)$. In this case, machine failures are considered in terms of a machine operating with a degraded functionality. As it gradually drifts away from zero, the squared deviation σ^2 is given by the following integral:

$$\overline{\sigma}^2 = \frac{1}{tpm}\int_0^{tpm} F^2\, dt \tag{10}$$

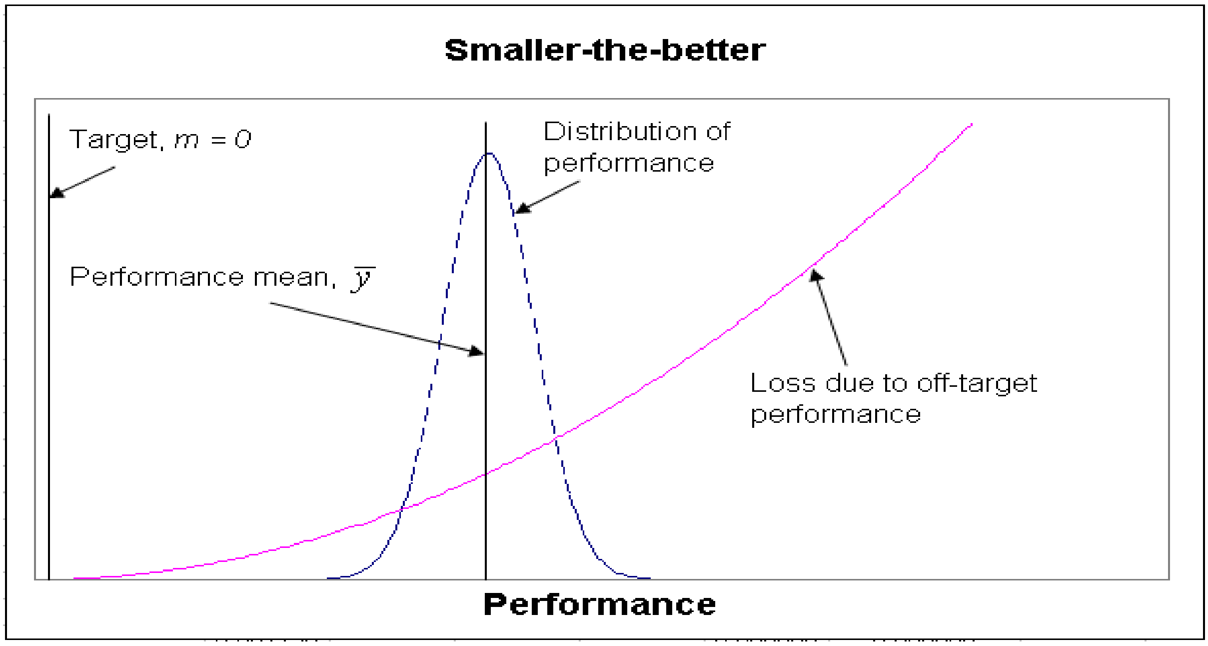


Figure 4.5 Smaller-the-better

The probability of occurrence of machine failures is captured from the past failure data. It can be written as:

$$F_j(t) = 1 - exp\left[-\left(t/\theta_j\right)\right]^{\beta_j}, \qquad \left(tpm, \theta_j, \beta_j\right) \geq 0, \tag{11}$$

where $F_j(t)$ is the cumulative failure probability of machine j at time tpm, for the Weibull distribution.

Analogous to Eq. (8), the average mean squared deviation $\overline{\sigma}^2$ is given by the following integral:

$$\overline{\sigma}^2 = \frac{1}{tpm}\int_0^{tpm}\left[1 - e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right]^2 dt,$$

which results in:

$$\sigma_1^2 := \bar{\sigma}^2 = \frac{1}{tpm}\sum_{j=1}^{z}\int_0^{tpm}\left(1 + \left[e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right]^2 - 2e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right)dt, \tag{12}$$

where *j* is the number of machines or components:

j = 1, 2, 3,…, z.

If the characteristic degradation is found to be out of control during the diagnosis at the interval of n months of time, then the average time when the parameter is outside the control limit is $n/2$. Thus, the mean squared deviation in this case becomes:

$$\sigma_2^2 := \left(\frac{n}{2}\right)\frac{F_0^2}{tpm} \tag{13}$$

By substituting Eq. (13) in Eq. (9):

$$L_2 = k\left(\frac{n}{2}\right)\frac{F_0^2}{tpm} \tag{14}$$

The measurement error is an independent source of variation, causing an increase in quality loss by:

$$L_3 = k\sigma_m^2 \tag{15}$$

The parameter Δ_0 is defined as the point of intolerance, as shown in Figure 4.6. It is the deviation from the target that causes an average customer to take action. It is assumed that the corresponding monetary loss caused by a defective component is A_0, also defined as the cost of a corrective action. When the deviation of the performance from the target of a product is Δ_0 and the corresponding loss is A_0, then for STB, $k = A_0/\Delta_0^2$.

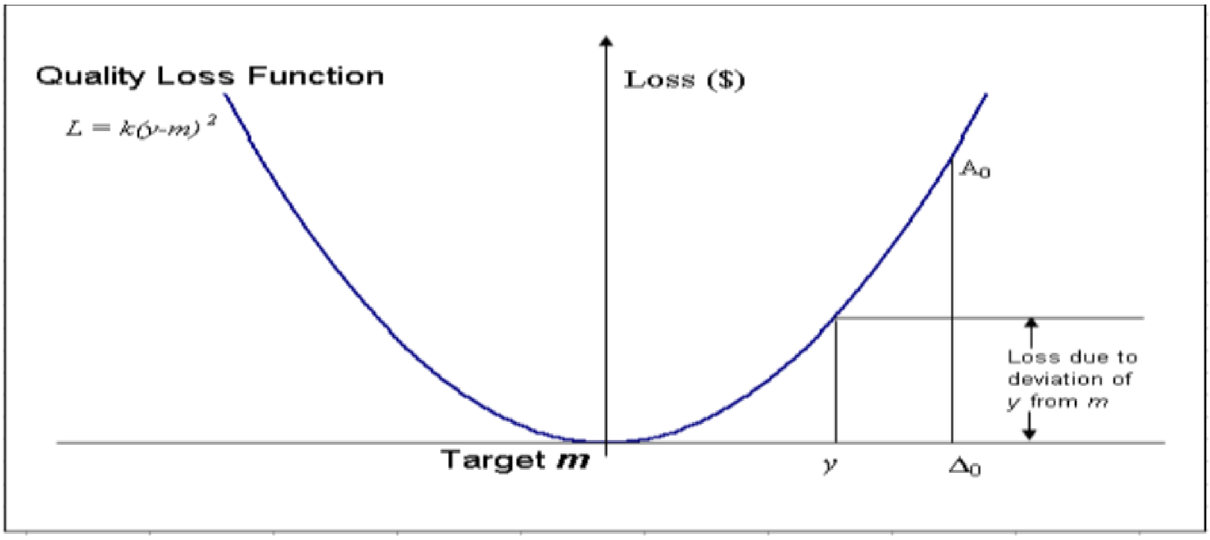


Figure 4.6 Loss due to off-target performance

The LD50 point could be taken as the value at which 50% of the people would do the PM. When the failure probability goes above F_0, the PM has an average loss of A, so the value of the loss function at $y = F_0$ is approximately A. Therefore, A can be substituted for the left side of Eq. (9) and F for y on the right side, obtaining:

$$A = \ kF_0^2 \tag{16}$$

Adding all the costs of the losses, that is, the loss function, L_1, L_2 and L_3, and using Eq. (8), the objective function of the losses per unit time is presented as:

$$L := L_1 + L_2 + L_3$$
$$= \frac{A}{F_0^2}\frac{1}{tpm}\left(\sum_{j=1}^{z}\int_0^{tpm}\left(1+\left[e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right]^2 - 2e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right)dt + \left(\frac{n}{2}\right)F_0^2 + \sigma_m^2\right) \quad (17)$$

4.3. Total Cost Model Optimisation

The basic cost-based approach (Das, Lashkari and Sengupta, 2007) accepts variability, which indicates that this method does not attempt to minimise the variability. On the other hand, the loss function approach attempts to minimise the variance for a given quality characteristic. The loss function approach improves the quality of a service by minimising the effects of the causes of variation without eliminating the causes, which explains why these two approaches can complement each other. The integrated model deals with two objectives of design methodologies that are subject to uncertainties – reliability and robustness. Reliability deals with the probability of failure, while robustness minimises the product quality loss.

Adding all the costs (i.e., costs of measurements and adjustments, plus the loss function), the complete objective optimisation model is now presented. The proposed model captures the merits of both the quality loss cost and the failure cost, as well as uses the objective function that is developed based on this concept. The proposed model is called the total cost (TC) model. The generic form of the TC per unit time in the optimisation model is given below:

$$TC = \frac{C_{meas}}{n} + \frac{\left(Co + \sum_{j=1}^{z} CPRM_j\right) + \sum_{j=1}^{z} cf_j\left(\frac{tpm}{\theta_j}\right)^{\beta_j}}{tpm} + \frac{A}{F_0^2}\frac{1}{tpm}\left(\sum_{j=1}^{z}\int_0^{tpm}\left(1+\left[e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right]^2 - 2e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right)dt + \left(\frac{n}{2}\right)F_0^2 + \sigma_m^2\right) \quad (18)$$

Example 1

To illustrate the proposed policy, a case of one component is considered. Table 4.2 presents the cost- and reliability-related input data. The parameter θ_j is computed from Eq. (6). The measurement error between the inspection and the repair of the defective unit is negligible.

Table 4.2 Input data for Example 1

	MTBF	Beta	Theta	CPRM	cf
Component 1	20	1.8	24.74	280	950
Co			150		
C(meas)			30		
Planned period, T			36		
CPRM	average maintenance cost				
cf	failure repair cost				
C(meas)	measurements cost				
Co	fixed cost of carrying out the PM				

Solution:

The optimal tpm value is computed to be $7\,months$; thus, the component will undergo a total of $36/7 = 5$ PM actions during the planning period. The PM cost is $\$105.59$, the loss cost is $\$77.42$, and the total PM cost equals $\$183.01$. Inspection interval, $n_{opt} = 1\,month$. Table 4.3 shows various costs (dollars) versus intervals (months) for fixed $\mathrm{n_{opt}} = 1$.

Table 4.3 Various costs (dollars) versus intervals (months) for fixed $\mathbf{n_{opt}} = \mathbf{1}$

tpm	LC	PM	TC
1	268.57	439.31	707.89
2	150.25	231.21	381.46
3	111.22	165.76	276.98
4	92.55	135.73	228.28
5	82.71	119.74	202.45
6	78.11	110.71	188.81
7	77.42	105.59	183.01
8	80.17	102.89	183.07
9	86.24	101.78	188.02
10	95.69	101.75	197.44
11	108.63	102.49	211.12
12	125.21	103.81	229.01

where

LC – quality loss cost,

PM - preventive maintenance cost,

TC - total cost.

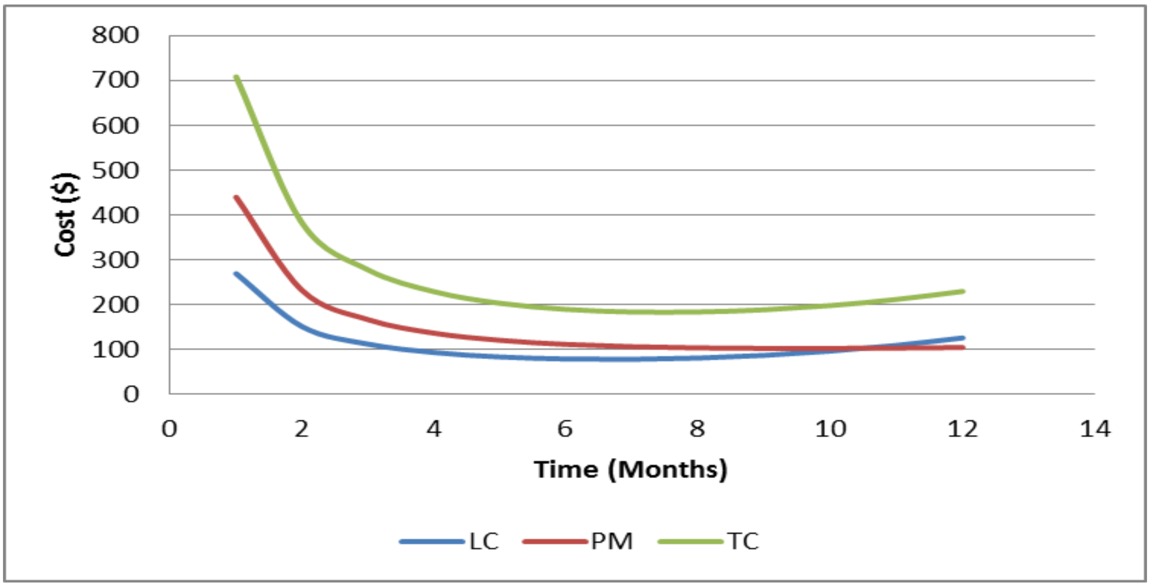


Figure 4. 7 Costs (dollars) versus interval (tpm)

Figure 4.7 shows that as the interval is maximised, the cost of quality loss, the PM cost and the TC decrease up to a certain value of the PM interval and increase from that point.

4.4. Combining Execution of Maintenance Activities

Maintenance costs can be reduced by combining the execution of maintenance activities. In various cases, preparatory work, such as shutting down a unit and travelling of the maintenance crew, has to take place before maintenance can be done. Combining activities allows savings on this work. On the other hand, combining mostly implies deviating from the originally planned execution moments, which costs money. This section considers combining maintenance actions and shows that the objective functions derived in the previous section allow a cost-effectiveness evaluation of combinations and assist in the timing of the execution. The main idea is to apply the developed approach. First, for each activity, determine its preferred execution moment and derive its TC. Next, consider groups of activities, for which the preferred moment of execution follows from a minimisation of the sum of the TC. If this sum is less than the set-up savings because of a joint execution, combining is cost-effective.

Example 2

A machine consisting of three components is considered to demonstrate the proposed model. Table 4.4 gives the cost- and reliability-related input data. The parameter θ_j is computed, as illustrated in Example 1.

Table 4.4 Input data for Example 2 with three components

	Component 1	Component 2	Component 3
MTBF	18	20	24
CPRM	280	350	200
cf	950	1100	1000
Beta	1.8	2	1.74
Theta	24.74	20.31	25.72
Co		150	
Cmeas		30	
Planed period, T		36	

Table 4.5 shows the solution when the maintenance is done for each component separately. When combining the maintenance activities for the three components, the solution is $tpm = 7\ months, n = 1\ months$ and the minimum total cost, $TC = \$420.49$, as shown in Table 4.6. Comparing the results provided in Tables 4.5 and 4.6 shows that because of a joint execution, combining is cost-effective.

Table 4.5 Components' total costs $(dollars)$ versus intervals $(months)$ for fixed $n_{opt} = 1$

PM intervals $tpm\ (months)$	Component 1	Component 2	Component 3
	$n = 1$	$n = 1$	$n = 1$
	TC	TC	TC
1	707.89	769.78	627.04
2	381.46	410.3	337.63
3	276.98	294.89	244.17
4	228.28	241.12	200.05
5	202.45	212.9	176.27
6	188.81	198.63	163.41
7	183.01	193.74	157.63
8	183.07	196.3	157.18
9	188.02	205.56	161.22
10	197.44	221.3	169.34

Table 4.6 Various costs (dollars) versus intervals (months) for fixed $n_{opt} = 1$

tpm	LC	PM	TC
1	258.86	1354.94	1613.8
2	146.52	708.97	855.48
3	110.49	504.7	615.19
4	95.37	410.32	505.69
5	91.02	359.6	450.61
6	94.91	330.54	425.46
7	106.74	313.75	420.49
8	126.96	304.55	431.51
9	156.36	300.34	456.71
10	195.81	299.59	495.4
11	246.14	301.3	547.44
12	308.09	304.84	612.93

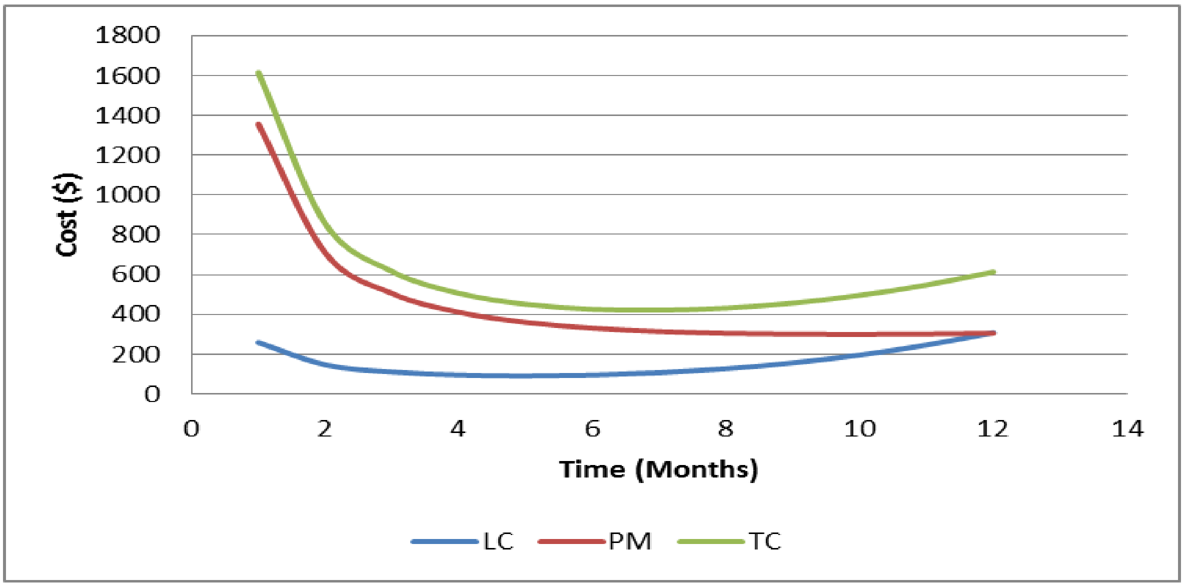


Figure 4.8 Costs (dollars) versus interval (tpm)

Figure 4.8 shows that as the interval is maximised, the cost of quality loss, the PM cost and the TC decrease up to a certain value of the PM interval and increase from that point.

4.5. Monte Carlo Simulation

The MC simulation relies on repeated random sampling and statistical analysis to compute the results. Mathematical models are applied in the previous section to describe the interactions in a system, using mathematical expressions. These models typically depend on a number of input parameters; when processed through the mathematical formulas in the model, these result in one or more outputs. Figure 4.9 shows a schematic diagram of the process.

Figure 4.9 Mathematical models

Models input parameters depend on various external factors. Because of these factors, realistic models are subject to risks from the systematic variations of the input parameters. A deterministic model, which does not consider these variations, is often termed as a base case since the values of these input parameters are their most likely values. An effective model should account for the risks associated with various input parameters. The MC simulation can help investigate the complete range of risks associated with each risky input variable.

In the MC simulation a statistical distribution which can be used as the source for each of the input parameters is identified. Next, from each distribution random samples are drawn which then represent the values of the input variables. A set of output parameters is obtained for each set of input parameters. In the simulation run, the value of each output parameter is a particular outcome scenario. Such output values are collected from a number of simulation runs. Finally, to make decisions about the course of action (whatever it may be) statistical analysis is performed on the values of the output parameters. The sampling statistics of the output parameters can be used to characterise the output variations.

Example 3

This example uses three components as shown in table 4.7. Assuming that all input variables for each component are independent random variables with a known probability distribution (uniform distribution), the distribution of the cost associated with any choice of maintenance decision variables is investigated.

The MC simulation provides the tool. It samples the realisations from output variable distributions by:

1) randomly generating a sequence of realisations for input parameters and

2) simulating each realisation against the value of the decision variables.

Table 4.7 Input data for Example 3 with three components

	Component 1	Component 2	Component 3
MTBF	[16-20]	[18-22]	[20-24]
CPRM	[200-300]	[300-400]	[180-250]
cf	[900-1100]	[1000-1200]	[900-1200]
Beta	[1.05-2]	[1.05-2.2]	[1.05-1.8]
Co	150		
Cmeas	30		
A	500		
Planned period, T	36		

Solution

Total of 1,000 random samples:

Expected tpm: 9.8256

Expected n: 1.0927

Expected TC: 266.15

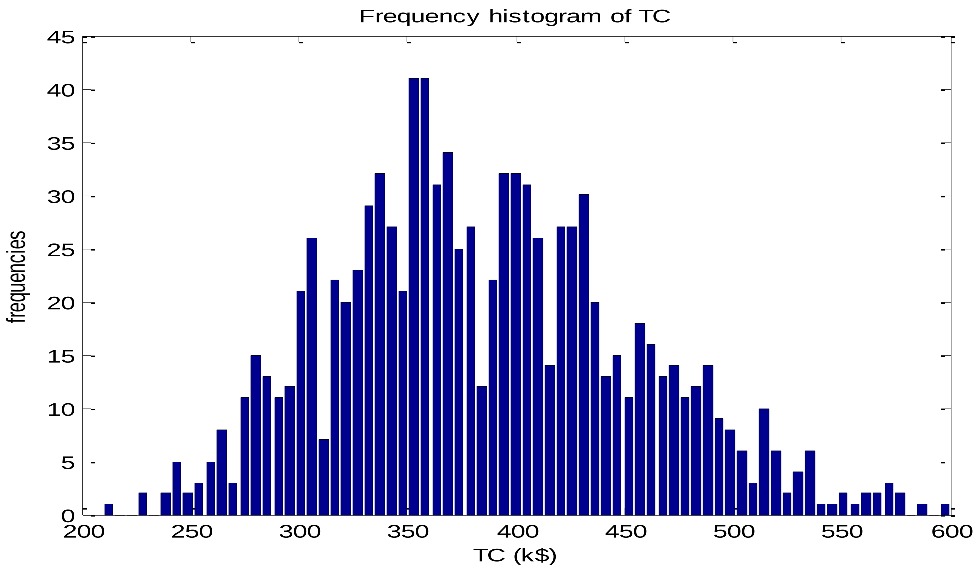


Figure 4.10 Total cost (TC) frequency histogram

The frequency histogram of the TC (Figure 4.10) shows that for this best known choice of decision variables, the TC has a distribution range of $\$220-\$600$, with an average of about $\$353.15$. Note that this range of possible futures includes the single value $\$420.49$ obtained in Example 2. Depending on what demand pattern is actually realised, many other costs might result.

4.6. Sensitivity Analysis

For each case, only one machine problem is used. This is because only one input parameter can be investigated at a time, so all the other input parameters remain constants. Thus, the parameter changes of only one machine can be captured at a time. The results displayed in table 4.8.

Table 4.8 Results of sensitivity analysis

	Basic	+10%	TC
Cmeas	30	33	+1.01%
Co	150	165	+0.12%
CPRM	280	308	+0.12%
cf	950	1045	+0.02%
beta	1.8	1.98	-69.43%
A	500	550	+0.10%
F_0	0.30	0.33	-136.35%

- TC slightly changes (≤1%) for C_{meas}, Co, $CPRM$, cf, A.
- TC decreases more than 69% if beta increases by 10%.
- TC decreases by 136% if the failure probability increases by 10%, that is, the control limit F_0 has the highest sensitivity value.

4.7. Summary

It has been observed that there are two parallel developments for determining the optimum PM interval, one based on the maintenance cost without considering the quality loss, and the other based on the quality loss without considering the maintenance cost. A novel approach combining the maintenance cost and quality loss has been developed. Numerical examples have illustrated the application of the model, and the sensitivity analysis has indicated the effects of the changes in key input parameters on the optimal solution. This model is generic in nature, which can be applied to many characteristic variables. Using this model, an optimal interval that can increase the quality and reduce the cost can be achieved in the early stage of the maintenance plan.

5. Maintenance Process Improvement Model by Integrating LSS and PM Optimisation

This chapter proposes a new model for maintenance process improvement in service organisations that integrates LSS and PM optimisation to improve maintenance efficiency and effectiveness.

5.1. Introduction

In order to manage service adequately and improve the maintenance process, a guideline model is an important tool that can be used to reach high performance. This chapter proposes a new model for vehicle fleet maintenance management that integrates LSS and PM optimisation activities to improve maintenance efficiency and effectiveness. This model bridges the service gaps between maintenance providers and customers and balances the requirements of maintenance managers, deliveries and customers by taking the benefits of the Lean speed and the Six Sigma high quality principle, as well as the optimisation process balance. Moreover, the TPM application within the Lean strategy which allows the organisations to develop advanced techniques in maintenance analysis and to be more technical in its approach to problem solving in maintenance. This combination can enhance the management performance of organisations, continuously raise the efficiency and effectiveness of enterprise management, and improve service quality and reliability.

5.2. Maintenance Management Process

The maintenance management process can be divided into two parts – the definition of the strategy and the strategy implementation (Uday et al., 2009). The first part requires defining the maintenance objectives as an input, which is derived directly from the business plan. This primary part, in an organisation, of the maintenance management process conditions the success of maintenance and determines the effectiveness of the subsequent implementation of the maintenance plans, schedules, controls and improvements. Effectiveness shows how well a department or function meets its goals or the company needs and is often discussed in terms of the quality of the service provided, viewed from the customer’s side. This allows maintenance managers to be in a position to reduce the indirect maintenance costs associated with losses and finally, to prevent customer dissatisfaction.

The second part of the process, the implementation of the selected strategy, has a different significance level. The managers' ability to sort out the problems of the maintenance management implementation (for instance, to ensure proper skill levels, proper work preparation, suitable tools and schedule fulfilment) will allow them to reduce the direct maintenance costs (labour and other required resources). This part of the process deals with the management efficiency. Efficiency means acting or producing with minimum waste, expense or unnecessary effort. Efficiency is then assumed as providing the same or better maintenance for the same cost. This chapter proposes a generic model for maintenance management that integrates LSS and PM optimisation for process improvement.

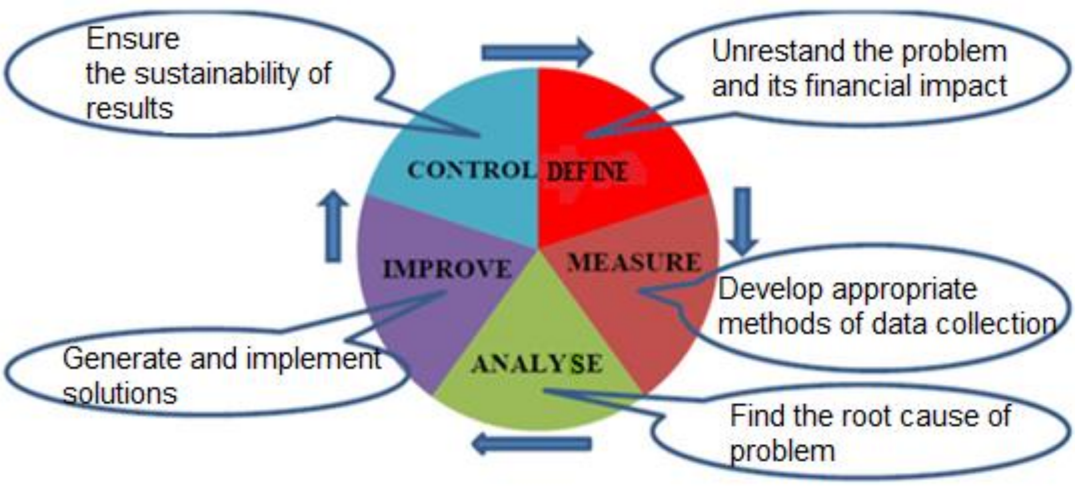


Figure 5.1 DMAIC framework

5.3. LSS Methodology

The LSS approach combines Lean methods and Six Sigma, using specific DMAIC processes to provide companies with better speed and lower variance in increasing customer satisfaction (George, 2002). Figure 5.1 shows the DMAIC framework. The first phase in DMAIC is defining project objectives and customer needs. The second phase includes measuring errors and process performance, as well as quantifying problems. The third phase involves analysing the data and finding the causes of the defects. The fourth phase entails correcting the causes of the defects and reducing errors. The final phase comprises controlling the process and maintaining performance, thus improving performance. These five phases can help Six Sigma teams to systematically and gradually develop the process rationalisation. First, they define the problem and then introduce the solutions targeting the fundamental causes, thus constructing the optimal implementation method and ensuring the sustainability of the solutions (Cheng and Chang, 2012).

5.3.1. Applications of Six Sigma Tools in Maintenance Process

The following Six Sigma tools are used in the model:

(1) Benchmarking is a tool that allows an organisation to measure its performance against best-in-class organisations. There are normally three types of benchmarking: 1) process benchmarking, which compares best practices across targeted organisations; 2) competitive benchmarking, which compares competitors' data on product features, pricing, and the quality of products and services; and 3) strategic benchmarking, which compares the strategies that have led to competitive advantage and market success (Furterer, 2004).

(2) Brainstorming is a tool to create ideas in a creative manner without evaluating the ideas as they are produced. Brainstorming can be structured, such as in a nominal group technique format, or unstructured, as in the free-form or free-wheeling type.

(3) Capability analysis includes conducting a study to recognise whether a process is capable of producing products within specifications. Two PCIs ($C_p$and C_{pk}) are usually produced after the process is found to be in control with respect to the variations (Furterer, 2004).

(4) Cause-and-effect/fishbone diagrams are graphical tools used to examine and organise the cause-and-effect relationships of problems.

(5) A histogram is a statistical tool used to know the nature of a process distribution.

(6) The Pareto Chart and the 80/20 rule comprise a graphical tool based on the Pareto standard that most effects result from only a few causes. This tool helps classify and summarise the causes for further investigation.

(7) Process mapping is a graphical flowcharting tool that provides support to document and understand the processes for investigation, problem identification and improvement. Process maps identify the sequence of activities or the flow of materials and information in a process (Furterer, 2004).

5.3.2. Applications of Lean Tools in Maintenance Process

The following Lean tools are used in the model:

(1) The single minute exchange of dies (SMED) means minimising downtimes for scheduled maintenance.

(2) Eliminate seven wastes, including over-processing, hidden and obsolete maintenance inventories, poor planning and scheduling of maintenance operations, reworks due to poor maintenance functions, waiting for maintenance services, excessive maintenance activities and unnecessary maintenance transportation (Furterer, 2004).

(3) Visual control refers to the application of simple and clear visual signals that make the problems, breakdowns or deviations from standards visible to everyone.

(4) The identification and elimination of wasteful activities that do not add value to the product or service being delivered constitute a critical concept of the Lean Enterprise.

(5) Total Productive Maintenance (TPM) offers a concept for maintaining plants and equipment. It includes tools to perform preventive maintenance, based on the cost of preventing equipment breakdown through a planned maintenance programme to avoid incurring the costs of downtime and lost sales due to products not being produced on time (Ahuja and Khamba, 2008).

5.4. Optimisation of PM Activities

The last five decades have witnessed quick growth in the use of statistical and operational research techniques that support managers, engineers and others in pursuing optimisation in maintenance policymaking (Ben-Daya, Duffuaa and Raouf, 2012). This section deals with a method of maintenance concept optimisation that allows reduction of the equipment’s TC, based on the knowledge of operating reliability data. Therefore, this section introduces the integrated model that can be used to minimise the expected TC of PM by combining PM cost and quality loss cost. The overall activities at this point may be divided as follows:

(1) Collection and analysis of the system’s reliability and availability data. Marquez (2007) states that maintenance management needs two categories of micro-level data – failure rates (which are possibly time dependent) and

repair/restoration and PM times. Several sources that may provide the failure rate information include (1) data books and databanks, (2) performance data from the actual plant, (3) expert opinions or (4) laboratory testing (Marquez, 2007).

(2) Analysis and preparation of the financial data on the system's maintenance. In addition to the system's failure history or reliability data, financial information is needed to determine the payoff of the different maintenance strategies being measured. For this purpose, besides the direct maintenance cost, the possible cost of quality losses due to maintenance should be considered. For example, a particular PM strategy might require certain costs of labour, spare parts, tools, information systems and human resources to support the programme. At the same time, PM would require a certain downtime of the equipment/line/plant, with a possible quality loss cost.

(3) Modelling systems for maintenance policy optimisation. The integral process of using optimisation models in maintenance has been discussed by some authors, such as Ormerod (1993), who describes the necessary aspects for modelling a scientific and exhaustive maintenance problem. These points may be summarised as follows: (1) recognition of the problem and aim of the study, (2) agreement on and enumeration of the required data for the study, (3) design of the system for the future withdrawal of data (if required), (4) preparation of the data and information to fit the models, (5) benchmark of the data with other sources/alternatives, (6) formulation of the suitable maintenance policies using the models, (7) explanation of the followed process to the maintenance manager and (8) discussion of model results and model utilisation payoff analysis. Figure 5.2 describes the necessary aspects for modelling the maintenance problem under consideration.

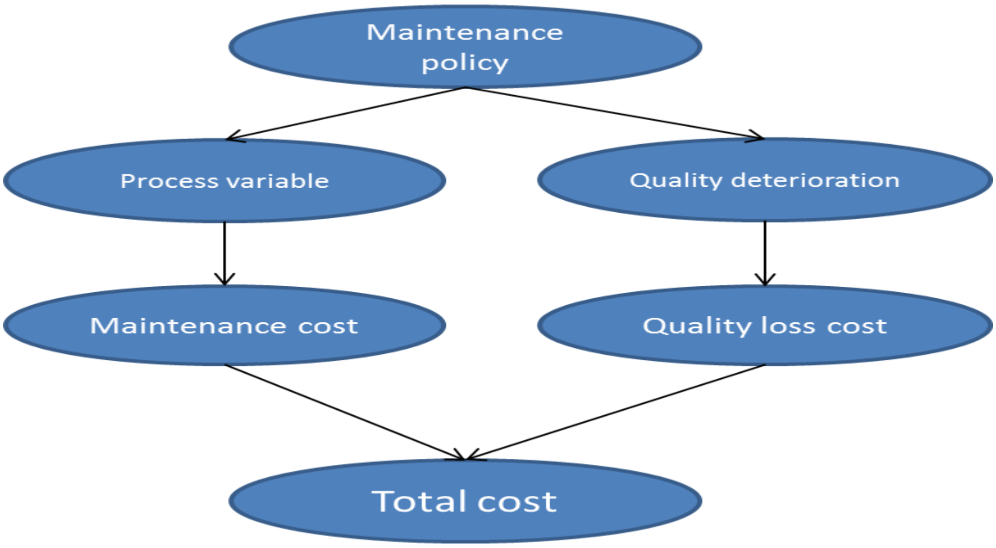


Figure 5.2 PM total cost model

5.5. Integrating LSS and PM Optimisation Model

As stated in chapter 2, Zhao et al (2012) suggested that LSS should be introduced to the process optimisation system to accomplish the aim of CI for the equipment maintenance process. In this chapter, a sound methodology and model to integrate LSS and PM optimisation is developed in the vehicle fleet maintenance process as shown in Figure 5.3. The integration of the LSS concept with PM optimisation in the model is presented by using the PDCA (Plan-Do-Check-Analyse) driven cycle called the DMAIC process of performance improvement. The LSS forms the basic foundation for the PM optimisation strategy and facilitates the understanding of shop-floor operators, who are the most important enablers of the successful implementation of PM optimisation. Within the DMAIC phases, different problems and circumstances of the maintenance department are defined, the process performance is measured, the main causes of defects are analysed, improvement or corrective actions are taken, and the improvements are maintained by continuous controlling. Additionally, the DMAIC iterative process is used as the main operational approach for implementing this model to achieve permanent improvement of maintenance activities and ideally attain the Six Sigma process performance. Furthermore, many Six Sigma, Lean and advanced, supportive tools for quality management are used in the improvement process to develop the performance of maintenance operations.

Table 5.1 Key activities and tools for implementing the maintenance management model

Stage	Activities	Tools
1. Definition	• Select quality improvement team members • Identify problems and weaknesses of the process • Emphasise importance of quality improvement efforts • Select CTQ characteristics • Analyse capability and performance of various processes	• Supplier-input-process-output-customer (SIPOC) • Brainstorming • VOC • Pareto analysis
2. Measurement	• Measure potential factors that can affect maintenance process • Gather information about key maintenance processes • Analyse measuring system • Calculate OEE for each machine	• Process map • TPM
3. Analysis	• Identify root causes of problems • Confirm problem causes • Implement basic practices of TPM • Identify improvement opportunities	• Cause-and-effect diagram • Weibull analysis • $Y = f(X)$ analysis • TPM
4. Improvement	• Propose ideas for changes and solutions to improve maintenance process • Standardise the best set of corrective actions • Provide maintenance instruction manuals • Classify responsibilities of employees • Redesign or re-engineer maintenance process • Implement continual improvement	• Visual control • Seven wastes • SMED • Poka-yoke • 5S • TPM • Mathematical model
5. Control	• Continuously control the improvement level • Develop control and response plan • Integrate the change into the organisation's knowledge base	• Performance management • Education and training

In any improvement project, the utilisation of a well-defined improvement procedure is critical. The typical form of LSS improvement projects is the DMAIC model. The DMAIC model can be used to improve any organisational process, regardless of the industry. Hence, it can be used to optimise the maintenance process in srevice. The DMAIC model is a roadmap that can be followed for all projects and process improvements. It is an analytical process cycle; each stage has its activity points and the corresponding tools. Table 5.1 shows the DMAIC model's key points and tools.

Since the scope of the organisational culture and the operational environment are significantly different in private-sector firms and in service organisations, it is necessary that the DMAIC methodology be properly modified and tailored in its implementation in the maintenance process. Consistent with the character of maintenance tasks, the maintenance process can be regarded as a workflow. Concerning the application of DMAIC in the maintenance process, the result of maintenance work can be regarded as the output of the process (Y), such as test-passing rate, repair rate, rework rate, maintenance ratio, MTTR, fault detection rate and so on. The output of process Y may be affected by a series of effect factors, namely, Xn. The relationship between Y and Xn is represented as:

$$Y = f(X1, X2, \dots \dots Xn).$$

However, only a small number of $X1's$ have serious effects on Y, which are known as the "key *X's*". These key *X's* may be technical factors, such as maintenance mode, facility, equipment, spare supply and repair staff's skill levels, and may also be administrative factors, such as procedures and policies of management. Due to the limitations of the cognition for the process, generally, the key *X's* cannot be identified, essentially understood and grasped from the large number of $X1's$ in the maintenance process. Therefore, large gaps (sometimes, even defects) are produced between the output of process Y and the requirements of equipment maintenance. By analysing the maintenance process data step by step, DMAIC can reveal the key *X's* and make available the measures for the best improvement and control programmes aiming at the key *X's*.

Considering the factual state of the equipment maintenance process, first, highlight the equipment readiness objective to identify opportunities and eliminate defects, as defined by the organisation. Next, recognise that the maintenance process waste and variations delay the ability to reliably support the materials. Then, require data-driven decisions and incorporate a complete set of quality tools under a powerful framework to solve the problem of the maintenance process. Finally, provide a highly prescriptive cultural infrastructure that is effective in obtaining sustainable results. Based on the above analysis, Figure 5.3 shows the DMAIC model application in the maintenance process. Some key points should be taken into account with reference to each phase of the DMAIC model.

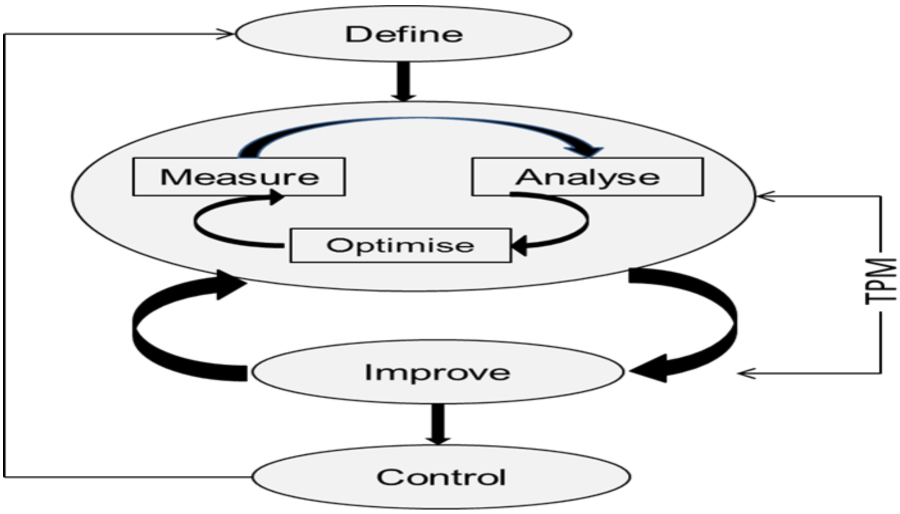


Figure 5.3 Methodology to develop integrated model

5.5.1. Phase 1 of DMAIC Model: Define

In improving the performance of the maintenance process, it is necessary to identify the problems that occur in the processes, determine the requirements, and define the planned results. The most responsible persons for this phase are the top managers in the company since they can have the most complete assessment of all processes and how they are carried out, the allocated resources, the process documentation, and the relations with other processes and so on. Regarding these processes, the managers should consult experts who have the knowledge and skills in the maintenance of technical systems and are best acquainted with the actual maintenance processes of certain parts or the entire system. This inclusive analysis represents a sort of a filter, which determines the willingness and readiness of the company to implement the new maintenance concept.

With their practical experience, the maintenance workers may contribute to recognising the problems as they are directly faced with actual issues in their daily activities. They know in detail the systems they operate and maintain. They can recognise and resolve the problems, which are sometimes specific to a certain technical system, and need not agree with the technical-technological measures for the correct functioning and maintenance of technical systems when these are in the state of "operation".

Generally, this phase of the concept includes the participation of the already formed LSS training teams and improves their work and decision making in team work. Trained operators and maintainers of technical systems form multidisciplinary teams with the necessary knowledge and skills in performing the maintenance procedures and making coordinated decisions. As they consist of participants in the process of implementing the new maintenance concept, these teams also actively participate in identifying problems and defining requirements.

It can be easily said that defining is the most important phase in the process of improving the maintenance system performance and its path concerning Six Sigma processes. This is a case in which consciousness is created, and the need to change the existing concept of maintenance is identified, in order for the company culture to finally be changed. This change is completed through education because people should learn new skills while overcoming old modes of thinking.

5.5.2. Phase 2 of DMAIC Model: Measure

This phase is applied when recording the current maintenance process and determining the processes that is relevant for maintenance. Thorough knowledge of the existing maintenance process includes describing it, drawing process charts and completing the supplier-input-process-output-customer (SIPOC) table. In doing so, the possible existence of problems in the process is set, the process is filtered and simplified, unnecessary and wasteful steps in the process are eliminated, and narrow points (which cause misuse of technical systems' capacities and transform serial activities into parallel ones) are eliminated, which reduce the waiting time in the process.

The measurement in the process includes collecting information from the process, as well as analysis of the existing information about the technical system, beginning from its delivery, implementation and putting into operation, to establishing a reliable way of measuring the process parameters and performance. The autonomous maintenance and improvement of maintenance processes should be the responsibility of teams whose members can readily identify the problems. Simultaneously, these teams gather and analyse the information about the efficiency of the process, the reliability of certain parts or the entire technical system, the time required for the maintenance process, maintenance costs and so on.

This phase includes the application of the following quality tools and advanced tools of the LSS concept:

- cause-and-effect diagram (Ishikawa diagram),
- process map,
- measuring customer satisfaction (MCS) and so on.

5.5.3. Phase 3 of DMAIC Model: Analyse

The purpose of analysing the maintenance process is to define what is not good in it, identify the causes of its inefficiency, as well as propose how it can be improved. Similar to the case with the previous two phases, this one is also related to defining the scope and phases in implementing the new model and applying the TPM concept in organisations.

Other companies' experiences in implementing TPM are used when applying the concept in an organisation. This phase assesses whether the applied measures are satisfactory, leading towards the planned results of the process improvement, and whether the established requirements for improving the maintenance process are really applicable or should be redefined and filtered. These activities are the responsibility of the TPM team leaders, as well as the possible coordinators for implementing TPM since they have the best knowledge of the implementation measures. The application of the TPM concept in maintenance organisation includes the following:

- application of the 5S programme,
- preparation of the standards for lubrication and cleaning,
- filtering and defining problems,
- elimination of the causes of dirtiness (with a detailed examination),
- repair,

- checking the state and
- autonomous maintenance.

This phase focuses on searching for the root cause in the maintenance process. The measurements and data collected in the measurement phase are analysed to ensure that they are reliable in relation to the defined problem and to check if they identify the root or potential cause of the problem. With the analysis of the phenomena of variations and waste in the maintenance process, the data are plotted to recognise the nature of the maintenance process. It must be determined whether the problem, as defined in the first phase, is real or a random event. If it is a random event, then a specific process change cannot be resolute. If the data reveal that the problem is real, the solutions are identified and prioritised according to their contribution to the equipment's operational readiness and the influence of the maintenance efficiency and quality.

In reliability performance studies of automobile (mechanical) components, the analysis of the field failure data is essential since it captures the actual usage profiles and the combined environmental exposures that are difficult to simulate in the laboratory. Applying life data analysis, reliability engineers use the product life data to determine the probability and capability of parts, components and systems to perform their required functions for desired periods of time without failure, in specified environments.

The analysis also includes potential errors that most frequently occur in the process, as well as their causes. The application of suitable quality tools enables eliminating these errors in the subsequent phases of the DMAIC model.

This phase (similar to the previous one) requires the application of quality tools and advanced tools of the LSS concept, such as:

- Pareto analysis,
- Cause-and-effect diagram (Ishikawa diagram) and
- Weibull analysis.

5.5.4. Phase 4 of DMAIC Model: Improve

The improvement phase consists of developing solutions and selecting the optimum one for the best results. Possible solutions that can reduce waste, complexity and variability can be identified as soon as the root cause of the problem in the maintenance process is understood, and qualitative data are available. Solutions are then verified to understand their effects on the process input variables and to ensure that the chosen solution is practicable. The best solution is implemented, and the results are tested to ensure that what was predicted is occurring in reality.

This phase also includes standardising the maintenance procedures. This involves producing procedure and instruction manuals that define the duties of workers-operators, provide a description of the workplace and the applied means of work, define the work procedure at the workplace, establish protective measures for the workers and the environment and so on.

Process improvement includes creating an application for improving the process, defining the strategy for improvement, recording the "to-be" process (whatever they should be), eliminating activities that do not create extra value, eliminating potential causes of variations in the process, assessing risks and testing.

Improving the maintenance process occasionally means redesigning or re-engineering the process, which is, designing and implementing an entirely new process, testing it and standardising the solution. In this case, the creativeness of all employees is required. Process redesign represents the changes made within the process, such as adding new activities, introducing new documents and different procedures and so on. Process re-engineering signifies essential changes that surpass the scope of a process.

Process improvement includes the following activities:

- making an action plan,
- measuring and tracking the efficiency of the improved process,
- tracking the newly created values,
- optimising relations in the superordinate process,
- managing the process and
- continually improving the process.

Through continual improvement, the maintenance process gradually reaches the Six Sigma level.

5.5.5. Phase 5 of DMAIC Model: Control

The control phase is very important as it enables the confirmation of the introduced improvements. Control relates to all steps of the model by establishing standard measurements of maintenance process performances, and problems are corrected where required. Starting from the top managers and the teams for LSS education and improvement to workers-operators and maintainers, this phase involves the participation of all company employees since they are in charge of the activities applying the LSS concept.

The process of control includes the following activities:

- making control charts,
- managing the change processes,
- documenting and standardising the improved maintenance process,
- supervising the maintenance process through control charts,
- checking the stability and capability of the maintenance process and
- proposing measures for further improvement of the maintenance process.

The control of the entire maintenance process is based on measuring process performances, which are continually tracked over time, with the goal of observing trends, the best and the worst practices, and possible areas for improvement. Each process has the possibility to get out of control and cause problems. For this reason, all participants in the implementation process must be controlled effectively, and control must become part of the everyday activities of all company employees. However, relying solely on control to improve the process (finding problems, errors, etc.) includes a high probability for the occurrence of an error or breakdown in the system. Instead, continual efforts are required to reduce or eradicate errors and breakdowns that depend on the human factor. Control as the only means of process improvement can frequently come too late. A long-term quality process comes not only from control but also from improving the process and the entire system. Practically, there are technical and financial constraints to process improvement, but the final goal is the Six Sigma maintenance process or performing the process completely without errors.

Moreover, Banuelas Coronado and Antony (2002) mention that training is a crucial factor in the successful implementation of LSS projects. Training or team training is not successful unless reinforced by regular follow-ups with ongoing systematic changes in how work is conducted (Wiklund and Wiklund, 2002). The lack of quality training causes insufficient implementation of quality methods and quality learning that are necessary for a permanent change in the way of working to create quality achievements (Karrlson Sandvik and Wiklund, 1997). Therefore, the Six Sigma belt system must be applied throughout the company, starting with the top management (i.e., the champions), and should be cascaded down the organisational hierarchy. The curriculum in the belt system varies from organisation to organisation and from consultant to consultant; however, it should be provided by identifying the key roles of the people directly involved in applying LSS. Table 5.2 compares the roles, profiles, training and numbers of people trained in the belt system, according to Air Academy Associates, Six Sigma training and consulting group (Banuelas Coronado and Antony, 2002).

Table 5.2 Comparison of roles, profiles and training in Six Sigma belt system

	Green belts	Black belts	Champions
Profile	Technical background Respected by peers Proficiency in basic and advanced tools	Technical degree Respected by peers and management Master of basic and advanced tools	Senior manager Respected leader and mentor of business issues Strong proponent of six sigma who asks the right questions
Role	Leads important process improvement teams Leads, trains and coaches on tools and analysis Assists black belts Typically part-time on a project	Leads strategic, high impact process improvement projects Change agent Teaches and mentors cross-functional team members Full-time project leader Cover gains into £	Provides resources and strong leadership for projects Inspires a shared vision Establishes plan and creates infrastructure Develops metrics Converts gain into £
Training	Two three-day sessions with one month in-between to apply Project review in second session	Four one-week sessions with three weeks in-between to apply Project review in sessions two, three and four	One week champion training Six sigma develop and implementation plan
Numbers	One per 20 employees (5 per cent)	One per 50 to 100 employees (1-2 per cent)	One per business group or major manufacturing site

Source: Air Academy Associates (1998)

Operators who know their work process better than anybody (Banuelas Coronado and Antony, 2002) should also be familiarised with the Six Sigma philosophy throughout the company since they are the main contributors of the quality in products and services. Although the belt system offers a broad knowledge of the Six Sigma initiative, it does not reinforce all the new knowledge and skills needed to sustain Six Sigma. Throughout the time, companies should look outside the Six Sigma discipline for other methods and ideas that complement it, passing from a trained organisation to a learning organisation (Banuelas Coronado and Antony, 2002). Wiklund and Wiklund (2002) claim that effective implementation of an improvement programme is about organisational learning, and without organisational learning, there can be no CI.

5.6. Integrating LSS and PM Optimisation Model at Operational Level

The conceptual design and model of the LSS and the optimisation for quality management at the operational level assist managers in the following ways:

(1) Define the TC for operational processes.
(2) Provide a data collection structure to collect cost and reliability data.
(3) Use a systematic approach and an integrated TC model to calculate the overall cost.
(4) Monitor changes in costs.
(5) Create a cycle of cost improvement and enhancement of operational processes' performance.
(6) Build a man-machine knowledge base system to propose solutions that could upgrade an organisation's overall performance through the improvement of its operational processes.

5.7. Integrating LSS and PM Optimisation Model at Strategic Level

The new model generates an assessment procedure for goal setting and action planning that may be used by organisations for strategic planning and satisfying the requirements of quality standards. To achieve the goals and create a system that adds value to organisations, the suggested model includes the following activities. (This is not an inclusive list; more activities may be added according to the needs).

(1) Introduce an organisational structure based on processes rather than functions. Identify all primary (e.g., product realisation) and supporting (e.g.,

training) processes that cover the entire organisation and establish their relationships (e.g., the relationship between the supplier evaluation process and incoming goods' quality inspection process) by building a complete value chain with well-defined input, output and interfaces.

(2) Introduce performance measures for each process. Some evaluation measures should be introduced for both individual processes and overall performance (e.g., the training effectiveness measure for the training process or MTBF for the PM process) to create an integrated performance evaluation system based on processes.

(3) Identify the factors that affect the value of the process performance improvement. It is important to do so and to understand how these factors can result in a decrease or an increase in the value of the corresponding process performance (e.g., the calibration of measurement tools or the training of maintenance personnel can affect the value of MTBF) to control the performance improvement and direct it towards specified targets. If calibration is not performed as stated by the standards, there is a chance that the MTBF value will decrease, and more failures will happen.

(4) Identify all cost items related to the changes in the factors affecting the value of the performance improvement (e.g., the calibration cost is considered a preventive type; the cost of producing a part that is not within the engineering standards that had not been identified by the measurement tools is considered an internal failure cost due to the lack of calibration of the measurement tools). The improvement in the value of the factors (e.g., calibration process) may reduce the associated costs. As a result, if the associated costs are controlled, the results will ultimately improve the performance through a sequence of events.

5.8. Advantages of Integrated Model of LSS and PM Optimisation

Model advantages can be summaries as following:

(1) It includes the process organisation of a company (its entire business, as well as maintenance), with the goal of guiding the process towards customers' requirements and increasing their satisfaction.

(2) It functions completely through team work, which confirms the high quality of work, aided by the talent, abilities, knowledge, skills and experiences of the team members, whose arrangement in team work has a synergic effect, which significantly increases available resources for problem solving.

(3) It educates and trains all participants in the implementation process, not only in the basic knowledge of maintenance systems but also in special skills and strategies for problem solving, from the top managers to the workers-operators, which increases the morale and motivation of all the company employees.

(4) It identifies significant processes in maintenance, which (as a "vital minority") have a crucial effect on the company's business since they are essential for its mission and give measurable effects with respect to the requirements of customers or users of services.

(5) The application of the TPM concept and autonomous maintenance (as its component part) makes all users in the maintenance process feel in charge of the state of the system for which they are responsible, have a sense of ownership and take care of its functioning without breakdowns and disturbances.

(6) The standardisation of maintenance procedures provides the possibility to transfer the experienced system operators' and maintainers' experiences, knowledge and skills to other participants in the process so as to accomplish given tasks without unnecessary effort and deviation from standard procedures and instructions.

(7) It allows continual improvement of the maintenance process, which continually results in the organisation's increased effectiveness and efficiency, reduced maintenance costs, and always leads to Six Sigma maintenance processes.

(8) It links the DMAIC model for the improvement of the maintenance process performance to all the required steps in the process of transferring the company's maintenance function from the "as-is" to the "to-be" state.

(9) It offers the opportunity for universal application in all systems, is simpler to understand, does not require high costs of training and implementation, and gives tangible results within a short period of time after introduction.

5.9. Summary

As any other service operation, vehicle fleet maintenance requires continuous and systematic innovation efforts to provide cost-effective and high quality services. This chapter has proposed a quality improvement model that integrates LSS and PM optimisation to upgrade the service process. This new model bridges the service gaps between service providers and customers and balances the requirements of maintenance managers, deliveries and customers by taking the benefits of the Lean speed and the Six Sigma high quality principles, as well as the TC optimisation.

The full benefits of the new framework will be realised when applied at both strategic and operational levels, with universal application only at the strategic level. The application at the operational level results only in cost reductions, whereas the application at the strategic level provides more extensive benefits for the organisation.

6. Model Validations through Application of a Case Study in the Maintenance Process of a Service Organisation

As previously stated, the third phase of the research constituted the actual implementation of LSS and the optimisation model. This phase can be considered the heart of this research because the whole work's objective is to apply the theoretically available knowledge of LSS and optimisation methods in practice, which shows the path for continuous quality improvement.

6.1. Introduction

To achieve significant outcomes in terms of cost, quality and time, best strategies should be applied to enhance the process performance. The LSS and optimisation are two powerful and effective strategies, supporting the organisation in overcoming its weaknesses and retaining its improvement. On one hand, LSS is an organisation-wide approach, aimed at improving the quality of products and services and mainly focused on CI. On the other hand, optimisation concentrates on achieving the "best" design relative to a set of prioritised criteria or constraints. Lockhart and Johnson (1996) define optimisation as "the process of finding the most effective or favourable value or condition" (Cited in Kelley, T. R., 2010). It is important to note that PM is justified only when it is cost-effective, reduces the occurrence of unscheduled breakdowns and extends the useful life of the equipment (Das, Lashkari and Sengupta, 2007). Appropriate guidelines for addressing these problems should therefore be given from the cost perspective. At present, service organisations are seeking a systematisation of PM to minimise the maintenance costs, suitably reduce the incidence of breakdowns and improve customer satisfaction.

This study aims to validate the model provided in the previous chapter by applying the integration of the LSS approach and PM optimisation. A combination of Lean and Six Sigma tools and the optimisation method has been utilised and applied in this study. The methodology has followed the framework of the DMAIC phases. A team has been formed for this project since LSS is a team-based technique. The selection has been based on the contributions that each member could bring to the process. The team has identified the critical parts of the current process by developing a SIPOC diagram. Historical data have been collected and reviewed. In the analysis phase of DMAIC, the goal has been to develop theories of root causes, confirm the theories with data and finally, identify the root causes of the problem. The solution has evolved from an in-depth analysis of the data, including input from customers and stakeholders.

6.2. Case Study

The organisation in this case study is a military unit, which is leading the activities in vehicles fleet maintenance management and equipment repair. The organisation is responsible for vehicles fleet maintenance and all services to keep military readiness. The application of the new framework will affect the maintenance planning. Hence, an efficient and effective maintenance plan will be applicable and appropriate guidelines for addressing problems would therefore be given from the cost perspective.

The most important part of a vehicle is its engine, which is as vital as the heart of a human being. Therefore, the maintenance of engines is essential. As demands on the quality of services and the costs of maintaining vehicles are both increasing, the effectiveness of a maintenance system for engines has become a crucial issue. Engines are subject to deterioration in terms of both usage and age, which leads to reduced product quality and increased maintenance costs. Service organisations execute PM on engines and equipment to prevent or slow down such deterioration. Preventive maintenance is a scheduled downtime, usually periodic, in which a well-defined set of tasks (e.g., inspection, repair, replacement, cleaning, lubrication, adjustment and alignment) is performed (Ebeling, 1997). It is important to note that PM is acceptable only when it is cost-effective, reduces the occurrence of unscheduled breakdowns and lengthens the useful life of the equipment. The maintenance manager’s goal is to maintain the highest possible level of reliability and quality at the lowest possible TC, normally expressed as maintenance optimisation.

Accurately defining and understanding the problem constitute the first important step of the proposed model. The problem definition is broken down into the problem statement, project objective and project benefits. This involves using the SIPOC table to gain a better understanding of the current process. The process also entails brainstorming sessions to identify CTQ characteristics based on customer input. The team members' goal is to identify the root causes of the problem and to reduce the defects occurring in the product. These causes are classified by using a fishbone diagram. This is followed by the root cause analysis technique, using the life data analysis (Weibull modelling) of the engine's data. Finally, the implementation plan is generated, incorporating all the process improvement recommendations. Figure 6.1 shows a summary of the tools used in each stage of the LSS management.

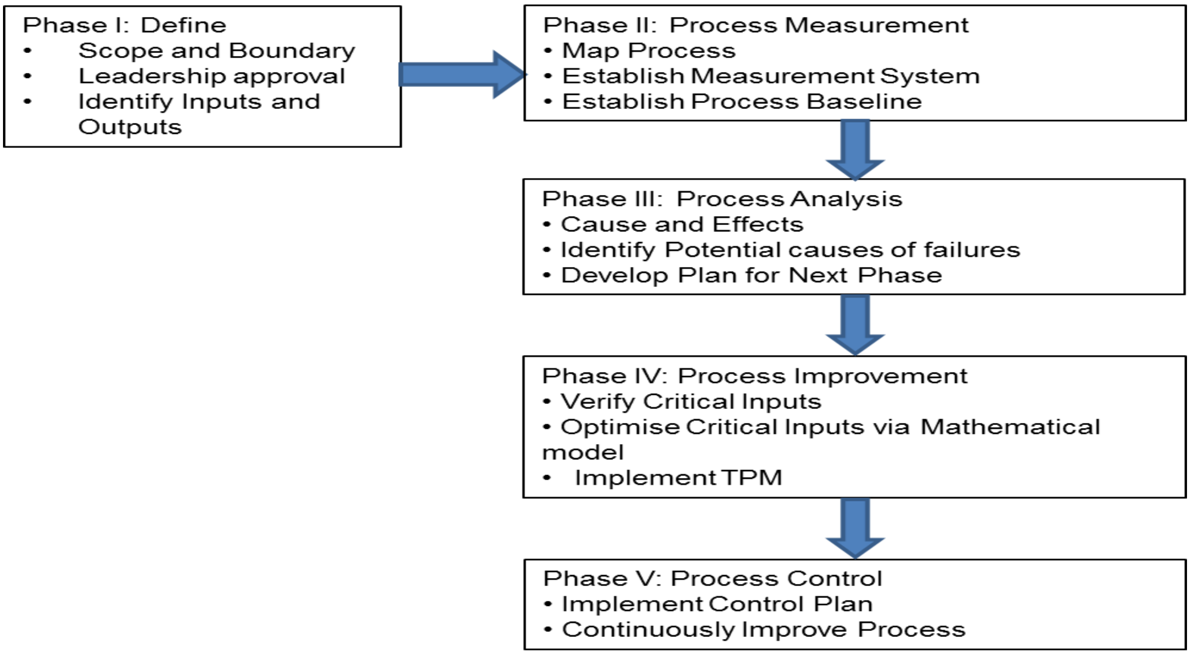


Figure 6.1 DMAIC process

6.2.1. Definition Phase

Step_D1. The project starts with a clear problem definition, using the SIPOC tool. This tool describes the step-by-step process for the engines maintenance, as shown in Figure 6.2. The first process is the engine maintenance. The input to this process includes the PM programme and procedure; the supplier is the maintenance crew. The output of this process is the maintained engine; the customer is the field service unit. The second process involves the repair and replacement of the engine. The inputs to this process are the operation notification and the work order; the supplier is the field service unit. The output of this process is the repaired or replaced engine; the customer is the field service unit.

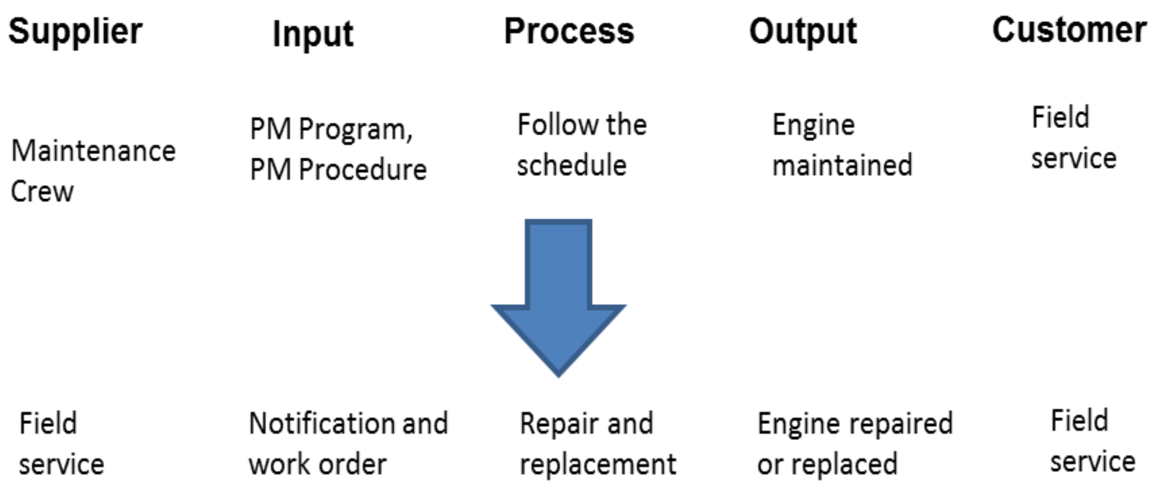


Figure 6.2 SIPOC flow chart

Step_D2. The situation being analysed is verified in the field study for its significance. The engine's PM cost represents a high percentage of the vehicle's PM cost, as shown in Figure 6.3. The team members participate in brainstorming sessions to identify the CTQ characteristics based on the customer input. It is important to classify equipment failure problems based on their degree of importance. This ensures that critical failure problems are tackled and that resources such as technician time and materials are optimised. Hence the oil and coolant leakages are the prime choice for being identified as a CTQ characteristic.

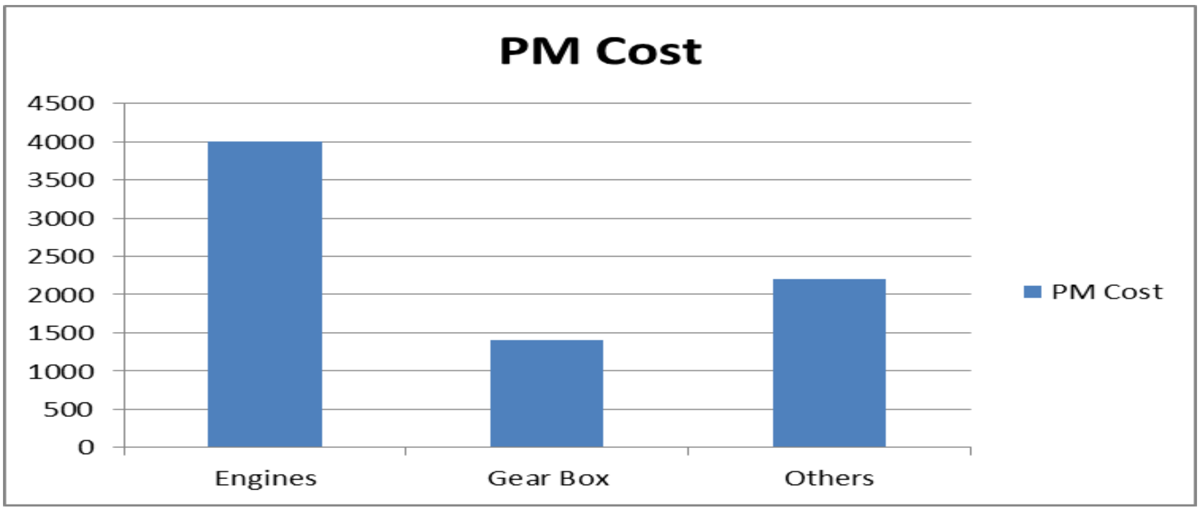


Figure 6.3 Vehicle components versus PM cost

Step_D3. In fact, a component failure is the main reason for the machine breakdown. A component failure that results in high machine downtime or cost (due to machine breakdown) is classified as a critical component. Critical engine failures have been reported for the engines in the field study, affecting the PM cost and causing deviations from the customer satisfaction targets. The project is scoped down to oil and coolant leakages since they contribute 70% of the failures' TC, as determined by the Pareto analysis (Figure 6.4). The Pareto analysis supports the organisation in zooming in on the most critical equipment failure problems. The Pareto analysis is based on the 80-20% rule, where about 80% of the failures could be ascribed to 20% of the equipment components. Conversely, approximately 20% of the causes of the defects contribute to about 80% of the product defects' observed cost.

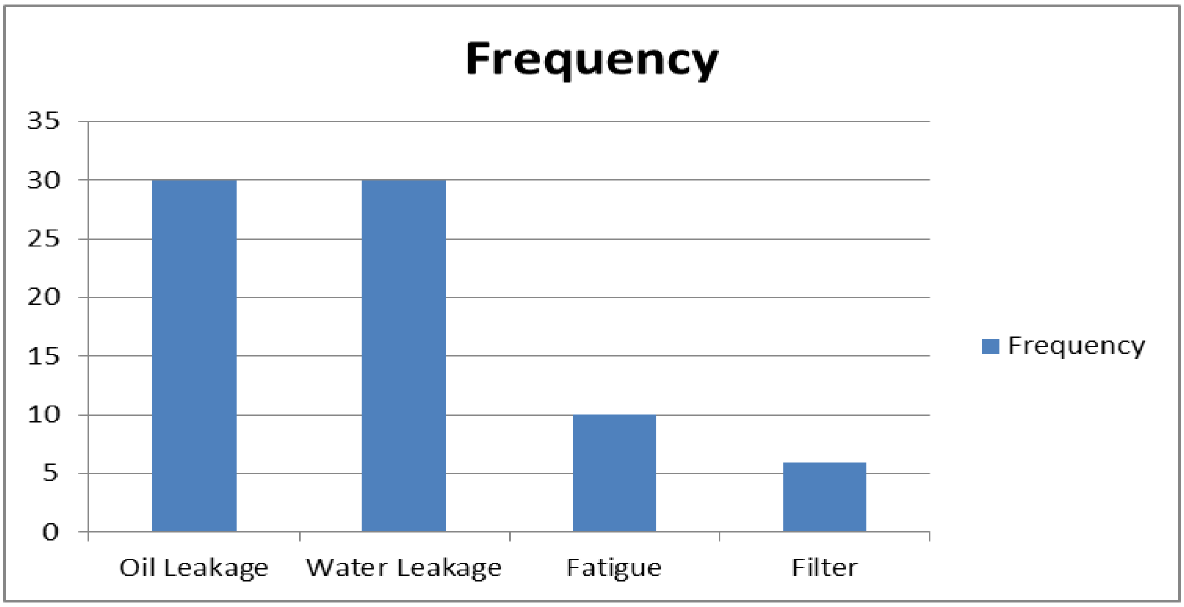


Figure 6.4 Pareto analysis

6.2.2. Measurement Phase

Step_M1. To measure the factors that contribute to the process and the failures in the subject equipment, a number of tools from the Six Sigma toolbox are used, such as the process map and the fishbone diagram. The process map (Figure 6.5) provides a visual view of all maintenance and operation steps that take place from the time an engine failure is detected through restoring it to service, all the way to operation and monitoring until it fails again.

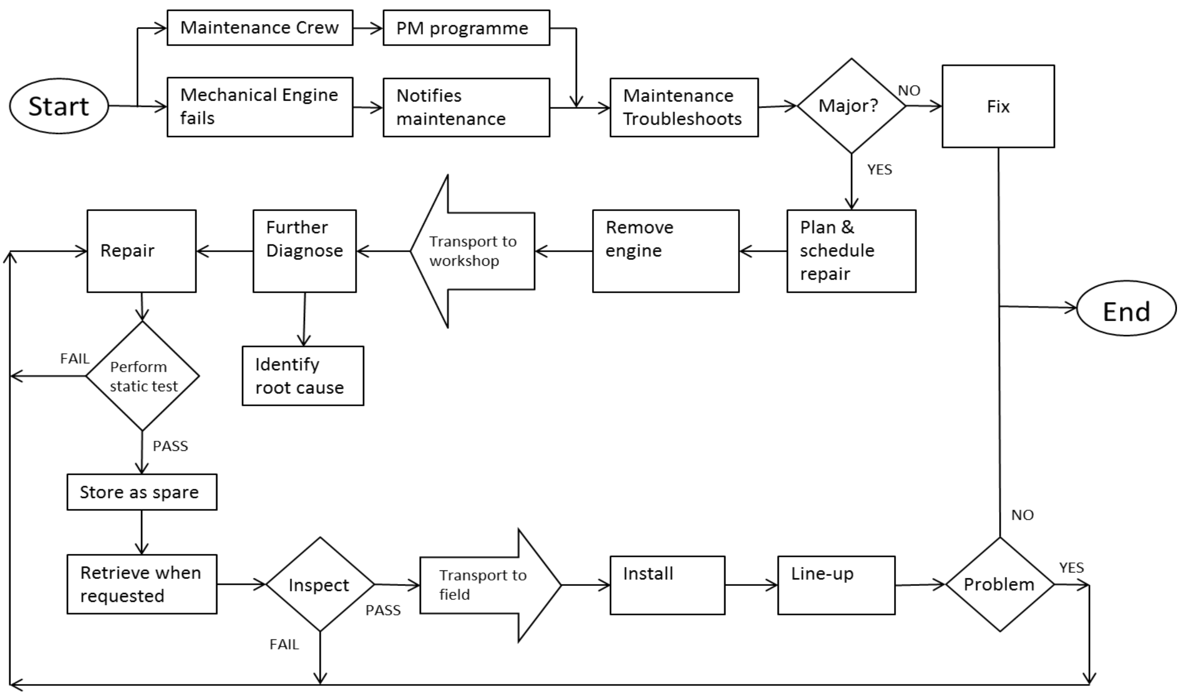


Figure 6.5 Process map

The system's performance powerfully depends on the breakdown-free operation of the equipment (Goh and Tay, 1995). The performance can be improved if these breakdowns can be minimised in a cost-effective manner. In the field study, casual observations of present maintenance services have revealed much room for quality improvement. Four key factors have also speeded the urgent need to improve the quality of maintenance services, as follows:

(1) The number of personnel involved in maintenance services is increased due mainly to an overall increase in maintenance activities.

(2) The cost of equipment maintenance has increased enormously. Keeping costs down is a major concern in the field study.

(3) The increased complexity of modern equipment requires a higher level of maintenance and technical skills.

(4) The equipment's quality and reliability reduce customer dissatisfaction.

To deal with these factors service organisations are seeking a systematisation of PM. Experts suggest that appropriate guidelines should be given to address these problems from the cost perspective.

Step_M2. Since the CTQ characteristics (i.e., oil and coolant leakages) have been identified in the definition phase, a data collection plan is developed. Prior to the data collection, the measurement system should be examined. In this case, the existing serviceability report format is used to facilitate the collection of primary data. A monthly report is used to monitor the maintenance tasks performed by the personnel and to calculate the costs, based on this report. Finally, each vehicle has its own maintenance history book to record the repairs/replacements done to it. Through these sources, the data on the maintenance history of the engines can be captured effectively. Then, data collection can begin. To quantify the problem, data gathering was initiated on the failure costs of the engines, which facilitates the measurement phase. Based on the data collection for a given period (48 months), 60 engines in total have been reported in the field study. The values of the cost and failure parameters used for the two types of the critical components (oil leakage and coolant leakage) are shown in Appendix A, Tables 1–7.

Step_M3. The ability of a process to meet the specifications (customer expectations) is defined as process capability, which is measured by the indices that compare the spread (variability) and centring of the process to the upper and lower specifications. The sigma level is a measure of process capability; the higher the sigma level, the more capable the process is. A Six Sigma process has a short-term sigma level of 6 and a long-term sigma level of 4.5. Simply stated, the sigma level indicates how many standard deviations ("sigmas") can fit inside the gap between the process average and the nearest specification limit. For a specific CTQ characteristic, the sigma level can be calculated as:

$$DPMO = \frac{total\ number\ of\ defects}{number\ of\ units\ x\ number\ of\ opportunities}$$

If an overall long-term defect rate is available for all defects, it is possible to state the sigma level for the entire process (all CTQ characteristics and their associated defects) by locating the defect rate on the Sigma Conversion Chart (see appendix A Table 8) and finding the corresponding sigma level. The capability indices C_{pk} and the sigma level at which the process operates are estimated and summarised in

Table 6.1. The sigma level of a process can be used to express its capability or how well it performs with respect to specifications.

Table 6.1 Data for a CTQ characteristic

CTQ	No. of units	No. of opportunities	No. of defects	dpmo	Sigma level	C_{pk}	Comment
Oil leakage	1000	7	30	4285	2.45	1.4	Capable
Coolant leakage	1000	3	30	10000	2.3	1.2	Less capable

6.2.3. Analysis Phase

Step_A1. To ascertain the root cause(s) of high machinery failure, an analysis using the cause-and-effect diagram is therefore carried out and identified during a brainstorming session of the LSS team. Figure 6.6 shows the root causes of the engine failure problems.

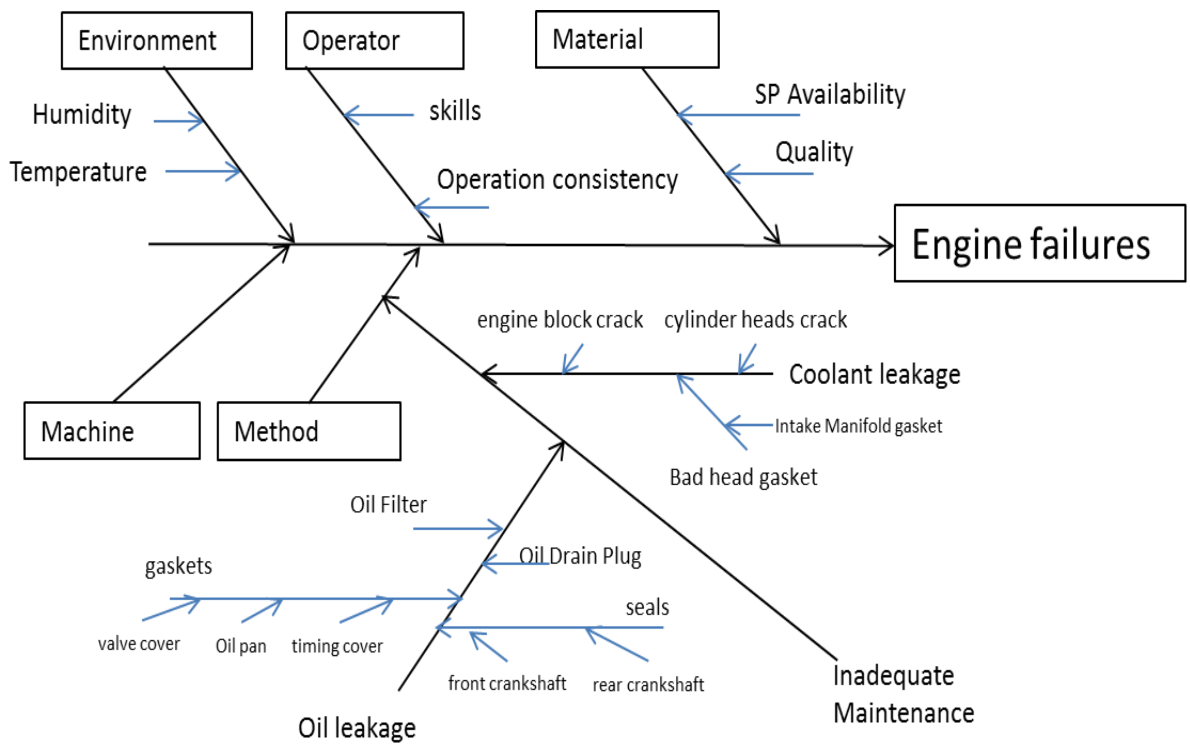


Figure 6.6 Fishbone diagram

Step_A2. Following the cause-and-effect diagram, the team creates the failure modes and effects and conducts the criticality analysis on each of the areas identified from the failure routes on the cause-and-effect diagram. The analysis of the failure data allows the organisation to identify the potential causes of failures, assess their effects on the machine and the process and most importantly, allow corrective actions to be identified. This step is achieved by using the following tools:

A. Methodology for analysis of failure data

Analysis procedures for the engine failure data are presented. These aim to verify the modes and improve the performance, reliability and safety of operating the engine. These procedures include the following elements:

- data gathering;
- choosing a lifetime distribution that will fit the data and model the life;
- estimating the parameters with the aim of fitting the distribution to the data; and
- making plots and obtaining results that estimate the life characteristics, such as reliability or mean life, of the engine.

B. Life data analysis (Weibull modelling) of the engine data

Life data analysis allows making predictions about the life of all products by "fitting" a statistical distribution to the life data from a representative sample of units. The distribution for the data can then be used to estimate important life characteristics of the product, such as reliability or probability of failure at a specific time, the mean life of the product and failure rate.

It is necessary to choose the appropriate statistical model for the distribution to make accurate predictions. Minitab is a statistical software package with a broad range of date analysis capabilities. Figure 6.7 shows the Minitab worksheet used in this project.

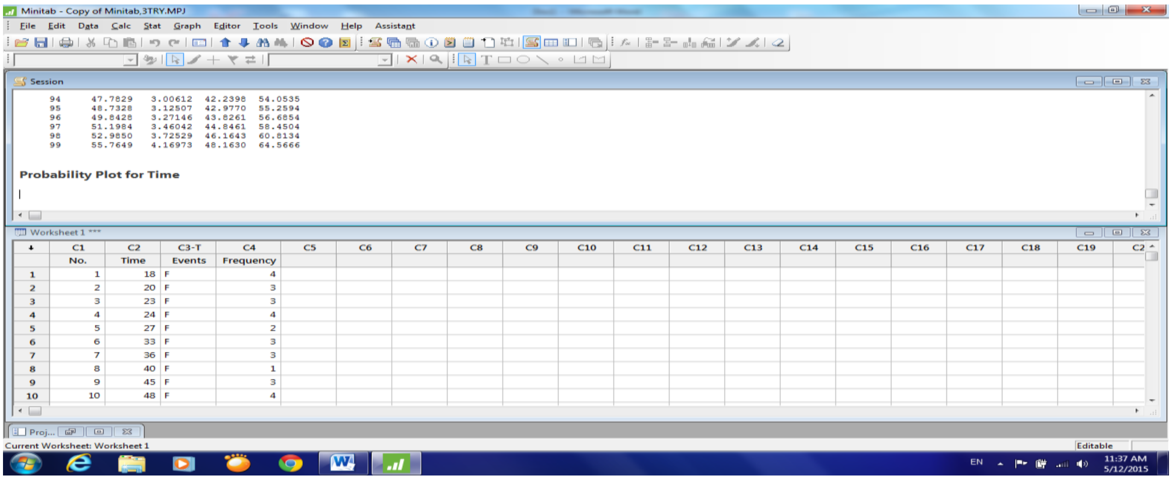


Figure 6.7 Minitab worksheet of engine data

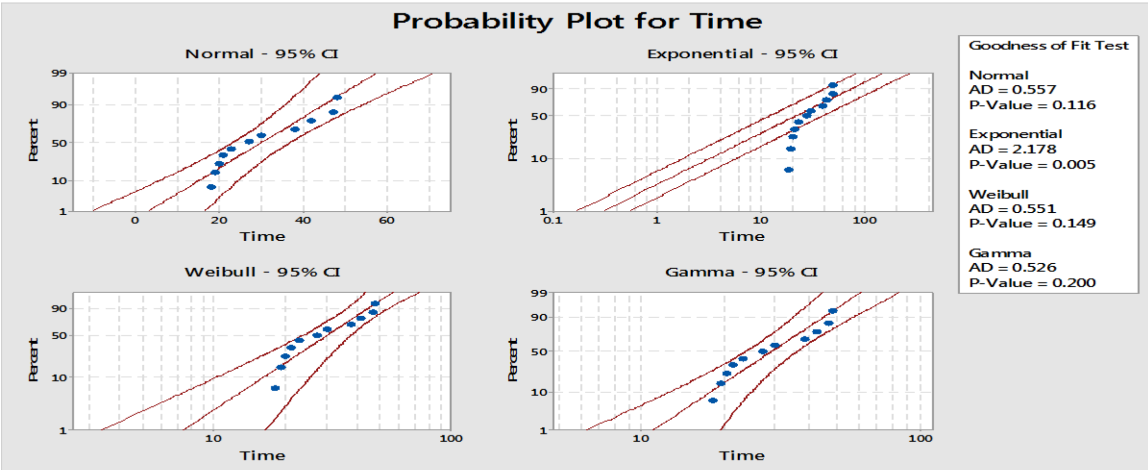


Figure 6.8 Oil leakage probability plots for different models

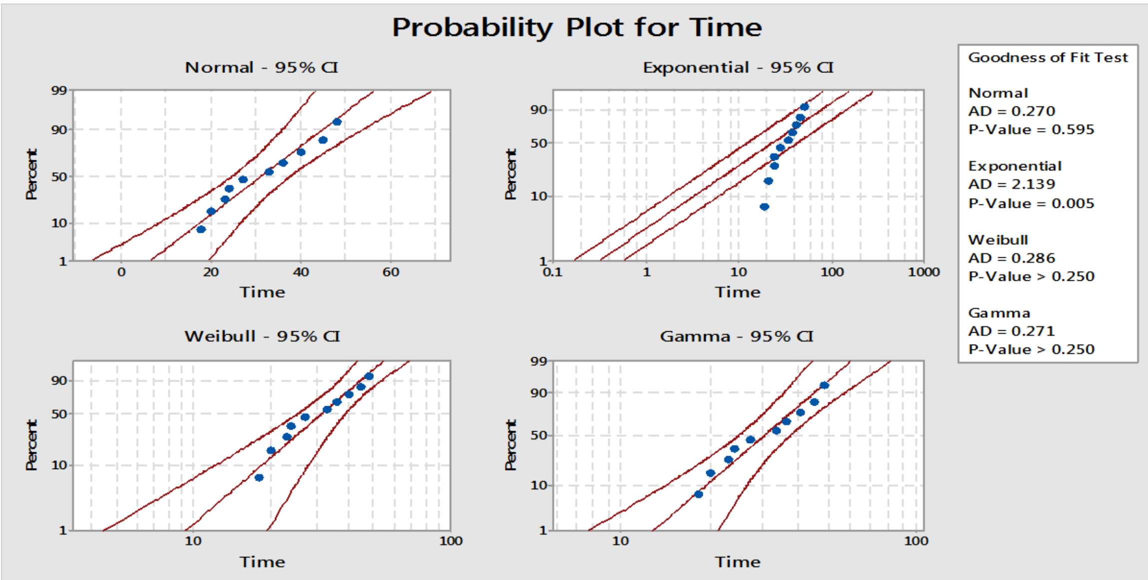


Figure 6.9 Coolant leakage probability plots for different models

Figure 6.8 and 6.9 shows the comparisons among different models (using Minitab) for the oil leakage and coolant leakage data. As shown in Figure 6.8, gamma seems better than the Weibull distribution since a larger p-value and a lower Anderson-Darling (AD) value indicate a better fit. Figure 6.9 also indicates that the normal distribution seems better than the Weibull one. However, the Weibull distribution is widely used in the analysis and description of reliability data. This statistical model is very popular due to its flexibility. The Weibull analysis is frequently used to examine the field or test failure data so as to understand how some items are failing and what specific underlying failure distribution is being followed.

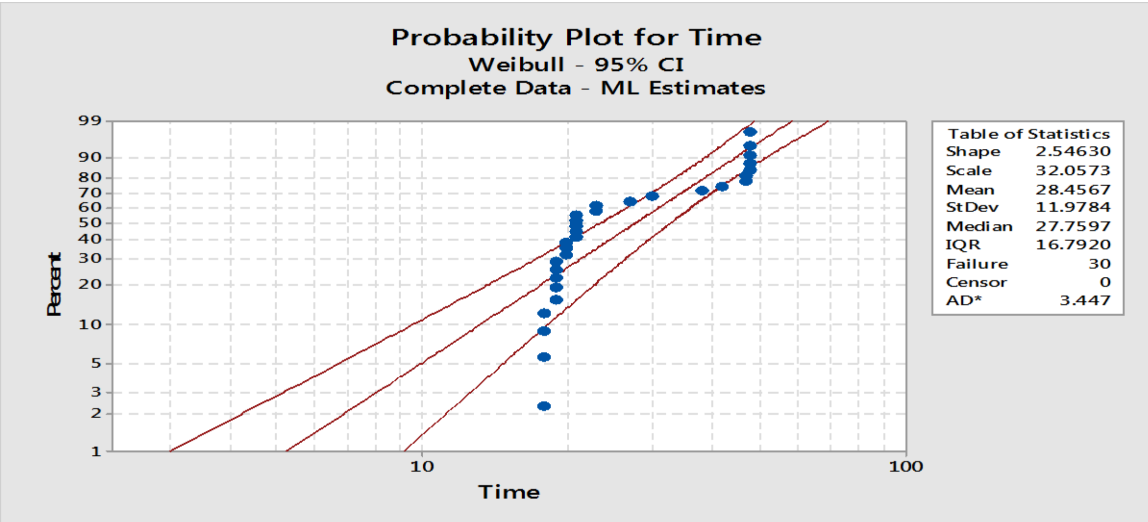


Figure 6.10 Oil leakages, Weibull distribution plot for time

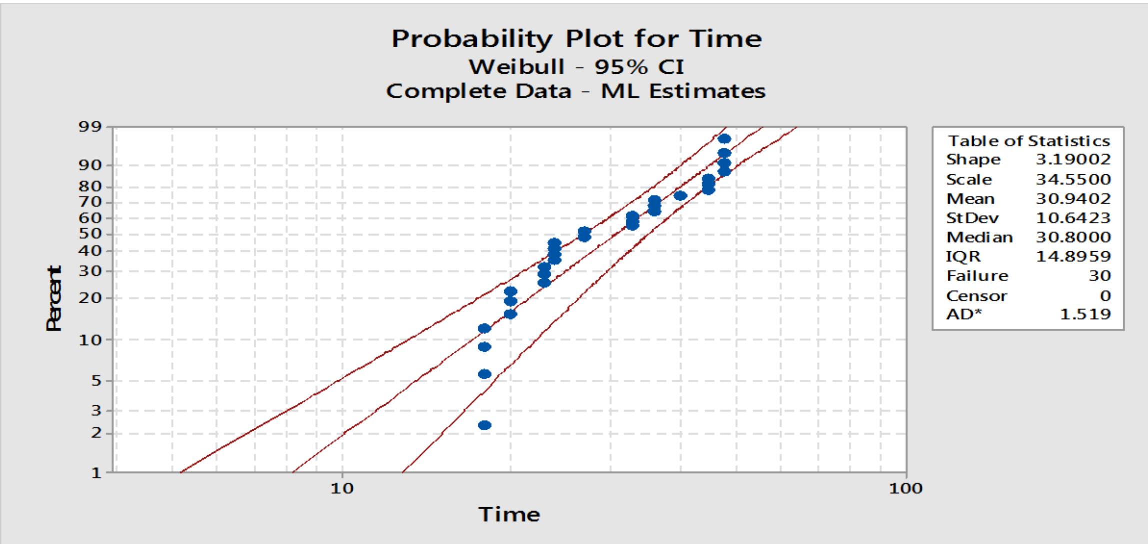


Figure 6.11 Coolant leakages, Weibull distribution plot for time

In Figures 6.10 and 6.11, each failure time is plotted against the probability of the percent failure up to that point. Only failure times are plotted. The units that have not had this failure are called censored units. Although their time to failure is not plotted, it influences the plot positions of the failure points and the nominal line. The goodness-of-fit is correlated to how large the p-value is and how small the AD value is. This is correct for all probability papers, such as Weibull, normal, log-normal, and so on.

From the results presented in Figures 6.10 and 6.11, the shape parameter (β) estimates for the engine data are 2.54 and 3.19 for oil and coolant leakages, respectively. This value suggests that the engine failure rate increases with age, which is the wear-out condition. Therefore, engine components should be replaced at some age when they are near failure. Slopes close to a value of one point out that the exponential distribution is suitable and that the failures are independent of age. Slopes less than one indicate infant mortality, quality problems or inadequate environmental stress screening. Slopes larger than one indicate a wear-out condition. In other words, β shows something about the physics of failure and is most helpful in determining the root cause analysis. In this case, the engine is wearing out.

For an LSS project, it is very important that the analysis be data driven as much as possible. Although the judgement of subject matter experts should be trusted, it should still be verified whenever practical. In the subject problem, experts have suggested that four key factors have the urgent need to improve the quality of maintenance services. To verify the respected experts' judgement with solid data, life data have been collected. The best fit to the data of a two-parameter Weibull distribution has initially confirmed the experts' judgement.

Step_A3. TPM can be defined in terms of OEE, which in turn can be considered a combination of the operation maintenance, equipment management and available resources. The goal of TPM is to maximise equipment effectiveness, and the OEE is used as a measure (Waeyenbergh and Pintelon, 2002). According to Nakajima (1988), the OEE measurement is an effective way of analysing the efficiency of a single machine or an integrated system. It is a function of availability, performance rate and quality rate and can be expressed as follows:

OEE= availability (A) x performance rate (PE) x quality rate (Q)

$$A = \frac{MTBF}{MTBF + MTTR}$$

$MTBF$ – mean time between failures, using pervious step Mean data as shown in figure 2.10 and 2.11, $MTTR$ – mean time to repair, engine workshops data for repair time which is equal to 5 months.

Engine maintenance workshops produced monthly 20 engines and the annual defect engines for both causes (oil and coolant leakages) are 7 engines. Hence, the quality rate (Q) which is the percentage of the good parts out of the total produced can be calculated as 97%. The workshop is scheduled to run for a 30 days with an 8 days scheduled break. Operating Time=22 days. The Standard Rate for the part being produced is 25 Units/months or 0.88 days/Unit. The workshop produces 240 Total Units during the year. Time to Produce Parts = 240 Units * 0.88 days/Unit = 211 days. Performance = 211 days / 264 days = 80%.

Table 6.2 process performance

Component	$MTBF$	$MTTR$	A	PE	Q	OEE	world-class performance			
							A	PE	Q	OEE
Engine	29.5	5	85%	80%	97%	66%	90%	95%	99%	85%

The OEE value is split down to its fundamental parts, namely, availability, performance and quality. Table 6.2 shows a comparison between the world-class performance and the process understudy performance. The results of this analysis show that machine availability is at 85% compared to performance at 80% and quality at 97%. These clearly indicate that machine breakdowns and major stoppage problems are the underlying reasons for the poor OEE value. Therefore, the application of TPM in this case aims to increase the availability/effectiveness of existing equipment to the level of world-class performance.

Step_A4. The C_{pk} indices show the need for deliberate process location adjustments and/or process variability reductions. Adjustments to the process location are required prior to variability reduction because process mean adjustments are considered relatively simple to accomplish. As such, process mean adjustments, when needed, can produce immediate improvements in process performance relative to the specifications. It is assumed that adjustments in the process mean will have no effect on process variability. In contrast, reductions in process variability are normally considered a more difficult task than adjustments to the process location.

Even within the specification limits, the quadratic loss function interpretation holds that there exists an ideal target value for each process, and any deviation from the target value is detrimental. Large deviations from the target are considered of poorer quality than small deviations. The defining characteristic of the penalty function is that it only takes on a value of zero when the process output is at the target; then, the penalty is proportional to the square of the deviation from the target. From this point of view, the quadratic loss is the leading quality measure of the process. Process improvement becomes a continuous effort to reduce loss, rather than an effort to achieve 100% conformance to specifications. The main goal is to reduce variability. This is the motivation for developing a loss function (which is a part of the mathematical model), which penalises the off-target process output that falls within the specification limits.

Step_A5. The output of process Y may be affected by a series of effect factors, namely, Xn. The relationship between Y and Xn is represented as $Y = f(X)$. By analysing the maintenance process data step by step, the CTQ-Y has been specified as the oil and coolant leakages. Generally, despite its lower frequency of maintenance, loose reliability indicates that the variability of the product characteristic will be high, resulting in poor quality and high quality loss. On the other hand, tight reliability (increase in the frequency of diagnosis) indicates that the variability of the product characteristic will be less, resulting in very good quality and reducing quality loss but increasing the PM cost. Hence, the PM activities (PM and inspection intervals), known as the key X's, have a critical effect on Y. Therefore, an effective PM policy should be scheduled appropriately. Optimisation models should be used for the purpose as much as possible. Maintenance optimisation models include the mathematical models that focus on finding either the optimal balance between the costs and benefits of maintenance or the most appropriate time to execute maintenance.

6.2.4. Improvement Phase

Step_I1. The TPM offers comprehensive equipment management that minimises equipment failures, product defects and accidents. It includes everyone in the organisation, from the top-level management to the shop-floor-level employees. The objectives are to constantly improve the availability and to prevent the degradation of equipment to achieve maximum effectiveness (Ahuja and Khamba, 2008). These objectives require solid management support, in addition to the continuous use of work teams and small group activities to achieve incremental improvements. This step discusses the implementation of TPM in the field study conducted in an organisation. Figure 6.12 shows the Pillar TPM implementation plan.

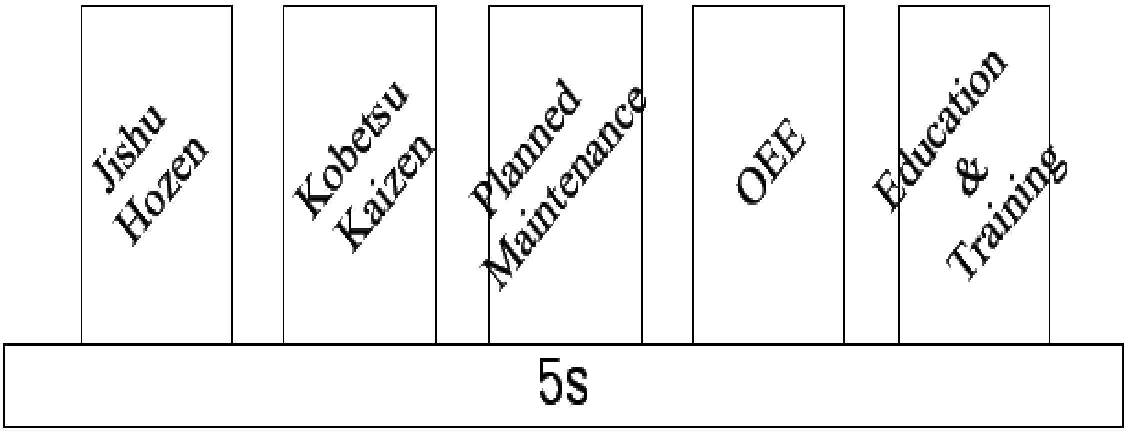


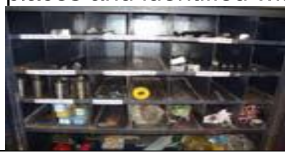
Figure 6.12 Pillars of TPM

Various pillars of TPM (i.e., 5S, Jishu Hozen, Kobetsu Kaizen, Planned Maintenance and OEE) have been implemented in this phase:

(1) 5S: Making problems visible is the first step of improvement. The 5S components are sort, set in order, shine, standardise and sustain. Table 6.3 shows some applications of this tool in the maintenance process.

(2) Jishu Hozen, also called autonomous maintenance: The operators are responsible for maintaining their equipment to prevent it from deteriorating. Step 2 explains the use of this tool.

Table 6.3 Some applications of 5S

5s	Before	After
Sort	Rejected parts were kept inside the workshop.	The parts are now removed, and the space is freed.
Set in order	Earlier patches on the floor were disturbing material movement, using a trolley.  Tools were placed randomly on racks, and no labelling was done. 	Patches are filled with cement, thus helping smoothen the material flow.  Tools are stored in their respective places and identified with labels. 
Shine	There was no dust bin, or it was not in the right place.	The dust bin is now relocated and the workshop area is clean.
Standardise	Employee details were not displayed on the notice board.	Employee details are displayed on the notice board.
Sustain	-	The organisation's mission and vision statements are displayed in Arabic, as well as in English. A suggestion scheme states that whoever gives the best suggestion will be given a reward of $200.

(3) Kobetsu Kaizen: Kaizen entails small improvements, is carried out on a frequent basis and involves people of all levels in the organisation. The principle behind Kaizen is that "a very large number of small improvements are more effective in an organizational environment than a few improvements of large value". This pillar aims to reduce the losses in the workplace that affect its efficiencies. By employing a detailed and thorough procedure, losses are systematically eliminated, using various Kaizen tools, as follows:

- Poka-yoke device: This is a Japanese term that means mistake proofing or error prevention. The Poka-yoke device can be of two types – warning/preventing and detecting.
- Leakage problem: To identify the reasons for a leakage, a fishbone diagram is prepared, as shown in Figure 6.13.

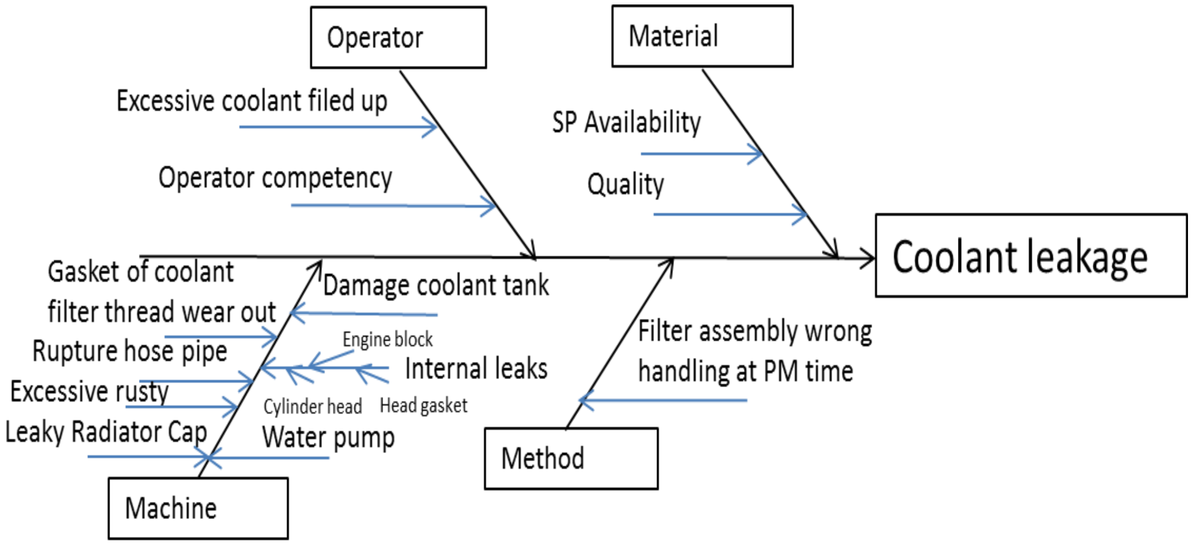


Figure 6.13 Fishbone diagram

- New layout: Figure 6.14 shows a proposed layout, which is designed to minimise the handling of parts.

(4) Education and training: During the TPM implementation period, managers, maintenance personnel and operators are trained to develop their skills and knowledge in maintenance. The aim of TPM is to train people to be highly skilled, motivated and self-reliant regarding the knowledge of their equipment and the process. The TPM education and training programme has been prepared, which is oriented towards three goals:

- Managers will learn to plan for higher equipment effectiveness and implement improvements intended at achieving zero breakdowns and zero defects.
- Maintenance staff will study the basic principles and techniques of maintenance and develop specialised skills concerning the organisation's equipment.
- Equipment operators will learn how to identify equipment abnormalities as such during their daily and periodic inspection activities.

The case under study has a good training structure but will require some expertise in conducting the training related to quality matters. Some aspects of the traditional quality improvement tools, such as the fishbone diagram, Pareto charts and control charts, have yet to be included in the curriculum of existing training courses. With adequate and proper training, such quality maintenance programmes should provide employees with new tools and skills, which can have a lasting effect on performance.

(5) Planned Maintenance: It aims to have trouble-free machines and equipment without any breakdown and to produce components at the quality level that will provide total customer satisfaction. The objectives of Planned Maintenance are the availability of machines, optimum maintenance cost, improvement in the reliability and maintainability of machines, zero equipment failure and breakdown and the availability of spares all the time. See Step 3.

(6) OEE: This is calculated for all the machines before and after implementation.

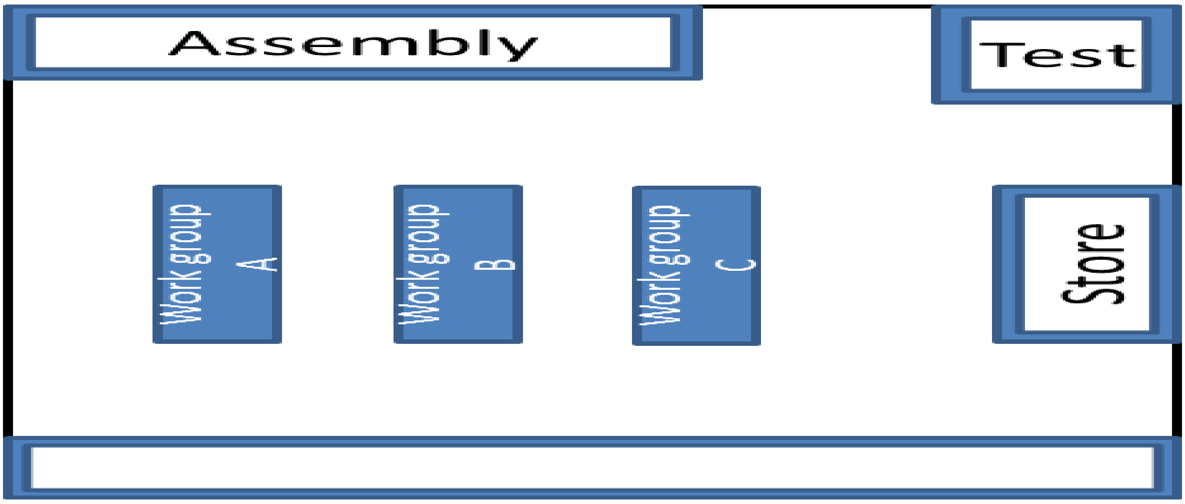


Figure 6.14 Layout of engine workshops

Step_I2. Four levels of maintenance have been implemented in the organisation to improve the machines' reliability. Level 1 is the introduction of the autonomous maintenance teams (drivers or operators). These teams apply basic maintenance practices, including regular daily cleaning regimes, as well as sensory maintenance tasks (smell, sound, sight, touch, etc.). Level 2 typically involves simple repairs or the replacement of components. Level 3 involves more difficult repairs and maintenance, including the repair and testing of components that have failed at the level 2. Level 3 in the maintenance system and the works carried out by the maintenance department. Level involves performing maintenance beyond the capabilities of the lower levels, usually on equipment requiring major overhaul or rebuilding of end-items, subassemblies, and parts. Level 4 involves the engineering department becoming more proactive in the development of PM practices, including machine modification and enhancement strategies that allow easier maintenance, among others. Level-4 works also entail monitoring maintenance activities and are directed primarily at approaches to increase the MTBF to achieve a higher degree of machine availability. The aim here is to scientifically extend the MTBF so that the machinery can remain productive longer, thus providing a greater return on machine performance. Table 6.4 shows the work undertaken at each level in the maintenance system.

Table 6.4 Maintenance levels and work definition

Levels of maintenance operation and typical activities			
Level 1	Level 2	Level 3	Level 4
Basic cleaning	Simple repairs	Machine overhaul	Machine redesign
Machine care plans	Simple replacement	Major maintenance	MTBF analysis
Sensory maintenance	Level-1 monitoring	Level-2 monitoring	Level-3 monitoring

Step_I3. Based on analysis phase and the suggested solution in step_A4 and step_A5 the Mathematical modelling which combined PM cost and loss cost can be used in this step to develop maintenance schedule based on the TC optimisation. Therefore, the following model (introduced in Chapter 4) is used to solve these problems:

$$TC = \frac{C_{meas}}{n} + \frac{\left(Co + \sum_{j=1}^{z} CPRM_j\right) + \sum_{j=1}^{z} cf_j (\frac{tpm}{\theta_j})^{\beta_j}}{tpm} + \frac{A}{F_0^2}\frac{1}{tpm}\left(\sum_{j=1}^{z}\int_0^{tpm}\left(1+\left[e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right]^2 - 2e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right)dt + \left(\frac{n}{2}\right)F_0^2 + \sigma_m^2\right),$$

where tpm is the maintenance interval, *n* is the maintenance inspection time, and *TC* is the total maintenance cost. Clearly, maintenance activity can be improved by increasing tpm and *n* and at the same time, keeping *TC* as low as possible. Thus, the key issues to improve systems are reliability and quality improvement and cost reduction.

The Weibull distribution model has been applied in fitting the failure time of the engines. Figures 6.10 and 6.11 show the results of the failure time process test. The failure time follows the increasing failure rate model. The results confirm the theory that the failure time of a repairable component usually follows the increasing failure rate model. The results show that the shape parameter values are 2.54 and 3.19 for both failures, implying the component's deteriorating state (increasing failure rate). Therefore, the application of PM, based on the new increasing failure rate model, is beneficial.

To apply the improvement using the proposed policy, consider Component 1 for oil leakage and Component 2 for coolant leakage (Table 6.5). The average PM costs $(CPRM)$ are generated from Tables 5 and 6 in Appendix A, based on the average calculations for oil and water leakage data, respectively. Likewise, the failure repair costs (cf) are generated from Tables 5 and 6 in Appendix A, based on the average calculations for oil and water leakage data, respectively. The cost- and reliability-related input data are given in Table 6.5.

The measurement error and time lag between the inspection and repair of the defective unit are negligible. The amount of deviation or drift at which PM should be performed (Δ) is equal to the failure probability (F) at the value of $A = 1{,}000\ dollars$. By using the PM increasing failure rate model and the parameters listed in Table 6.5, the PM interval and inspection time at a lower cost are determined and displayed in Table 6.6.

Table 6.5 Input data

	Component 1	Component 2
$MTBF$	28.46	30.94
$CPRM$	490	330
cf	1490	1225
β	2.54	3.19
θ	32.06	34.55
Co	200	
C_{meas}	30	
Planned period, T	48	

The results are as follows:

Optimisation is completed because the objective function is no decreasing in feasible directions, to within the default value of the function tolerance, and the constraints are satisfied, to within the default value of the constraint tolerance.

<stopping criteria details>

$Optimums$:

$tpm\ = 13.7\ months, n\ = 1.2\ months, Minimum\ cost: TC\ = \$151.68$

Table 6.6 The $\boldsymbol{tpm}$ versus costs (if n = 1 month)

tpm	LC	PM	TC
1	344.29	1020.24	1364.52
2	183.83	510.72	694.55
3	130.35	341.38	471.73
4	103.62	257.2	360.82
5	87.63	207.17	294.8
6	77.05	174.29	251.33
7	69.64	151.25	220.89
8	64.33	134.42	198.75
9	60.57	121.77	182.33
10	58.1	112.07	170.18
11	56.85	104.57	161.42
12	56.83	98.73	155.57
13	58.17	94.21	152.37
14	61.04	90.73	151.77
15	65.69	88.13	153.82
16	72.41	86.26	158.67

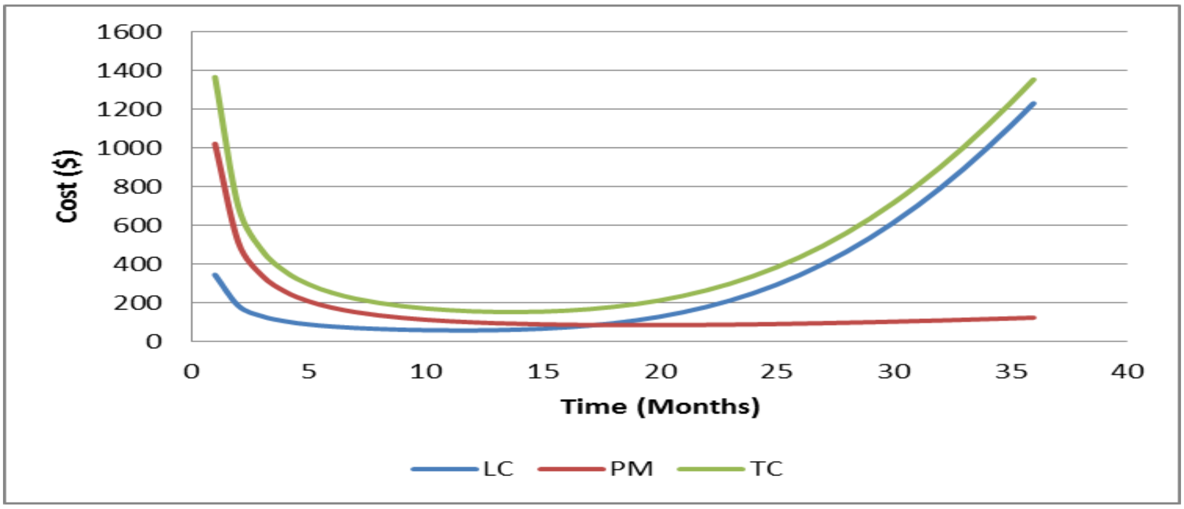


Figure 6. 15 Costs versus interval

Step_I4. It is possible to apply a framework for assessing risks, using both probability and cost estimates and accounting for uncertainty. While individuals may be hesitant to use a single-point estimate for probability or cost, using a range of values with a “best estimate” is conceivable without having detailed information. Estimates for probability distributions and cost distributions can be combined mathematically to determine the expected-cost distribution or the “risk-profile”. Using an MC simulation with MATLAB, a simulation can be developed and proposed to estimate the cost (or a cost objective) as a function of maintenance decision variables.

In the MC simulation, a statistical distribution is identified, which can be used as the source for each of the input parameters. To identify the cost- and reliability-related input data fit distribution, a chi-square test will be used. The chi-square test can be considered a formal comparison of a histogram of the data with the density or mass function of the fitted distribution. The results in Figures 1–6 in Appendix B show that all cases' best fit distribution is uniform distribution. The p-value is between 0.352 and 0.976, which indicates a better fit. Table 6.7 gives the cost- and reliability-related input data.

Table 6.7 Cost and reliability input data for simulation

	Component 1	Component 2
$MTBF$	[18, 48]	[18, 48]
$CPRM$	[400, 600]	[250, 400]
cf	[1400, 1600]	[1100, 1400]
β	[1.05, 2.54]	[1.05, 3.19]
Co	200	
A	1000	
F	1	
C_{meas}	30	
$Planned\ period, T$	48	

Parameter θ_j is computed from the relationship:

$$\theta_j = \frac{MTBF_j}{\Gamma\left(1 + {}^{1}/_{\beta_j}\right)},$$

where Γ is the gamma function.

The results are as follows:

Optimisation is completed because the objective function is nondecreasing in feasible directions, to within the default value of the function tolerance, and the constraints are satisfied, to within the default value of the constraint tolerance.

<stopping criteria details>

$Total$ 1000 $random\ samples$:

$Expected\ tpm$: 9.3 $months$

$Expected\ \ n$: 1.1 $months$

$Expected\ \ TC$: \$135.8

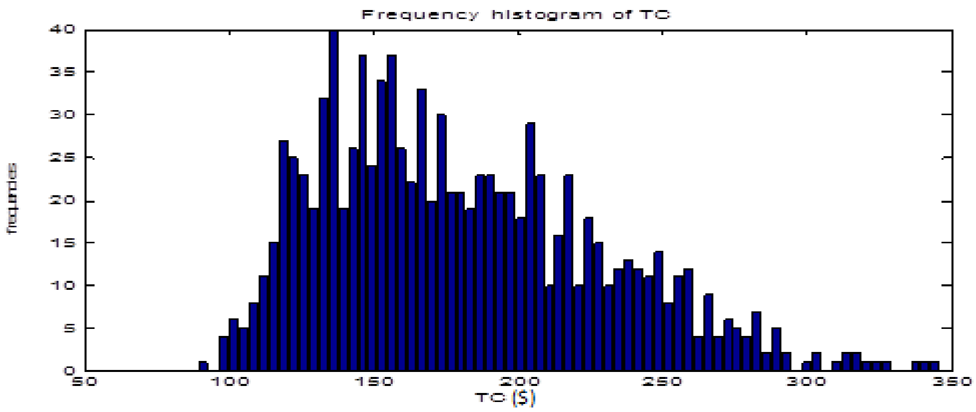


Figure 6.16 TC frequency histogram

The frequency histogram of TC in Figure 6.16 shows that for this best-known choice of decision variables, the TC has a distribution range of $\$100 - \$320$, with an average of about $\$135.80$. Notice that this range of possible futures includes the single value of $\$151.68$ obtained in the previous example.

6.2.5. Control Phase

The following steps can be applied in this phase:

- The implementation schedules should be monitored step by step.
- Comparison between the times of preventive works before and after using the LSS project.
- As of this writing, the Six Sigma team is trying to uncover other possible causes of unacceptable deviation or cost so that other optimisation efforts can be conducted for CI of the process. For example, if defects occur after the optimal condition, the Six Sigma team will follow the DMAIC procedure (Figure 6.1) to pursue the next cycle of process improvement.

6.3. Conclusion

The LSS management is one of the most advanced management ideas and methods. This chapter has applied the concept of LSS management in the process optimisation of equipment maintenance. In the actual equipment maintenance in the case study, the process optimisation method based on the business process model has been introduced into the LSS system to create a more powerful toolbox and ultimately accomplish the general aim of CI for the equipment maintenance process.

7. Conclusions, Discussion and Future Work

This chapter presents the conclusions and discussion of this study, which are drawn from the research findings. It also explains contributions to knowledge in the field. Finally, this chapter closes with suggestions for further research.

7.1. Introduction

This research has developed a sound model and framework for maintenance activities to attain effectiveness and efficiency in maintenance management and to fulfil enterprise objectives in vehicle fleet maintenance. This model has been validated by testing in a real environment.

The literature review on the research topic has identified the importance of the integrated model of LSS and PM optimisation. It has also pointed out the need for the Total Cost (TC) model, which contains the maintenance cost and quality loss cost for the service sector, as well as the model optimisation and simulation application.

A case study has been used to validate the model by testing in a real environment for its integrity, ability to be implemented and effectiveness in improving operation performance.

7.2. Conclusions

The implementation of the integrated model of LSS and PM optimisation has provided an impetus for establishing best practices within the organisation under study. The implementation of this model will also enhance the future performance of the organisation. It has enabled the maintenance of a strong customer-supplier relationship by satisfying customer requirements. The proper utilisation of the resources and the application of LSS tools and techniques will upgrade the company standards and reduce the product defects with improved process parameters. The optimal settings of the process parameters can be also obtained. Moreover, TPM as a lean tool is a proven and successful procedure for introducing maintenance considerations into organisational activities.

7.3. Discussion

This research has proposed a quality improvement model that integrates LSS and PM optimisation to improve the maintenance process. To validate this model, a real field study has been conducted by applying the integration of the LSS approach and PM optimisation. A combination of Lean and Six Sigma tools and the optimisation method have been utilised in this study. The methodology follows the DMAIC framework. This phase of the research constitutes the actual implementation of LSS and the optimisation model. This stage can be considered the core of this research since the entire work aims at transferring the theoretically available knowledge of LSS and optimisation methods into practice, which shows the path for continuous quality improvement.

Despite the extensive research on the PM optimisation of maintenance systems, only a few studies have considered the quality loss cost in the design and analysis of PM optimisation. Another important aspect, which has rarely received attention in the PM process optimisation, is the consideration of PM cost and quality cost in an integral model. These two activities optimised have shown that a relationship exists between maintenance and quality and the joint consideration of these two shop-floor policies is cost-effective in improving the system performance as shown in figures 6.15, TC=$151.68. Using an MC simulation with MATLAB, a simulation developed and proposed to estimate the cost (or a cost objective) as a function of maintenance decision variables. The frequency histogram of TC in Figure 6.16 shows that for this best-known choice of decision variables, the TC has an average of about $\$135.80$. Using MC, estimates for probability distributions and cost distributions can be combined mathematically to determine the expected-cost.

One of the major improvements in this study is that the average TC for an engine maintenance has been reduced by 15.88 $/months compared with the performance before implementing the TC simulation model while the reliability is at the same level. Also, the model considers the loss cost which cause by the product variation in the hand of customers and hence customer's satisfactions is high. On the other hand, before implanting the integral model, loss cost not considers, the PM cost decrease as the maintenance interval, tpm increase as shown in Table 6.5 but the risk is high and the reliability is decreases.

LSS is an organisation-wide approach, aimed at improving the quality of products and services and mainly focused on CI. These five phases helped Six Sigma team in the case study to systematically and gradually develop the process rationalisation. First, they define the problem and then introduce the solutions targeting the fundamental causes, thus constructing the optimal implementation method and ensuring the sustainability of the solutions. Integrate the LSS and PM optimisation model has improved the maintenance efficiency and effectiveness. This model bridges the service gaps between maintenance providers and customers and balances the requirements of maintenance managers, deliveries and customers by taking the benefits of the Lean speed and the Six Sigma high quality principle, as well as the optimisation process balance. A successful implementation has been reached by the reduction of the total PM cost, the reduction of the PM activities, and customer satisfaction and hence an efficient and effectiveness maintenance.

Due to the application of new maintenance guideline model and with a comparison to the problems statements in chapter one, the following important aspect has improved. First, the maintenance waste has decreased due to the maintenance plane has been applied efficiently. Second, the statistical system has introduced which give the effective supervision of maintenance quality issues. Third, the maintenance workshops repair cycle time improved by improving the MTTR. Finally, as stated earlier, improvement of maintenance total cost while at the same time keeping the reliability and quality at high levels.

This research has also proven the importance of applying TPM within the Lean strategy in the service process, which provides a significant improvement in the case under study through the implementation of the TPM pillars. TPM application within the Lean strategy allows the organisations to develop advanced techniques in maintenance analysis and to be more technical in its approach to problem solving in maintenance. This combination enhances the management performance of organisations, continuously raise the efficiency and effectiveness of enterprise management, and improve service quality and reliability.

7.4. Contributions to Knowledge

The research has made contribution to the area of maintenance management by integrating a LSS and PM optimisation model. The contributions of the research may be summarized as:

(1) This study has developed a total cost model to optimise the PM activities based on the PM maintenance cost and the quality loss cost.

(2) This project has developed a method of using the failure probability as a novel generic quality characteristic. Hence, quality loss function using multi-quality characteristics can be used.

(3) This research has established and demonstrated a sound methodology and model to integrate LSS and PM optimisation in the vehicle fleet maintenance process.

(4) The integral model has been validated with a field study. The model tested in real environment for its integrity, ability to be implemented and effectiveness in improving operation performance.

(5) The TPM implementation in the service process and the tool integration with the LSS/PM optimisation enhanced the theory and practice of continual improvement in maintenance.

7.5. Future Work

The following points provide a summary of suggestions for future research:

- This study has been conducted in a single service organisation. The proposed methodology will have continuous improvement, but it is important to address the difficulties encountered during implementation
- The proposed model for implementing the LSS and PM optimisation needs to be validated in different scenarios. The recommended area for further research is the development of standards for the model. The identification of critical success factors is also required.
- The implementation could be extended to other service organisations, with small modifications to suit each company.
- The practical aspects should also be improved by conducting more case studies.

- The LSS framework could be integrated with additional LSS tools to improve its effectiveness. The LSS approach could be extended to ensure sustainable benefits by integrating sustainability tools and techniques.
- Finally, a decision support system could be exclusively developed to enhance the effectiveness of the LSS approach in enabling managers to make the right decisions in a complex business environment.

References

Adzakpa, K.P., Adjallah, K.H. and Yalaoui, F. (2004) 'On-line maintenance job scheduling and assignment to resources in distributed systems by heuristic-based optimization', *Journal of Intelligent Manufacturing,* 15(2), pp. 131-140.

Ahuja, I.P.S. and Khamba, J.S. (2008) 'Total productive maintenance: literature review and directions', *International Journal of Quality & Reliability Management,* 25(7), pp. 709-756.

Albliwi, S.A., Antony, J., Lim, S.A.h. and Al-Mashari, M. (2015) 'A systematic review of Lean Six Sigma for the manufacturing industry', *Business Process Management Journal,* 21(3), pp.665-691.

Aldairi, J., Khan, M. and Munive-Hernandez, J. (2015) 'A Conceptual Model for a Hybrid Knowledge-based Lean Six Sigma Maintenance System for Sustainable Buildings', *Proceedings of the World Congress on Engineering (Vol. 2).*

Antony, J., Kumar, M. and Tiwari, M. (2005) 'An application of Six Sigma methodology to reduce the engine-overheating problem in an automotive company', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* 219(8), pp. 633-646.

Antony, J. and Banuelas, R. (2002) 'Critical success factors for the successful implementation of Six Sigma projects in organizations', *The TQM magazine,* 14(2), pp. 92-99.

Antony, J. (2014) 'Readiness factors for the Lean Six Sigma journey in the higher education sector', *International Journal of Productivity and Performance Management,* 63(2), pp. 257-264.

Antony, J. (2008) 'Can Six Sigma be effectively implemented in SMEs?', *International journal of productivity and performance management,* 57(5), pp. 420-423.

Apte, U. and Kang, K. (2006) 'Lean Six Sigma for reduced cycle costs and improved readiness', Technical Report NPS-LM-06-033, Naval Postgraduate School, Monterey, CA.

Arifin, K. and Nehzati, T. (2012) 'Development of world class manufacturing framework by using six-sigma, total productive maintenance and lean', Scientific Research and Essays, 7(50), pp. 4230 -4241.

Artiba, A., Castagliola, P., Al-Mishari, S.T. and Suliman, S. (2008) 'Integrating Six-Sigma with other reliability improvement methods in equipment reliability and maintenance applications', *Journal of Quality in Maintenance Engineering,* 14(1), pp. 59-70.

Baluch, N., Abdullah, C.S. and Mohtar, S. (2012) 'TPM and lean maintenance–a critical review', *Interdisciplinary Journal of Contemporary Research in Business,* 4(2), pp. 850-85 .

Banuelas Coronado, R. and Antony, J. (2002) 'Critical success factors for the successful implementation of six sigma projects in organisations', *The TQM magazine,* 14(2), pp. 92-99.

Ben-Daya, M., Duffuaa, S.O. and Raouf, A. (2012) *Maintenance, modeling and optimization.* Springer Science & Business Media New York.

Ben-Daya, M. and Duffuaa, S. (1995) 'Maintenance and quality: the missing link', *Journal of Quality in Maintenance Engineering,* 1(1), pp. 20-26.

Better, M., Glover, F. and Kochenberger, G. (2015) 'Simulation Optimization: Improving decisions under uncertainty', *Breakthroughs in Decision Science and Risk Analysis,* p. 59.

Bokrantz, J., Ylipää, T. and Skoogh, A. (2014) ''Lean principles and engineering tools in maintenance organizations–a survey study'', *Swedish Production Symposium, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden.*

Box, G., Bisgaard, S. and Fung, C. (1988) 'An explanation and critique of Taguchi's contributions to quality engineering', *Quality and Reliability Engineering International,* 4(2), pp. 123-131.

Box, G. and Fung, C.A. (1994) Quality quandaries – is your robust design procedure robust? Quality Engineering, 6 (3), 503–514.

Cassady, C.R., Murdock, W.P., Nachlas, J. and Pohl, E. (1998). 'Comprehensive fleet maintenance management'. *SMC'98 Conference Proceedings. 1998 IEEE International Conference on Systems, Man, and Cybernetics (Vol. 5, pp. 4665-4669). New York, NY:* IEEE.

Chan, F., Lau, H., Ip, R., Chan, H. and Kong, S. (2005) 'Implementation of total productive maintenance: A case study', *International Journal of Production Economics,* 95(1), pp. 71-94.

Chaneski, W. (2002) 'Total productive maintenance–an effective technique', *Modern Machine Shop,* 75(2), pp. 46-48.

Charles, A., Floru, I., Azzaro-Pantel, C., Pibouleau, L. and Domenech, S. (2003) 'Optimization of preventive maintenance strategies in a multipurpose batch plant: application to semiconductor manufacturing', *Computers & Chemical Engineering,* 27(4), pp. 449-467.

Cheng, C. and Chang, P. (2012) 'Implementation of the Lean Six Sigma framework in non-profit organisations: A case study', *Total Quality Management & Business Excellence,* 23(3-4), pp. 431-447.

Chu, C., Proth, J. and Wolff, P. (1998) 'Predictive maintenance: The one-unit replacement model', *International Journal of Production Economics,* 54(3), pp. 285-295.

Das, K., Lashkari, R. and Sengupta, S. (2007) 'Machine reliability and preventive maintenance planning for cellular manufacturing systems', *European Journal of Operational Research,* 183(1), pp. 162-180.

Das, K.K. (2006) 'Modeling reliability considerations in the design and analysis of cellular manufacturing systems.' *Electronic Theses and Dissertations,* paper 2756.

Dekker, R. (1996) 'Applications of maintenance optimization models: a review and analysis', *Reliability Engineering & System Safety,* 51(3), pp. 229-240.

Dekker, R. and Scarf, P.A. (1998) 'On the impact of optimisation models in maintenance decision making: the state of the art', *Reliability Engineering & System Safety,* 60(2), pp. 111-119.

Deming, W.E. (1982) 'Out of the Crisis. Massachusetts Institute of Technology, Center for Advanced Engineering Study, Cambridge, MA.

Deming, W.E. (1982) Quality, Productivity, and Competitive Position, MIT Center for Advanced Engineering Study: Boston, MA.

Deming, W.E. (2000) *The new economics: for industry, government, education.* Massachusetts Institute of Technology, Center for Advanced Engineering Study, Cambridge, MA.

Dhillon, B.S. (2006) *Maintainability, maintenance, and reliability for engineers. New York: Taylor & Francis*.

Dodson, B. (1994) 'Determining the optimum schedule for preventive maintenance', *Quality Engineering,* 6(4), pp. 667-679.

Ebeling, C.E. (1997) *An introduction to reliability and maintainability engineering*. New York: McGraw Hill.

English, J. and Taylor, G. (1993) 'Process capability analysis—a robustness study', *International Journal of Production Research,* 31(7), pp. 1621-1635.

Fatemi, A., Fuchs, H.O., Stephens, R.I. and Stephens, R.R. (2001) 'Metal fatigue in Engineering', John Wiley & Sons.

Furterer, S.L. (2004) *A framework roadmap for implementing Lean Six Sigma in local governmental entities, (Doctoral dissertation, University of Central Florida Orlando, Florida)*.

George, M.L. (2002) 'Lean six sigma: combining six sigma with lean speed', McGraw-Hill New York, NY.

George, M.L. and George, M. (2003) *Lean six sigma for service.* McGraw-Hill New York, NY.

Goh, M. and Tay, G. (1995) 'Implementing a quality maintenance system in a military organization', *International Journal of Quality & Reliability Management,* 12(4), pp. 26-39.

Hadidi, L.A., Al-Turki, U.M. and Rahim, A. (2011) 'Integrated models in production planning and scheduling, maintenance and quality: a review', *International Journal of Industrial and Systems Engineering,* 10(1), pp. 21-50.

Hammer, M. (2002) 'The future of Six Sigma', *MIT Sloan management review, 43(2), p.26.*

Harry, M.J. (1998) 'Six Sigma: a breakthrough strategy for profitability', *Quality Progress,* 31(5), pp. 60.

Jayabalan, V. and Chaudhuri, D. (1992) 'Cost optimization of maintenance scheduling for a system with assured reliability', *Reliability, IEEE Transactions on,* 41(1), pp. 21-25.

Jiju Antony, P., Svensson, C., Antony, J., Ba-Essa, M., Bakhsh, M. and Albliwi, S. (2015) 'A Lean Six Sigma program in higher education', *International Journal of Quality & Reliability Management,* 32(9), pp. 951-969.

Kackar, R.N. (1989) 'Off-line quality control, parameter design, and the Taguchi method', in *Quality Control, Robust Design, and the Taguchi Method.* Springer, pp. 51-76.

Karlsson, S. and Wiklund, P.S. (1997) 'Critical aspects of quality method implementation', *Total Quality Management,* 8(1), pp. 55-66.

Kelley, T.R. (2010) 'Optimization, an important stage of engineering design', *The Technology Teacher,* 69(5), pp. 18.

Kumar, A., Motwani, J. and Otero, L. (1996) 'An application of Taguchi's robust experimental design technique to improve service performance', *International Journal of Quality & Reliability Management,* 13(4), pp. 85-98.

Márquez, A.C. (2007) 'Maintenance Management Characterization: Process, Framework and Supporting Pillars', *The Maintenance Management Framework: Models and Methods for Complex Systems Maintenance, Part of the series Springer Series in Reliability Engineering pp 11-40*.

McClusky, R. (2000) 'The rise, fall and revival of Six Sigma quality', *Measuring Business Excellence,* 4 (2), pp. 6–17.

Meeker, W.Q. and Escobar, L.A. (2003) 'Reliability: the other dimension of quality', *Quality Technology & Qualitative Management,* 1(1), pp. 1-25.

Milana, M., Khan, M.K. and Munive, J.E. (2014) 'A Framework of Knowledge Based System for Integrated Maintenance Strategy and Operation', *Applied Mechanics and Materials.* Trans Tech Publ, 619-624.

Mishra, R.P., Anand, G. and Kodali, R. (2006) 'Development of a framework for world-class maintenance systems', *Journal of Advanced Manufacturing Systems,* 5(02), pp. 141-165.

Misterek, S., Anderson, J. and Dooley, K. (1990) 'The strategic nature of process quality', *Proceedings of the National Decision Sciences Institute Conference,* (Vol. 1517, p. 1519).

Mobley, R.K. (2002) *An introduction to predictive maintenance.* Butterworth-Heinemann.

Moghaddam, K.S. and Usher, J.S. (2011) 'Preventive maintenance and replacement scheduling for repairable and maintainable systems using dynamic programming', *Computers & Industrial Engineering,* 60(4), pp. 654-665.

Montgomery, D.C. (2009) 'Statistical Quality Control-A Modern Introduction, *6 ed.* International Student Version John Whiley & Sons', *Inc., New York*.

Naidu, N. (2008) 'Mathematical model for quality cost optimization', *Robotics and Computer-Integrated Manufacturing,* 24(6), pp. 811-815.

Nakajima, S. (1988) 'Introduction to TPM: Total Productive Maintenance.(Translation)', *Productivity Press, Cambridge, MA, Inc., 1988,* , pp. 129.

Nakajima, S. (1989) *TPM development program: implementing total productive maintenance.* Productivity Press, Cambridge, MA.

Nelson, W. (1982) 'Applied Life Data Analysis, New York: John Wiley & Sons.

Nelson, W.B. (2005). *Applied life data analysis (Vol. 577).* John Wiley & Sons.

Nicholas, J.M. (1998) *Competitive manufacturing management: continuous improvement, lean production, customer-focused quality. Boston:* McGraw-Hill/Irwin.

Ormerod, R. (1993) 'The OR/MS contribution to maintenance management Comment on "Maintenance management decision making"', *European Journal of Operational Research,* 65(1), pp. 140-142.

Pandey, D., Kulkarni, M.S. and Vrat, P. (2012) 'A methodology for simultaneous optimisation of design parameters for the preventive maintenance and quality policy incorporating Taguchi loss function', *International Journal of Production Research,* 50(7), pp. 2030-2045.

Pandey, D., Kulkarni, M.S. and Vrat, P. (2010) 'Joint consideration of production scheduling, maintenance and quality policies: a review and conceptual framework', *International Journal of Advanced Operations Management,* 2(1-2), pp. 1-24.

Pascovici, D.S. (2008) 'Thermo economic and risk analysis for advanced long-range aero engines', (PhD thesis), Cranfield University, Cranfield, United Kingdom.

Pfeifer, T., Reissiger, W. and Canales, C. (2004) 'Integrating six sigma with quality management systems', *The TQM Magazine,* 16(4), pp. 241-249.

Pintelon, L.M. and Gelders, L. (1992) 'Maintenance management decision making', *European Journal of Operational Research,* 58(3), pp. 301-317.

Pongpech, J. and Murthy, D. (2006) 'Optimal periodic preventive maintenance policy for leased equipment', *Reliability Engineering & System Safety,* 91(7), pp. 772-777.

Pophaley, M. and Vyas, R.K. (2015) 'FORTIFICATION OF PLANT MAINTENANCE MANAGEMENT PRACTICES: ROLE OF SIX SIGMA APPROACH', *Brazilian Journal of Operations & Production Management,* 12(1), pp. 56-64.

Psychogios, A.G. and Tsironis, L.K. (2012) 'Towards an integrated framework for Lean Six Sigma application: Lessons from the airline industry', *Total Quality Management & Business Excellence,* 23(3-4), pp. 397-415.

Raouf, A. and Ben-Daya, M. (1995) 'Total maintenance management: a systematic approach', *Journal of Quality in Maintenance Engineering,* 1(1), pp. 6-14.

Rardin, R.L. (1998) *Optimization in operations research.* Prentice Hall New Jersey.

Raychaudhuri, S. (2008) 'Introduction to monte carlo simulation', *Winter Simulation Conference, 2008.* IEEE, 91-100.

Sandve, K. and Aven, T. (1999) 'Cost optimal replacement of monotone, repairable systems', *European Journal of Operational Research,* 116(2), pp. 235-248.

Sauers, D.G. (1999) 'Using the Taguchi loss function to reduce common-cause variation', *Quality Engineering,* 12(2), pp. 245-252.

Şenvar, Ö. and Tozan, H. (2010) 'Process capability and six sigma methodology including fuzzy and lean approaches', *Products and Services; from R&D to Final Solutions*. (Accessed 13 May 2015), ISBN: 978-953-307-211-1.

Shamou, M. and Arunachalam, S. (2008) 'Challenges facing modern manufacturing industry', *Conference proceedings, Fascinating Advancements in Mechanical Engineering FAME (vol. 8).*

Shirose, K. and Guide, T.T. (1995) Portland, Oregon: Productivity Press, Inc.

Shrivastava, D., Kulkarni, M.S. and Vrat, P. (2015) 'Integrated design of preventive maintenance and quality control policy parameters with CUSUM chart', *The International Journal of Advanced Manufacturing Technology, Volume 82, Issue 9*, pp. 1-12.

Snee, R.D. (2010) 'Lean Six Sigma-getting better all the time', *International Journal of Lean Six Sigma,* 1(1), pp. 9-29.

Su, C., Chiang, T. and Chang, C. (2006) 'Improving service quality by capitalising on an integrated Lean Six Sigma methodology', *International Journal of Six Sigma and Competitive Advantage,* 2(1), pp. 1-22.

Tabikh, M. and Khattab, A. (2011) 'Scheduled maintenance policy for minimum cost: a case study', Linnaeus University.

Taguchi, G. (1986) *Introduction to quality engineering: designing quality into products and processes. Asian Productivity Organization, Tokyo.*

Taguchi, G., Elsayed, E.A. and Hsiang, T.C. (1989) *Quality engineering in production systems.* McGraw-Hill New York.

Taguchi, G. and Rafanelli, A.J. (1994) *Taguchi on robust technology development: bringing quality engineering upstream, ASME Press, New York*.

Taguchi, G. and Wu, Y. (1979) *Introduction to off-line quality control.* Central Japan Quality Control Assoc.

Taner, T. and Antony, J. (2006) 'Applying Taguchi methods to health care', *Leadership in Health Services,* 19(1), pp. 26-35.

Thomas, A., Barton, R. and Byard, P. (2008) 'Developing a Six Sigma maintenance model', *Journal of Quality in Maintenance Engineering,* 14(3), pp. 262-271.

Uday, K., Parida, A., Crespo Márquez, A., Moreu de León, P., Gómez Fernández, J., Parra Márquez, C. and López Campos, M. (2009) 'The maintenance management framework: A practical view to maintenance management', *Journal of Quality in Maintenance Engineering,* 15(2), pp. 167-178.

Vasili, M., Hong, T.S. and Ismail, N. (2011) 'Maintenance optimization models: a review and analysis', *optimization.* In *Proceedings of the 2011 international conference on industrial engineering and operations management, 22–24 January 2011, Kuala Lumpur, Malaysia* (pp. 1131–1138).

Waeyenbergh, G. and Pintelon, L. (2002) 'A framework for maintenance concept development', *International Journal of Production Economics,* 77(3), pp. 299-313.

Wang, X., Wang, Y. and Xu, D. (2012) 'Lean six sigma implementation in equipment maintenance process', *Quality, Reliability, Risk, Maintenance, and Safety Engineering (ICQR2MSE), 2012 International Conference on.* IEEE, 1391-1395.

Wiklund, H. and Wiklund, P.S. (2002) 'Widening the Six Sigma concept: An approach to improve organizational learning', *Total Quality Management,* 13(2), pp. 233-239.

Zhang, L., Feng, F., Wang, J. and Jiang, P. 'Research on the reliability assessment methods based on single performance parameters degradation data for diesel engine', *2013 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE), 978 – 982.*

Zhao, D., Ye, W. and Gao, C. (2012) 'Research on process optimization for equipment maintenance based on lean six sigma management', *Quality, Reliability, Risk, Maintenance, and Safety Engineering (ICQR2MSE), 2012 International Conference on.* IEEE, 1333-1337.

Zhao, D., Ye, W. and Gao, C. (2012) 'Research on process optimization for equipment maintenance based on lean six sigma management', *Quality, Reliability, Risk, Maintenance, and Safety Engineering (ICQR2MSE), 2012 International Conference on.* IEEE, 1333-1337.

Appendix A

Table 1 Engines′ oil leakage failure parameters

Number	Time	Events	Frequency
1	18	F	4
2	19	F	5
3	20	F	3
4	21	F	5
5	23	F	2
6	27	F	1
7	30	F	1
8	38	F	1
9	42	F	1
10	47	F	2
11	48	F	5

Table 2 Engines′ water leakage failure parameters

Number	Time	Events	Frequency
1	18	F	4
2	20	F	3
3	23	F	3
4	24	F	4
5	27	F	2
6	33	F	3
7	36	F	3
8	40	F	1
9	45	F	3
10	48	F	4

Table 3 Oil leakage repair cost for 30 engines in dollars

1600	1450	1500	1600	1400	1550
1400	1350	1400	1450	1400	1550
1550	1600	1450	1350	1600	1500
1450	1550	1600	1600	1500	1450
1400	1500	1550	1450	1350	1600

Table 4 Water leakage repair cost for 30 engines in dollars

1100	1250	1100	1100	1250	1100
1200	1150	1300	1200	1150	1150
1400	1100	1200	1400	1250	1200
1350	1250	1300	1200	1100	1350
1300	1000	1250	1350	1300	1400

Table 5 Oil leakage average maintenance cost for 30 engines in dollars

400	450	600	400	450	550
450	350	400	450	400	550
500	600	400	350	600	500
450	550	600	600	500	450
400	500	500	550	450	600

Table 6 Water leakage average maintenance cost for 30 engines in dollars

300	250	300	400	250	350
300	400	350	300	350	250
400	400	400	400	250	400
350	250	300	250	350	350
300	300	350	350	300	400

Table 7 PM Fixed and Measurement cost

Fixed cost of PM, Co	$150\ dollars$
Measurement cost, C_{meas}	$30\ dollars$

Table 8 Sigma Conversion Chart

Defect Rates for Various Sigma Levels

Sigma Conversion Chart

Long Term Sigma Level	Short Term Sigma Level	Defects Per Million	Long Term Sigma Level	Short Term Sigma Level	Defects Per Million
4.5	6	3	1.9	3.4	28,717
4.4	5.9	5	1.8	3.3	35,930
4.3	5.8	9	1.7	3.2	44,565
4.2	5.7	13	1.6	3.1	54,799
4.1	5.6	21	1.5	3	66,807
4	5.5	32	1.4	2.9	80,757
3.9	5.4	48	1.3	2.8	96,800
3.8	5.3	72	1.2	2.7	115,070
3.7	5.2	108	1.1	2.6	135,666
3.6	5.1	159	1	2.5	158,655
3.5	5	233	0.9	2.4	184,060
3.4	4.9	337	0.8	2.3	211,855
3.3	4.8	483	0.7	2.2	241,964
3.2	4.7	687	0.6	2.1	274,253
3.1	4.6	968	0.5	2	308,538
3	4.5	1,350	0.4	1.9	344,578
2.9	4.4	1,866	0.3	1.8	382,089
2.8	4.3	2,555	0.2	1.7	420,740
2.7	4.2	3,467	0.1	1.6	460,172
2.6	4.1	4,661	0	1.5	500,000
2.5	4	6,210	-0.1	1.4	539,828
2.4	3.9	8,198	-0.2	1.3	579,260
2.3	3.8	10,724	-0.3	1.2	617,911
2.2	3.7	13,903	-0.4	1.1	655,422
2.1	3.6	17,864	-0.5	1	691,462
2	3.5	22,750			

Example: If a sigma level of 4 is calculated using <u>long term data</u>, the theoretical defect rate would is 32 DPM

If a sigma level of 4 is calculated using <u>short term data</u>, the theoretical defect rate would is 6,120 DPM

Appendix B

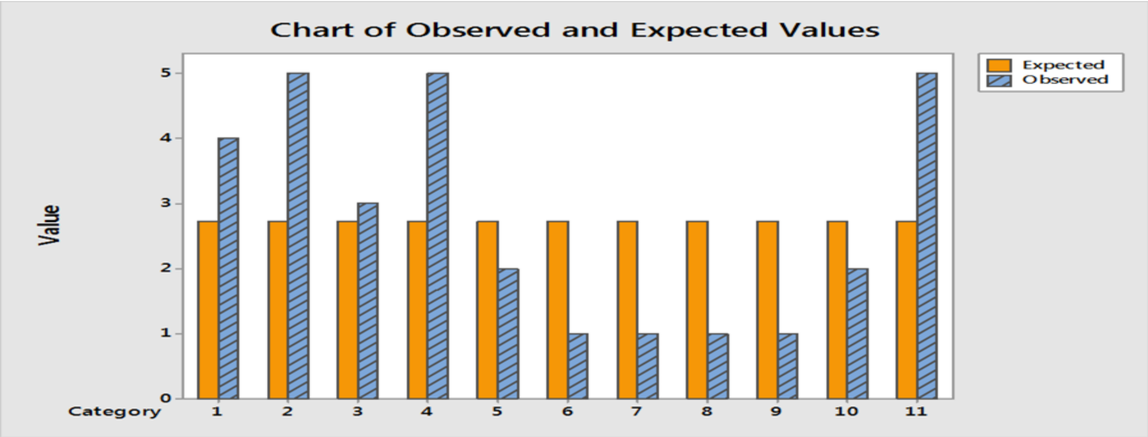


Figure 1 Chi-square test for oil leakage failures

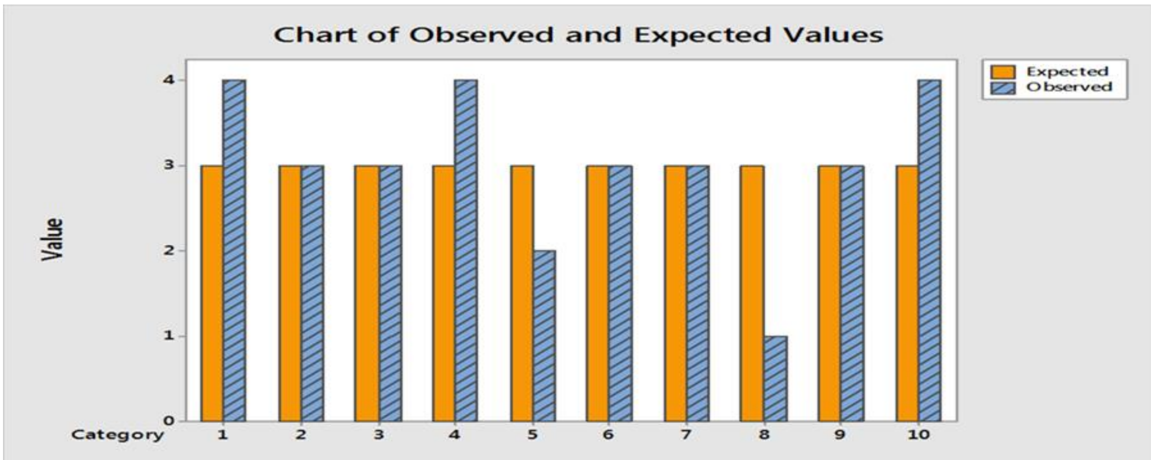


Figure 2 Chi-square test for water leakage failures

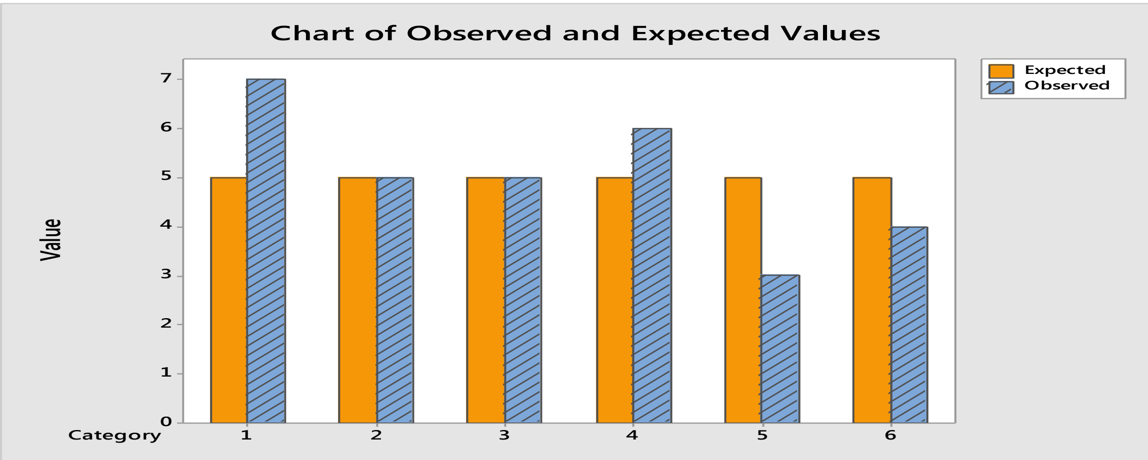


Figure 3 Chi-square test for oil leakage repair cost

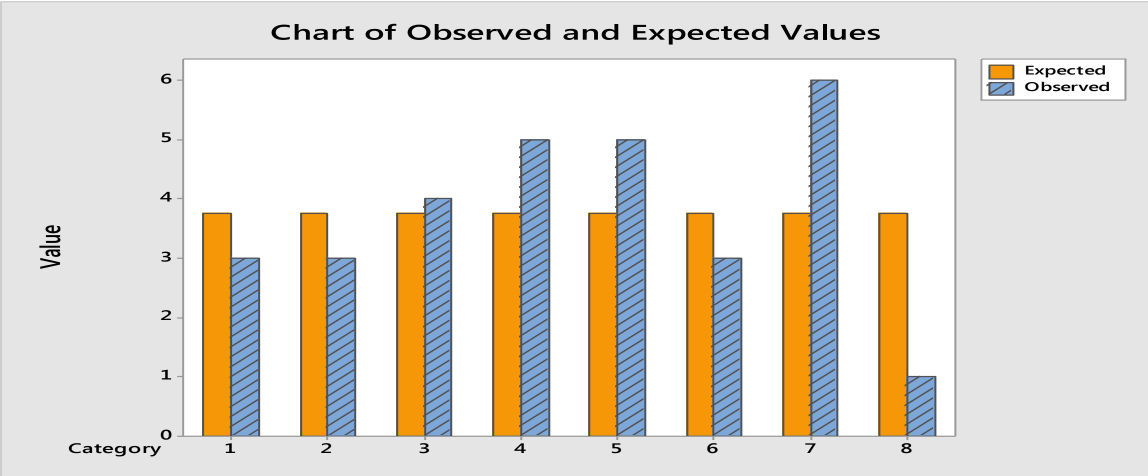


Figure 4 Chi-square test for water leakage repair cost

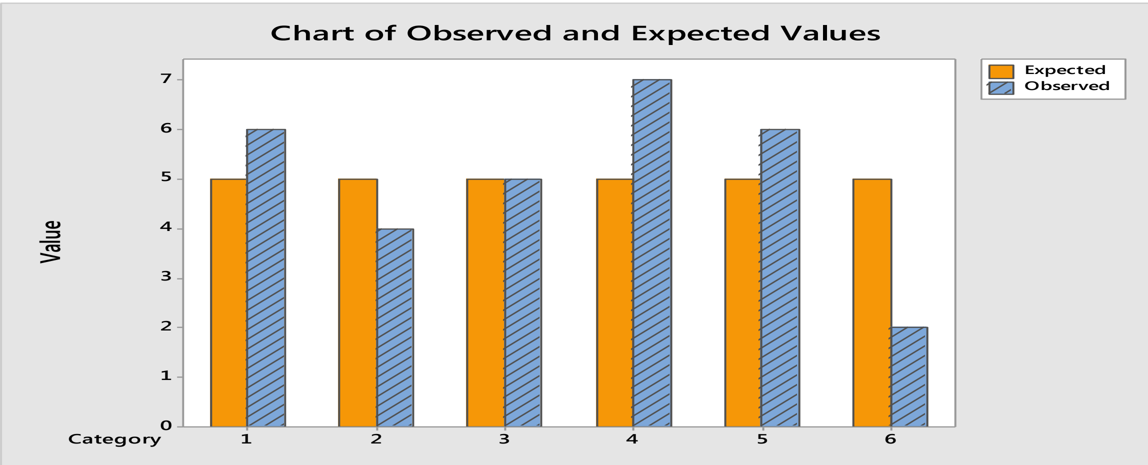


Figure 5 Chi-square test for oil leakage average maintenance cost

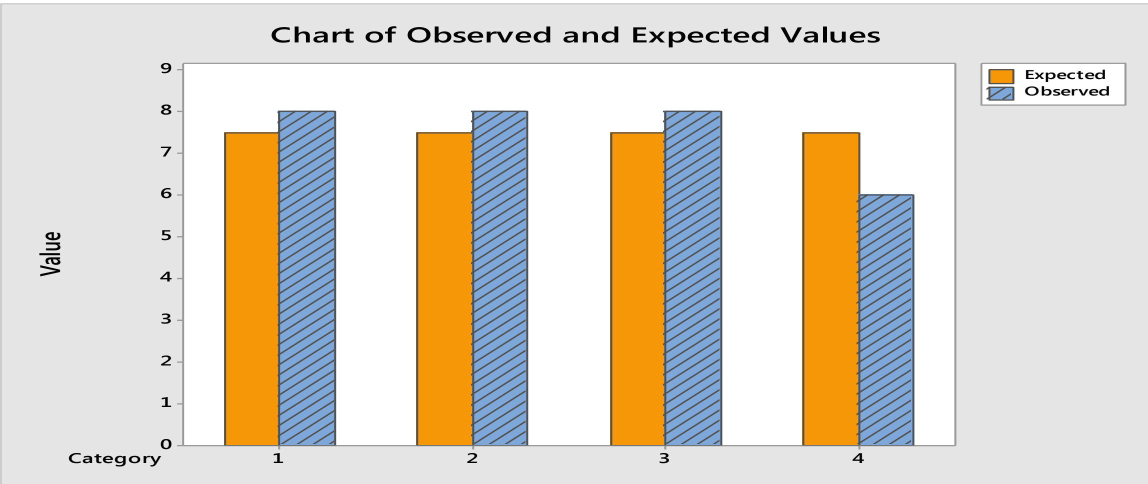


Figure 6 Chi-square test for water leakage average maintenance cost