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Assessment of Total Productive Maintenance (TPM) Implementation in Industrial Environment

By

Abdullatif Ben Hassan

A Dissertation

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through the Industrial and Manufacturing Systems Engineering Graduate Program

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Assessment of Total Productive Maintenance (TPM) Implementation in Industrial Environment

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DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is the result of joint research. In all cases, the key ideas, primary contributions, experimental designs, data analysis, and interpretation were performed by the author with the contribution of Dr. Walid Abdul-Kader, the advisor.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis. I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Previous Publication

This thesis includes two original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Dissertation Chapter	Publication title/full citation	Publication status*
Chapter 2,3	Ben Hassan, A. & Abdul-Kader, W., (2016). Assessment of 5S and overall equipment effectiveness contributions towards promoting total productive maintenance implementation. Proceedings of the Global Joint Conference on Industrial Engineering and Its Application Areas (14-15) July Istanbul, Turkey, (197-204)	Published
Chapter 4,5	Ben Hassan, A. & Abdul-Kader, W., (2020). Short-Term TPM Implementation in SME. 5th NA Industrial Engineering and Operations Management Conference, Detroit, USA, August 9-11, 2020	Will be submitted soon

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ABSTRACT

Maintenance strategies play a crucial role in achieving organizations' goals and abilities to reach their profit targets and survive in the competitive global marketplace and changing economies. Total productive maintenance (TPM) is one of the lean manufacturing approaches that help to improve equipment performance by increasing production rate and equipment availability and enhancing the overall productivity of manufacturing. Implementing the eight pillars of TPM involves many challenges and difficulties, and it is difficult for small to medium enterprises (SMEs) in Canada to successfully implement TPM.

The main objective of this study is to determine whether the Short-Term TPM (STTPM), based on Autonomous Maintenance and Planned Maintenance pillars and 5S technique can minimize losses in a production process and have a positive impact on manufacturing performance (MP). Furthermore, this study is to facilitate successful TPM implementation using the Short-Term TPM (STTPM) approach. Therefore, this research is to develop an implementation framework for the introduction of the TPM improvement approach into SMEs. The framework's fundamentals are STTPM team commitment and involvement, training, member involvement, and culture change. Overall line effectiveness (OLE) should be calculated based on the overall equipment effectiveness (OEE) metrics. The OLE was analyzed for different production line configurations and the multivariate consideration of quality rate through principal component analysis (PCA).

Daily data from production lines was collected from a real manufacturing environment. A paired t-test was conducted to compare a production rate (P_rR), equipment availability (EV), and cycle time (CT) before and after STTPM implementation for each production line. The study was performed using Minitab 19 software to identify the effect of STTPM on MP. The result shows that P_rR, EV, and CT had significant differences before and after the implementation of STTPM in the production line. Similarly, the OEE was significantly different before and after the implementation of STTPM in the production line. This study will also make a meaningful contribution to the related scholarly literature in the form of a novel model of TPM implementation, mainly among Canada’s SMEs.

DEDICATION

This dissertation is dedicated to the souls of my father, mother and my brother Hassan, to my brothers, sisters, and my entire Ben Hassan families, especially to my wife and to my children: Abbas, Obeida, Abdulrehman, Fatima and Eshaima.

ACKNOWLEDGEMENTS

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I express my gratitude to my colleagues at the Industrial and Manufacturing Systems Engineering Department at the University of Windsor. In addition, I would like to thank Mr. Chris Duchene & Mr. Joe Hartney for all the cooperation they provided me during my research project at Rulmeca Canada Limited.

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LIST OF ABBREVIATIONS

Abbreviation	Full-Form
5S	Sort, Set in Order, Shine, Standardize, Sustain
AIPE	American Institute of Plant Engineers
AITPM	American Institute for Total Productive Maintenance
AM	Autonomous Maintenance
C	Cost
CT	Cycle Time
D	Delivery
EV	Equipment Availability
F	Flexibility
FI	Focused Improvement
IIE	Institute of Industrial Engineers
IMI	International Maintenance Institute
JIPM	Japan Institute of Plant Maintenance
OEE	Overall Equipment Effectiveness
P	Productivity
PDCA	Plan-DO-Check-Act cycle
PR	Performance Rate
P_rR	Production Rate
PL	Production Line
PM	Planned Maintenance
Q	Quality
QM	Quality Maintenance
SMEs	Small to Medium Enterprises
SMRP	Society of Maintenance and Reliability Professionals
STTPM	Short-Term Total Productive Maintenance
TPM	Total Productive Maintenance

CHAPTER 1 INTRODUCTION

1.1 Background and Need for Research

In an industrial environment, it has become essential to apply lean manufacturing approaches to improve processes and eliminate losses. Manufacturing operations, in particular, often operate at much less than full capacity, with low throughput, and with high cost. Therefore, equipment maintenance is a necessary function in manufacturing companies. Jain et al., (2014) states that in this very competitive environment, organizations should consider maintenance function as a possible source for cost reduction and competitive utility. The role of maintenance functions in modern manufacturing is becoming ever more critical in improving the equipment availability, productivity, quality and considering maintenance as a profit-generating business element (Singh et al., 2012). In industry, Total Productive Maintenance (TPM) is a system of maintaining and improving the integrity of production and quality systems through the machines, equipment, processes, and employees that add business value to an organization (Total Productive Maintenance, 2017).

According to Nakajima (1988), vice-chairman of the Japan Institute of Plant Maintenance (JIPM), TPM is a combination of American preventive maintenance and Japanese concepts of total quality management and total employee involvement. There are eight essential parts, each with distinct responsibilities, known as the eight pillars of TPM. These pillars are autonomous maintenance, focused maintenance, planned maintenance, quality maintenance, education and training, safety, health and environment, office TPM, and development management (Nakajima, 1988; Ahuja & Khamba, 2008). Implementing these eight pillars of TPM comes with many challenges and difficulties. Mora (2002) states that less than ten percent of companies established TPM programs within their organizations. Furthermore, a minimal number of North American companies obtained the TPM Award for Excellence from JIPM. It appears that North American organizations struggle with the eight pillars of TPM. Canadian manufacturing organizations, in particular, struggle significantly when trying to implement a TPM strategy.

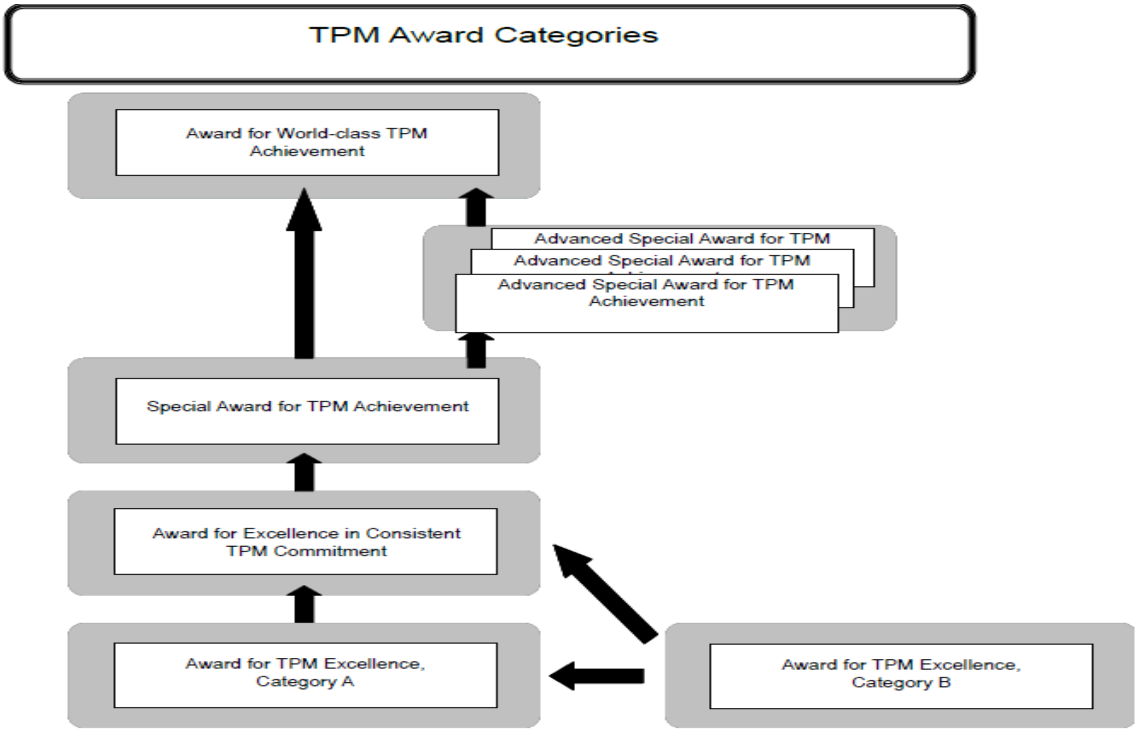


Figure 1-1. The flow of TPM Award Categories (JIPM 2018).

JIPM's TPM Award is based on the improvements achieved through proper equipment maintenance, increased productivity, the elimination of accidents, and the creation of favourable work conditions. The flow of TPM Award Categories (JIPM 2018) is shown in Figure 1-1. According to the TPM Award for Excellence Plant List 2004- 2012, there was only one company in Canada (Unilever Canada Inc.) that won an award (Jain et al., 2014). During the same period, a total of 18 American companies won the TPM Award regardless of classification. That displays the lack of interest in the TPM Program Award, as well as the extensive time required to implement TPM to get the desired benefit. Moreover, the eight pillars of the TPM approach are not usually well accepted by decision-makers. This led to the need for a way to help organizations implement a short-term TPM approach as a critical step in the process of obtaining a TPM Award. That is why this research will focus on developing a short-term TPM approach to more easily facilitate the procedures in TPM implementation.

Mishra et al., (2008) reported that of the different TPM models available, very few are proposed by academicians. Moreover, studies attempting to link short-term TPM and manufacturing performance are limited. Each company may have a different approach to selecting its pillar activities (Digalwar & Nayagam, 2014). Consequently, most studies on TPM implementation tend to focus on all the eight TPM pillars at the same time. However, not many studies have been conducted to verify that short-term TPM is successful in Canada and to enhance its ability to improve manufacturing performance. Chlebus et al., (2015) find that short-term TPM implementation can bring other, non-economic benefits, such as increased safety and facilitation of repairs. Krishnamoorthy (2014) emphasizes that focusing on some TPM pillars will have a significant impact on equipment performance in less time.

Prabowo (2018) highlighted that TPM cannot be implemented in the same way across all organizations, because of the differences in their culture, environment, and structure. The short-term TPM approach includes 5S, Autonomous Maintenance (AM) and Planned Maintenance (PM), and the remaining pillars are considered as long-term elements that support the TPM program and promote manufacturing performances (Lazim et al., 2013; Ahuja and Khamba, 2007; Bernstein, 2005; Cooke, 2000; and Ljungberg, 1998).

1.2 Problem Statement and Objective

As discussed earlier, practical activities of short-term TPM are vital for the successful implementation of TPM to improve the manufacturing performance of the firm. Therefore, it is essential to assess and verify the effectiveness of short-term TPM pillars. In summary, the purpose of this thesis is to investigate the characteristics of short-term TPM that have an impact on manufacturing performance. TPM aims to maximize equipment effectiveness by increasing equipment availability, equipment performance, and decreasing defects. However, cases of numerous companies that have failed to implement such approaches successfully are well documented. Implementing TPM from a current state to the desired future condition is not an easy task (Ahuja & Khamba, 2008). Due to this difficulty, an implementation framework and accompanying monitoring guidelines are critical to increasing the probability of successful implementation. Several studies have been done on the extent of evaluating the TPM approach, including the studies conducted by, Seth & Tripathi (2005), Wickramasinghe & Perera (2016) and McKone et al., (2001). From the literature review, a fundamental problem is a lack of introducing a short-term TPM process or a framework that can provide a smooth transformation of the maintenance function from its current state to the desired future condition. However, there are very few studies that have focused on assessing the stages of short-term TPM implementation according to JIPM guidelines and evaluating the impact of implementation on equipment performance (Prabowo, 2018 and Moradi et al., 2011).

This research aims to provide a means of monitoring the implementation of TPM in an SME to support managers to maintain the highest equipment performance. Moreover, the short-term TPM implementation framework will be developed to assist the company in comparing the effectiveness of short-term TPM implementation with JIPM guidelines. This study will evaluate the impact of 5S, as a foundation of TPM, Autonomous Maintenance (AM) and Planned Maintenance (PM) on the shop floor and provide an opportunity to improve the production rate. It will address the lack of quantitative, data-based research that specifically studies whether implementing short-term TPM affects improvements in manufacturing performance. In summary, the research objectives are the following:

- To facilitate the implementation of short-term TPM through developing a framework.
- To evaluate short-term TPM impact on manufacturing equipment performance.
- To evaluate the implementation of STTPM framework stages.
- To determine if the implementation of the STTPM approach will contribute to improving Production Rate (P_rR), and Equipment Availability (EV).

1.3 Research Scope and Limitations

The scope of this research includes 5S, Autonomous and Planned Maintenance activities that are associated with TPM implementation in a manner consistent with the pursuit of continuous improvement and lean manufacturing. The aim is to study the role of STTPM in the context of the Canadian industry through significant improvement in manufacturing performance (MP). This thesis is focused on an STTPM approach, which is specifically used for Small to Medium Enterprises (SME) as a case study. This approach has the potential to apply to all companies for the facilitation of TPM implementation and improvement of manufacturing performance.

1.4 Research Contributions

In summary, this thesis will contribute to knowledge in the following areas:

- The development of a novel Framework and its associated models to help to implement Short-Term TPM for small to medium enterprises SME in the Canadian industry.
- The STTPM approach introduced in this study supports SME's in four ways. Firstly, the framework is convivial and flexible for companies to implement. Secondly, the framework does not require significant financial support. Thirdly, manufacturing improvement can be achieved after implementation. Lastly, the framework does not require the expertise of an external TPM team.
- The methodology and the developed STTPM framework can be used as a general framework to improve manufacturing performance.
- The identification of Overall Line Effectiveness OLE for different production line configurations and multivariate consideration of quality through Principal Component Analysis PCA.
- Analysis of the data to identify current problems in production lines and possible solutions for the implementation of TPM in the SME industry.
- Minimizing losses associated with equipment and production efficiency and have a positive impact on manufacturing performance.

- Applying a simulation approach to determine the predicted OEE value over the number of production shifts.

1.5 Research Design

In this study, the research design and analytical path have a specific methodological direction based on the research objectives and framework. The framework is developed for the short-term TPM approach to investigate the current problems and possible solutions. A literature review is conducted within the area of this study to investigate the general aspects. This is followed by collecting statistical data from a company, and case studies. Figure 1-2 shows a summary of the research design used in this research work.

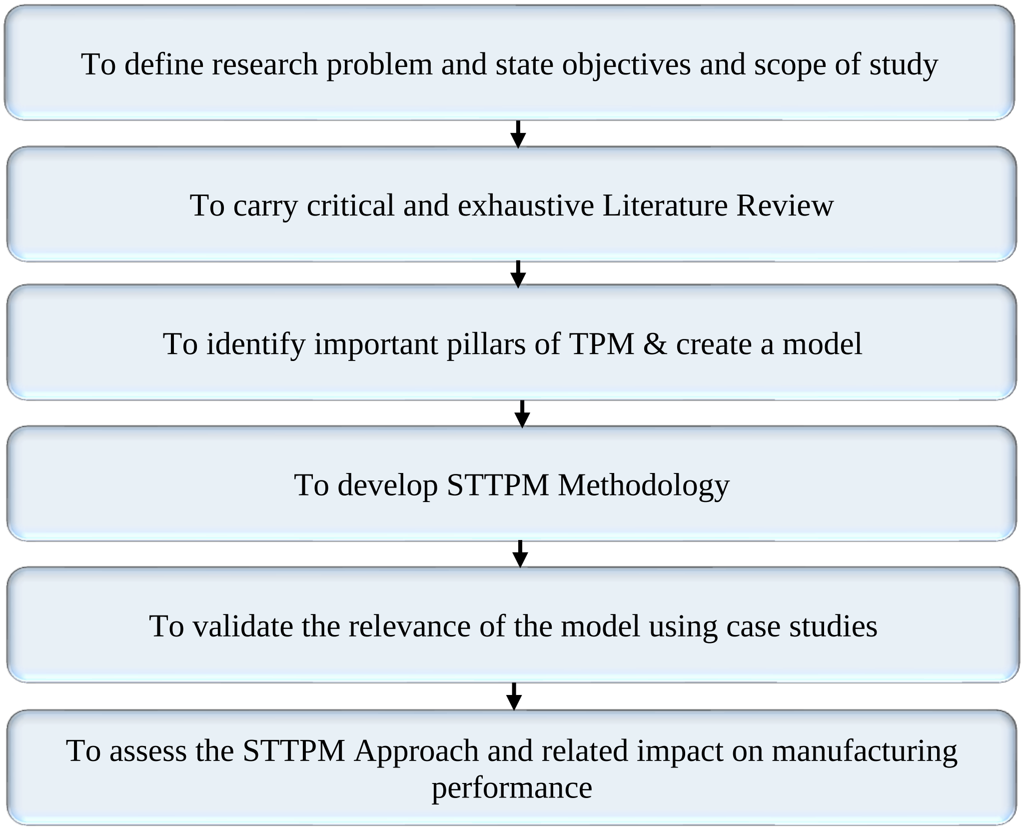


Figure 1-2. Summary of Research Design.

1.6 Dissertation Outline

This dissertation is structured into seven chapters. The following discussion describes the content of each chapter:

Chapter 1 – *Introduction*: This chapter introduces an understanding of the overall research. It includes discussing the background and research motivations, stating the aim and objectives of the research, and outlining research contributions. This chapter also describes the research scope and limitations.

Chapter 2 - *Literature Survey*: This chapter presents and discusses the review of literature in the areas of total productive maintenance (TPM) approach, TPM implementation, the impact of the TPM approach on manufacturing performance, and benefits of TPM implementation. From these discussions, the Short-Term TPM methodology is established.

Chapter 3 – *Short-Term TPM Methodology*: This chapter provides the details of the proposed STTPM methodology that is developed and used in this study. This chapter also discusses the STTPM stages used in the implementation of TPM.

Chapter 4 - *STTPM Approach Implementation*: This chapter discusses how Small to Medium Enterprises (SMEs) could implement STTPM and provides a step-by-step approach for the STTPM implementation. It also discusses the five stages of the STTPM implementation process.

Chapter 5 - *Pilot Case Study*: This chapter describes a pilot case study, based on the STTPM methodology. This chapter presents a case study that was conducted in one of Canada’s manufacturers of heavy-duty equipment for quarries and mining applications. It also explains the case study, to demonstrate the effectiveness of this developed methodology.

Chapter 6 - *Results and Analysis*: This chapter presents the data and statistical analysis for the t-test, which is performed to identify the effect of STTPM implementation on manufacturing performance. This chapter also assesses the STTPM approach in SMEs by using paired t-test analysis to test the hypothesis before and after STTPM implementation.

Chapter 7 - *Conclusions and Recommendations*. This chapter presents the conclusions and summarizes the findings of the research. It also suggests potential areas for future research.

1.7 Summary

In summary, this chapter has provided an introductory overview of the research study in the TPM approach for organizations. The background of the TPM approach is presented at the start of the chapter. Also, the necessary background information was outlined, which has led to defining the problem statement and objective. The need for a way to help different SMEs more easily implement short-term TPM approach was discussed. Therefore, this study will focus on developing a flexible framework to implement short-term TPM. This study is looking to expose this opportunity by proposing a new approach to implement TPM. Figure 1-2 presented a summary of the research design. In the next chapter, a review of the literature related to the short-term TPM approach within the SMEs will be discussed.

CHAPTER 2 LITERATURE SURVEY

2.1 Introduction

This chapter presents a review of the literature related to this study. The study purposes to assess and quantify the impact of a new approach to implement TPM on manufacturing performance. Section 2.2 discusses the definitions of TPM to provide a background on this lean approach. Section 2.3 investigates the different models of TPM implementation in various industries with a specific focus on implementing some of the eight TPM pillars. Section 2.4 is an overview of the impact of TPM implementation on manufacturing performance. Section 2.5 is a brief review of the six major losses that can result from poor performance and how to measure Overall Equipment Efficiency (OEE). Section 2.6 introduces the potential benefits of successful TPM implementation

2.2 Total Productive Maintenance (TPM) Approach

The literature offers a few definitions of Total Productive Maintenance. Ahuja & Khamba (2008) define the TPM program as a Japanese philosophy, which has been developed based on Productive Maintenance concepts and methodologies. TPM is an approach to maintenance that optimizes equipment effectiveness, reduces breakdowns and promotes Autonomous Maintenance by operators through daily activities involving everybody from top to bottom (Nakajima, 1988). The progress of maintenance concepts over the years is shown in Figure 2-1. In 1990, autonomous maintenance and planned maintenance became the cornerstone of the TPM approach.

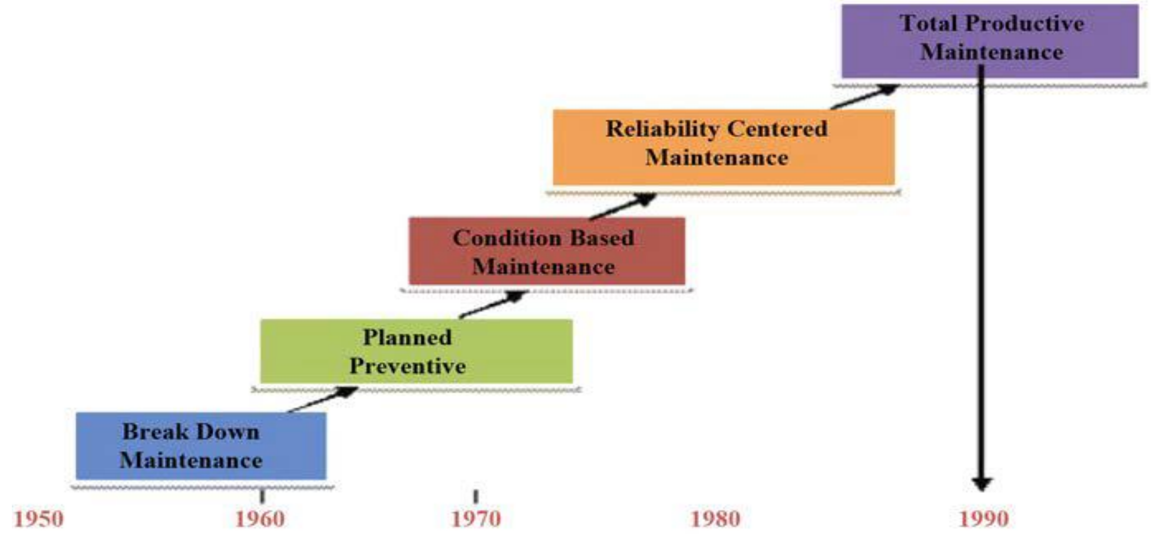


Figure 2-1. Evolution of TPM (Jain et al., 2014).

TPM literature shows that there are two main approaches to defining a TPM program, the Western approach and the Japanese approach (Bamber et al., 1999). TPM is focused on keeping all equipment in a top working condition, which leads to significant improvements in the manufacturing organizations in Western countries and Japan (Bhasin et al., 2006). From the Japanese Institute of Plant Maintenance's (JIPM), an eight-pillar approach for TPM implementation is depicted in Figure 2-2. The TPM model includes autonomous maintenance, focused maintenance, planned maintenance, quality maintenance, education and training, safety, health and environment, office TPM, and development management (Nakajima, 1988; Ahuja & Khamba, 2008). The key concepts of each pillar are discussed in further detail.

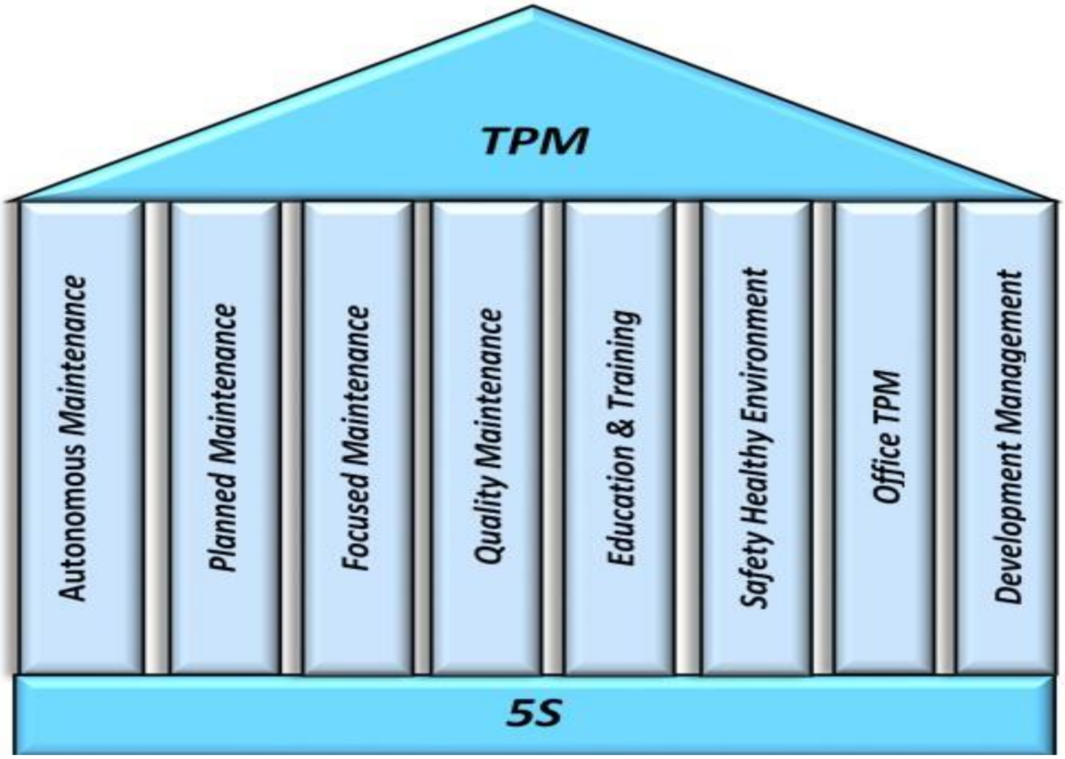


Figure 2-2. Eight TPM Pillars Nakajima's Model.

Some Western TPM practitioners have simplified the Nakajima model by eliminating some of the pillars. Figure 2-3, for example, presents a five-pillar model (Yeomans and Millington, 1997). A similar simplified pillar model is presented in Figure 2-4 (Steinbacher and Steinbacher, 1993). In this model, Training and Education are an integral element of the other pillars rather than a stand-alone pillar as in the Nakajima Model. Chlebus et al., (2015) model presented in Figure 2-5 is based on three main pillars.

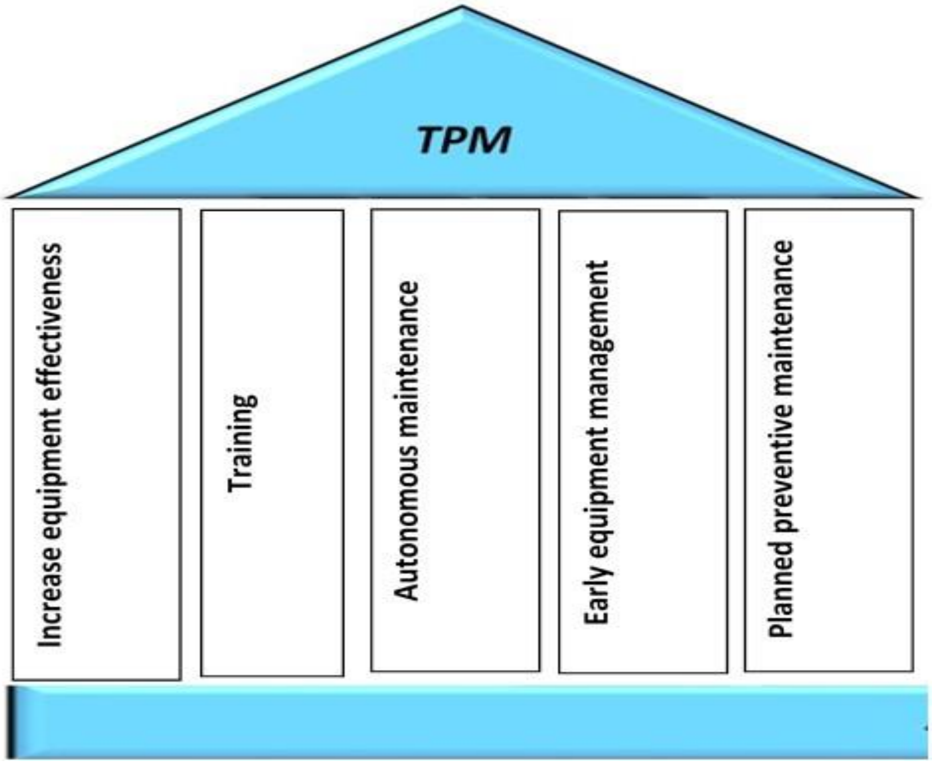


Figure 2-3. TPM Pillars (Yoemans and Millington Model).

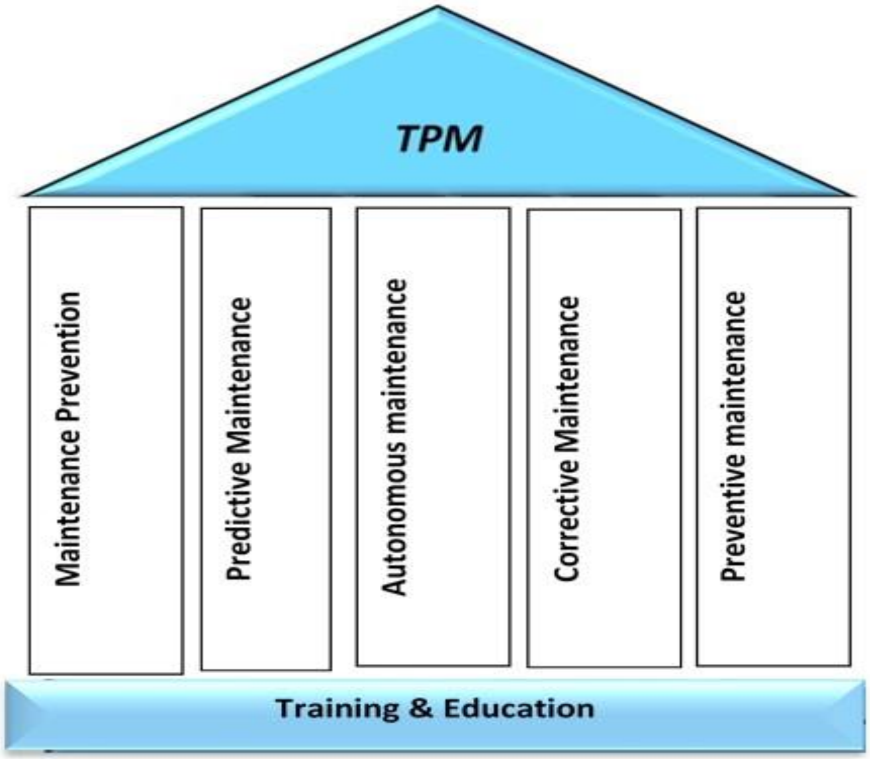


Figure 2-4. TPM Pillars (Steinbacher and Steinbacher Model).

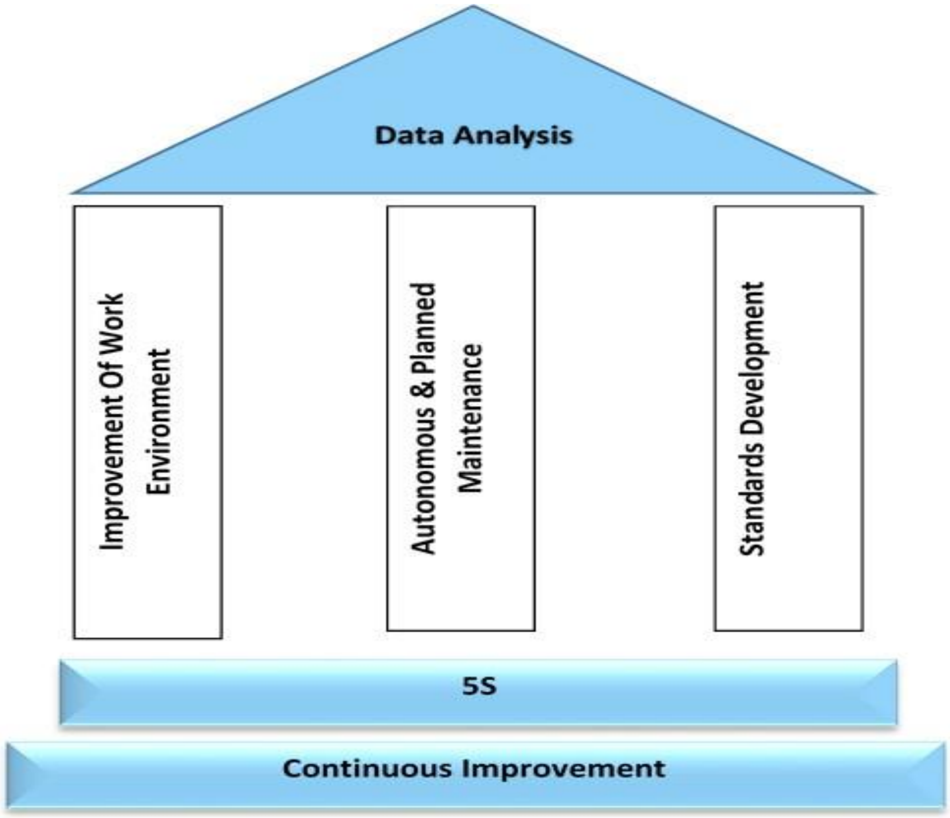


Figure 2-5. TPM Pillars (Chlebus et al., Model).

Banagar et al., (2013) state that in industries, major losses occur on the manufacturing shop floor. These losses are due to operators, maintenance programs and processes, tooling problems and non-availability of components in time. Moreover, there are other forms of loss/waste, such as idle machines, idle labour, rejected parts, etc. The concept of TPM is one of the lean tools to address these losses issues. The six major causes of equipment losses, according to Nakajima (1988) are:

1. Failure;
2. Set-up and adjustments;
3. Idling and minor stoppage;
4. Reduced speed;
5. Process defects; and
6. Reduced yield.

Therefore, the purpose of TPM is to reduce/eliminate the six categories of equipment losses to improve OEE. Table 2-1 shows the detailed maintenance and organizational improvement initiatives and activities associated with the respective TPM pillars.

Table 2-1: Detail of TPM Pillars (Jain et al., 2014).

Nakajima Model	Maintenance
Autonomous maintenance	• Fostering operator ownership • Perform cleaning, lubricating, tightening, adjustment, inspection, readjustment of production equipment
Focused maintenance	• Systematic identification and elimination of major losses • Working out loss structure and loss mitigation through structured why-why, FMEA analysis • Achieve improved system efficiency • Improved OEE on production systems
Planned maintenance	• Planning efficient and effective PM, and PdM systems over the equipment life cycle • Establishing PM check sheets • Improving the mean time between failures and mean time to repair
Quality maintenance	• Achieving zero defects • Tracking and addressing equipment problems and root causes • Setting 3M (machine/manpower/material) conditions
Education and training	• Imparting technological, quality control, interpersonal skills multi-skilling of employees • Aligning employees with organizational goals • Periodic skill evaluation and updating
Safety, health, and environment	• Ensuring the safe working environment • Providing an appropriate work environment • Eliminating incidents of injuries and accidents • Providing standard operating procedures
Office TPM	• Improving synergy between various business functions • Removing procedural hassles • Focusing on addressing cost-related issues • Applying 5S in office and working areas
Development management	• Minimal problems and running in time on new equipment • Utilizing learning from existing systems to new systems • Maintenance improvement initiatives

Note: Failure Mode and Effect Analysis (FMEA), Preventive Maintenance (PM), and Predictive Maintenance (PdM)

In this research, the short-term TPM approach recommends focussing on autonomous and planned maintenance activities to prevent equipment failures and avoid poor quality. The short-term TPM approach will enable companies to make a smooth transition in the maintenance function from its current state to the desired future state. TPM is a subject that has not been researched thoroughly, especially in Europe and North America (Willmott, 1994). Robinson and Ginder (1995), while developing a framework for implementing TPM in the North American manufacturing industry, recognize that both management and workforce must address issues strategically while operating in an environment of trust and cooperation. Several North American organizations and conferences are dedicated to maintenance professionals or maintenance improvement, such as the American Institute of Plant Engineers (AIPE), the Society of Maintenance and Reliability Professionals (SMRP), the American Institute for Total Productive Maintenance (AITPM), the International Maintenance Institute (IMI), and the Institute of Industrial Engineers (IIE). Robinson and Ginder (1995) state that none of the above-indicated organizations has a nationally recognized award system or benchmark of excellence. Moreover, none of these carries the weight or standing of the recognition provided by the Japan Institute of Plant Maintenance (JIPM). Many companies have moved away from the traditional eight-pillar implementation process. These days, companies do engage in TPM programs to have a general understanding, but the pillar implementation process is selected according to their needs. Similarly, a firm has the option to select and implement those pillars that will achieve the objectives and goals of TPM effectively and efficiently in their organization. Therefore, focusing on specific TPM pillars will produce faster and quicker results in improving equipment performance and higher productivity for manufacturing companies. According to Chlebus et al., (2015) approach, TPM in a mining industry should be based on three main pillars: autonomous maintenance planned maintenance and improvement of quality maintenance.

Table 2-2 illustrates the focus on some pillars of TPM practices based on different researchers' findings and their perceptions of the importance of each TPM pillar. However, all research findings are based on Nakajima's model of eight TPM pillars. Therefore, this thesis uses a short-term TPM approach, comprised of two pillars (Autonomous Maintenance [AM] and Planned Maintenance [PM]) instead of the original eight pillars. Moreover, the thesis will develop the short-term TPM framework to produce faster results. Safety, Health & Environment and Office TPM are two pillars of support for the TPM program that is why they have not been chosen in many studies. However, quality maintenance and maintenance prevention can be studied as potential pillars in the future.

2.3 TPM implementation

Several empirical studies have been conducted on TPM implementation, and their impacts on companies' performance have been assessed. This section presents a review of TPM implementation studies, observations, and the importance of TPM pillars. TPM and maintenance strategy is considered by many researchers to be the most important elements to improve manufacturing efficiency and effectiveness, (Sharma & Singh, 2015). Wireman (1991) states that one-third of maintenance expenditure is unnecessary or wasted. Total Productive Maintenance (TPM) is a management practice system that began in Japan in the 1970s and then, spread around the world during the last twenty years.

Table 2-2: Illustration of The Pillars of TPM Practices Based on Different Researchers’ Findings.

No.	**Nakajima Model**	**Steinbacher & Steinbacher**	**Yoemans & Millinton**	**McKone et al.**	**Swanson**	**Halim & Ramayah**	**Krishnamoorthy**	**Chlebus et al.**	**Ben Hassan & Abdul_kader**	**Pavan et al.**
	1988	1993	1997	1998	2001	2010	2014	2015	2016	2017
1	Autonomous Maintenance	x	x	x	x	x	x	x	x	
2	Focused Maintenance		x				x	x		x
3	Planned Maintenance	x	x	x	x	x	x		x	
4	Quality Maintenance							x		
5	Education and Training	x	x		x					
6	Safety, Health & Environment									
7	Office TPM									
8	Maintenance Prevention		x							

Nakajima (1989) describes TPM as a management philosophy that promotes the change of the organizational culture towards quality and productivity at all levels of the company under a scheme of contributing from top to bottom. Moses (2017) states that the core of the TPM pillars is autonomous and planned maintenance. Because of this, the focus of this thesis will be on the autonomous and planned maintenance pillars to facilitate the implementation of TPM and the need to develop a new method to implement TPM to reduce maintenance costs and increase productivity.

Chlebus, et al., (2015) suggest that TPM implementation in a mining industry should be based on three main pillars: improvement of the environment of work, autonomous and planned maintenance, and standards in development. To adopt such a TPM system in this industry, it is necessary to consider two important factors: analyzing the failure rate and selecting a group leader (Chlebus et al., 2015). In Chlebus et al., (2015) study, the TPM approach as lean production at the copper mine is investigated by using some foundations of TPM with a basic message to avoid any kind of waste through continuous improvement of the entire company. They indicate that TPM in a mine, in comparison to the standard of Nakajima's model of eight pillars, should be reduced to three main pillars. They also establish the TPM model, which is based on data analysis of failure and supported by 5S practices. 5S refers to five principles: Sort, Set in order, Shine, Standardize, and Sustain. The study finds that the implementation of TPM steps can bring other non-economic benefits, such as increased safety of miners and facilitation of repairs. On the other hand, establishing the TPM model would add costs to workers' training programs and would require a lengthy period to get the desired benefit as well as increase the profit for the mines.

Mwanza & Mbohwa (2015) propose an effective TPM model at a chemical manufacturing company to improve company performance by reducing the six most common causes of efficiency loss in chemical manufacturing. The main objectives of the study were to evaluate the current maintenance system, to calculate the overall equipment effectiveness, and to identify key performance indicators and success factors of TPM. An evaluation of the existing maintenance system presented in their study shows that production lines were facing several problems such as less availability and reliability of equipment, machine downtime, frequent failures of equipment, and low production output. The researchers employed both a quantitative and qualitative approach. The results showed a TPM program can be used as a tool to enhance the performance of the company equipment. The results of the study indicate that the adoption of the TPM approach can reduce losses which helps the company increase profitability and image. However, the obtained results of the improvement in the equipment performance were mainly due to the contribution of 5S implementation. Expected tangible and beneficial results from applying all eight TPM pillars might be after three to five years. This period depends on several factors such as skill and age of the workforce, the complexity of the equipment, age of the equipment, company culture, and current status of the maintenance program. Furthermore, TPM implementation is not an easy task by any means because TPM requires not only commitment but also structural changes and direction within the organization

Monica (2014) presents a case study to investigate if total productive maintenance (TPM) can be copied from one location to another. The researcher used a broad TPM approach to optimize the elements of productivity of equipment, teamwork, the involvement of employees, and continuous improvement activities. The implementation cannot achieve its targeted results without collaboration between maintenance and production departments. The case study is related to a company that has two production plants, one is in Norway and the other in Canada. Both have similar technology, equipment, products, and consumers. The outcome of the study showed that the implementation of the TPM program in one location or the other, with the same production and organization systems, could be successful. However, the implemented TPM program proposed some modifications which have led to a translation with better results. Monica (2014) used different techniques such as interviews, group discussions, written documentation, and observation from both plants in Norway and Canada to determine the impact of teamwork, maintenance, participation and technology on the transfer process. Transfer and adaptation will necessarily require a change in the organization's processes such as a change in work and change in the formal structures.

Czarniawska and Sevon, (2005) stated that instead of transfer, the term "translation" describes how management ideas "travel" from one location or context to another. The research methodology employed a qualitative study for the two plants to provide a detailed description and a better understanding of the TPM translation. The study found that the implementation of TPM was more successful in Canada than in the original Norwegian plant. The contribution of the study was to develop an understanding of the adaptation of TPM from one location to another by modifying the model according to the local culture of the organization. From the study, the cooperation of the production and maintenance departments must be taken into consideration to develop our proposed framework of short-term TPM approach and to ensure a smooth implementation process. However, Monica (2014) concluded that the TPM transfer from one location to another with similar production and organization systems should be considered to provide solid proof to generalize the model.

Krishnamoorthy (2014) develops a TPM model for integrating with Equipment Communication Standard (ECS) and Generic Equipment Model (GEM) which enables data acquisition and keeps track of data between the operator and the equipment. The TPM model uses Semiconductor Equipment and Materials International (SEMI) Standards which facilitate real-time data collection from the production equipment. The SEMI Equipment Communication Standard (SECS) and GEM were established to define a set of communication interface protocols between a host computer and the production equipment. The study suggested the three key elements of the TPM model as Asset Productivity (AP), Autonomous Maintenance (AM) and Planned Maintenance (PM)) for implementing TPM systematically and successfully. This study focused on the maintenance practices that were used in the Electronic Contract Manufacturing industry in Malaysia. The study used descriptive statistics, regression analysis, and panel data analysis. The main results showed that TPM pillars, and SECS/GEM standards, together with labour and cost, can reduce losses in the production process and have a positive impact on manufacturing performance, while SECS/GEM standard integration with Autonomous Maintenance does not. The study confirms that focusing on a few TPM pillars will have a significant effect on equipment performance. Because of their impact on equipment performance, the autonomous and planned maintenance pillars will be the first two pillars selected for our proposed TPM approach. On the other hand, the study focuses on specific manufacturing industry and country; therefore, the empirical analysis was based on a small sample size of data that did not allow for a more detailed investigation about industry differences and country differences.

Another study by McKone et al., (1999) proposed a theoretical framework for understanding the use of TPM and how it depends on environmental and organizational factors such as country, industry and company characteristics. As well, TPM depends on managerial features such as Just-in-Time (JIT), Total Quality Management (TQM) and Employee Involvement (EI). Regarding TPM implementation, the study focused on the short-term TPM efforts that include both autonomous and planned maintenance activities. Autonomous maintenance includes three elements: 5S, cross-training, and production & maintenance teams. Planned maintenance has two elements which are scheduled maintenance activities and information tracking. In the study, the data used for the analysis of the framework were collected as part of the World Class Manufacturing (WCM) Study. The WCM database used for this study was from the USA, Asia and Europe encompassed three different industries using a common set of questionnaires and included 97 different manufacturing plants. The study focused on the assessment of the TPM implementation level by considering both autonomous and planned maintenance pillars and using a hierarchical regression approach. The authors conclude that environmental, organizational and managerial features had the most effect on TPM implementation. However, it may be that the implementation of TPM is more directly linked to the management of the plant than to the environmental and organizational factors themselves. The study also highlighted the fact that the TPM system is not widely adopted by every type of company as their study described and measured.

Wang and Lee (2001) address that the goal of TPM is to increase the productivity of plants and equipment. In order to maximize output, the most efficient way is to eliminate the causes of the production losses in TPM. In the evaluation of maintenance performance, OEE is used as a metric to evaluate the manufacturing capability. A random effect nonlinear regression model called the Time Constant Model was used to formulate a prediction model for learning rate in terms of the size of the company, sales, whether as ISO 9000 and number of years from the start of the TPM program to the TPM award. A two-stage analysis was employed to estimate the parameters. From the approach of this study, one can determine the appropriate time for checking the performance of implementing TPM. Their research results show that TQM and TPM programs are closely related. Nakajima (1988) outlined a twelve-step model for TPM implementation in four phases, as shown in Table 2-3.

Table 2-3: The Twelve Steps of TPM Development (Nakajima, 1988).

Stage	**Step**
Preparation	1. Announce top management decision to introduce TPM 2. Launch education and campaign to introduce TPM 3. Create organizations to promote TPM 4. Establish basic TPM policies and goals 5. Formulate a master plan for TPM development
Preliminary Implement	6. Hold TPM kick-off
TPM Implementation	7. Improve the effectiveness of each piece of equipment

	8. Develop an autonomous maintenance (AM) program 9. Develop a scheduled maintenance program for the maintenance department 10. Conduct training to improve operation and maintenance skills 11. Develop initial equipment management program
Stabilization	12. Perfect TPM implementation and raise TPM level

Moreover, in Japan, TPM philosophy has been generated by Total Operations Management (TOM), Just-In-Time (JIT) strategies and productive maintenance. These concepts are relative1y new in many North American companies. Furthermore, the significant differences between North American and Japanese manufacturing companies are management philosophy, workplace culture, and employee work ethic, which makes it extremely difficult to use this model in Canada. Consequently, the short-term TPM model has been developed for the implementation of TPM. Chapter 3 will describe this short-term TPM implementation model.

In summary, as mentioned in this literature review, researchers have made some progress in addressing the concerns associated with the TPM implementation. It also shows the different models of TPM implementation in various industries. Most of these studies do suggest steps for TPM implementation. However, there is a need to develop a clear process specifically to help companies make a smooth and easy TPM implementation. Moreover, a few TPM models directly consider a short-term TPM approach to improving equipment performance. A short-term TPM approach is needed to increase production by reducing manufacturing losses. We will consider this gap in more detail in this study.

2.4 Impact of TPM Approach and Manufacturing Performance

Over the last two decades, manufacturing plants have used different approaches to improve manufacturing performance. One approach to improving the performance of manufacturing activities is to implement and develop TPM pillars. Pradeep et al., (2014); Teonas et al., (2014); Banagar et al., (2013); and Ahuja & Khamba (2008), all agree that the goal of TPM implementation is to improve productivity, reduce quality costs and the final cost of products, improve the delivery of products, and increase the safety of operations. These researchers also agree that TPM is to strive for the three ultimate goals of zero defects, zero accidents, and zero breakdowns. Autonomous maintenance focused maintenance, planned maintenance, and quality maintenance pillars are TPM essentials that focus on maximizing production effectiveness and efficiencies, which have a direct influence on manufacturing performance, while the other pillars support the TPM program and promote manufacturing performances (Lazim et al., 2013; Ahuja and Khamba, 2007; Bernstein, 2005; Cooke, 2000; and Ljungberg, 1998). Several researchers and practitioners have assessed the contributions of TPM implementation philosophy towards improving manufacturing performance. The impact of the TPM approach on manufacturing performance has been discussed in several studies using qualitative and quantitative methods.

Lai et al. (2016) use a qualitative method to study the use of multidimensionality of total productive maintenance (TPM) and its relationship with manufacturing performance improvement in the manufacturing sector. Specifically, this study assessed the contribution of each TPM success factor in improving manufacturing performance. A questionnaire and a survey were used to test the proposed research framework. The study found that traditional maintenance initiatives and TPM implementation initiatives significantly affect manufacturing performance but does not affect top management leadership and maintenance organization.

A quantitative method was used by McKone et al., (2001) who study the relationship between TPM and manufacturing performance through Structural Equation Modeling (SEM) using Analysis of Moment Structures (AMOS) software. SEM is a multivariate statistical analysis technique that is used to analyze structural relationships. This technique is the combination of factor analysis and multiple regression analysis, and it is used to analyze the structural relationship between measured variables and latent constructs.

Wickramasinghe and Perera (2016) conduct a study to examine the effect of total productive maintenance (TPM) pillars on the manufacturing performance of textile and apparel manufacturing firms. In their research, a survey questionnaire was used for data collection. Correlation and regression analysis were the technique used in this study. It was performed using SPSS software to identify the effect of TPM on manufacturing performance. The study found that all the TPM pillars have a positive and significant relationship with manufacturing performance and significantly improve cost-effectiveness, product quality, on-time delivery, and volume flexibility. Consistent in their findings, Sharma and Bhaerdwaj (2012) propose that achieving the objectives of TPM leads to improving manufacturing performance.

Additionally, Brah and Chong (2004) find the TPM program to be a strong predictor of manufacturing strengths. They also, concluded that TPM leads to improving business performance in several aspects such as operations performance, safety and cleanliness, employee morale and customer satisfaction. Furthermore, several researchers used quantitative methods to study the impact of the TPM approach on manufacturing performance. For instance, Aziz et al., (2013) conduct a study about a proper planning system for implementing TPM at the early stage in the organization. The study discusses the important key performance indicators (KPIs) of TPM, which are machine breakdown time, mean time between failure (MTBF), mean time to repair (MTTR) and setup time. The case study of TPM implementation was taken from a manufacturing company that had recently started implementing TPM. Since then, the KPIs have been significantly improved. Also, the study explains how TPM transforms an industry's overall maintenance system to increase productivity.

Moreover, measuring the situations before and after the implementation of TPM is very important to see improvement opportunities (Hartmann, 1992). Similarly, Rodrigues and Hatakeyama (2006) stated that the success of TPM implementation is closely linked to the management of people and it is necessary to develop key indicators for the assessment of the performance of the program. These key performance indicators are used to validate the progress of TPM activities and productivity, quality, cost, safety, and moral issues (Rodrigues and Hatakeyama, 2006).

Table 2-4 shows a summary of qualitative methods that study the impact of TPM on manufacturing performance; i.e., cost (C), Quality (Q), Delivery (D), Flexibility (F), and Productivity (P).

Table 2-4: Summary of Qualitative Methods Addressing the Impact of TPM on Manufacturing Performance.

Year, Author	Manufacturing performance					Qualitative Method	TPM system
	C	Q	D	F	P		
2001, McKone et al.	√	√	√	√		Structural Equation Modelling (SEM)	TPM, JIT and TQM
2002, Ramayah, et al.		√			√	Data analysis	Autonomous maintenance. Planned maintenance.
2004, Brah & Chong	√	√			√	Data analysis Questionnaire	Productive maintenance
2005, Seth & Tripathi	√	√	√		√	Statistical Analysis (SPSS) Survey 108 companies	TPM and TQM
2007, Ahuja and Khamba	√	√	√	√	√	Data analysis survey	TPM
2012, Sharma & Bhaerdwaj	√	√	√	√	√	Data analysis Survey	TPM & Six Sigma
2014, Monica		√			√	Data analysis Interviews, Observation, Document collection.	TPM
2016, Wickramasinghe & Perera	√	√	√	√		Statistical Analysis (SPSS)	TPM
2016, Lai et al.	√	√	√		√	Data analysis Questionnaire	TPM

Table 2-5: Summary of Quantitative Methods That Study the Impact of TPM on Manufacturing Performance.

Year, Author	Manufacturing performance						Quantitative Method	TPM system
	C	Q	D	F	P	Av		
2003, Sun et al.		√		√			Net Equipment Effectiveness OEE	TPM
2004 Thun		√			√	√	System Dynamics Model Analyzing	TPM
2007, Tsarouhas		√			√	√	Statistical Analysis (SPSS), OEE	TPM
2011, Bon and Lim	√	√	√		√	√	OEE	TPM
2012, Pascale		√			√	√	Mathematical Decision Model	TPM
2013, Aziz et al.		√		√	√	√	OEE	Focused Improvement Autonomous Maintenance Planned Maintenance Education & Training
2014, Waghmare et al.		√	√			√	FMEA	TPM
2016, Ben Hassan and Abdul-Kader		√			√	√	OEE	5S Autonomous maintenance. Planned maintenance.

Table 2-5 illustrates a summary of quantitative methods that study the impact of TPM on manufacturing performance; i.e., cost (C), Quality (Q), Delivery (D), Flexibility (F), Productivity (P) and Availability (Av). However, very little progress has been made related to the efficiency measurement in TPM implementation.

2.5 Overall Equipment Effectiveness (OEE)

Banagar et al., (2013) state that TPM focuses on maximizing the Overall Equipment Efficiency (OEE) with the involvement of each and everyone in the organization. It will not only establish a complete maintenance system but also aims to improve the maintenance skills and knowledge among the shop floor operators. OEE is a tool to measure the success of TPM implementation. OEE measurement is also commonly used as a key performance indicator (KPI) in conjunction with lean manufacturing efforts to provide an indicator of success. According to Robinson and Ginder (1995), OEE is a powerful component of the TPM process, which clearly indicates the implementation progress and equipment performance. According to Ahmad et al., (2018), OEE is a metric for the evaluation of equipment effectiveness and often used as a driver for improving equipment performance. The authors then classify the losses into six major categories as mentioned in section 2.2. Six major losses can result from poor maintenance, faulty equipment or inefficient operation. These six types of losses are combined into one measure of OEE as shown in Figure 2-6, which is:

$$\begin{aligned} OEE\% = {} & Equipment\ Availability\ (EV)\% \times Performance\ Rate\ (PR)\% \\ & \times Quality\ Rate\ (QR)\%. \end{aligned} \tag{2.1}$$

Where,

$$EV = \frac{Operating\ Time}{Planned\ Production\ Time} \tag{2.2}$$

- *Operating time = Planned production time - Downtime*
- *Planned production time = Shift length – Breaks*

$$PR = \frac{(\text{ Ideal Cycle Time} * \text{Total Pieces })}{\text{Operating Time}} \tag{2.3}$$

$$QR = \frac{\text{Good Pieces}}{\text{Total Pieces}} \tag{2.4}$$

As indicated earlier, OEE is one of the performance assessment measures commonly used in manufacturing industries. Because of that, OEE will be used in our study to assess the success of short-term TPM implementation as well as to evaluate the short-term TPM impact on the performance of equipment.

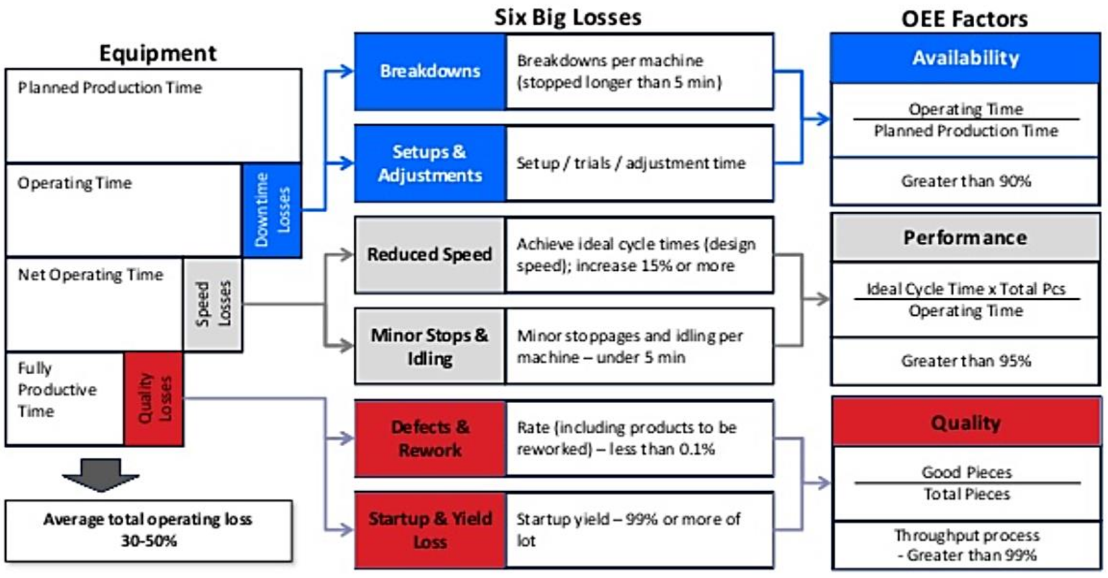


Figure 2-6. Overall Equipment Effectiveness Factors (Ahmad et al., 2018).

2.6 Benefits of TPM Implementation

The following are the potential benefits of successful TPM implementation in any organization or industry:

- *Improved Productivity:* Productivity will be improved by reducing all major losses in the plant.
- *Improved Quality:* Quality will be improved by reducing all types of defects and malfunctions.
- *Reduction in cost:* Since the TPM focuses on the optimum utilization of the resources, then it leads to the reduction in cost which is a paramount benefit for any company.
- *Employee Ownership:* Due to the implementation of TPM, operators perform the autonomous maintenance of their machine and this brings the employee ownership in the organization which leads to the creation of continuous improvement culture.
- *Improved working environment:* Since the 5S is the base of TPM, the neat and clean shop floor improves the working conditions and the environment in the industry, and this leads to increased reliability.
- *Customer satisfaction:* TPM creates a world-class manufacturing infrastructure in any industry and this leads to high quality, prompt delivery, which ultimately increases customer satisfaction.

2.7 Summary

The background of the Total Productive Maintenance approach is presented at the start of the chapter. Many of TPM models' implementation is identified which needs to be addressed to achieve a flexible TPM approach. Besides, the focus on some pillars of TPM practices and their impacts on manufacturing performance is discussed in this chapter.

Autonomous Maintenance and Planned Maintenance pillars are considered as short-term TPM, and their use supports the decision making of the enterprise. The OEE tool to measure the success of TPM implementation is presented in this chapter. This chapter summarizes the key areas of the literature that may develop an understanding of TPM models and their impacts. The gaps in research in TPM implementation were evaluated, and the need for a more flexible TPM framework for SMEs is identified. This chapter contributes to the literature by introducing a short-term TPM framework covering the 5S technique, as well as two pillars and their impact on manufacturing performance. The last section presents the potential benefits of successful TPM implementation in any organization or industry. The review of the literature and the gaps identified in this chapter represent the TPM approach for the development of the short-term TPM methodology presented in the next chapter.

CHAPTER 3 STTPM METHODOLOGY

3.1 Introduction

The purpose of this chapter is to provide the details of the STTPM methodology that was developed and used in this study. Innovation, Science and Economic Development Canada (2016) stated that 97.9 percent of businesses were small businesses, 1.8 percent were medium-sized businesses and 0.3 percent were large enterprises, therefore almost 99.7 percent of all Canadian manufacturers are small and medium-sized enterprises (SMEs). These data highlight the important role SMEs play in the national economy; their survival and success are essential. Industry Canada (2019) defined SME based on workforce size or number of employees in a firm, which vary according to the industry. Foe example, firm with 99 or less employees are considered small, while firm with 100 to 499 employees are considered medium enterprises. Moreover, this study is intended to benefit SMEs to better understand TPM practice and to facilitate its adoption and impact on their performance. Implementing the eight pillars TPM model in SMEs is still considered a major challenge due to several non-conducive environments and factors in the adoption and implementation process. This chapter discusses the proposal for short-term TPM methodology that the researcher followed in the development of the short-term TPM implementation. The STTPM stages used in the implementation of TPM are also discussed in this chapter. The details of the STTPM implementation will be given in the next chapter.

3.2 Justification of Short-Term TPM Initiatives

From the literature review, for a long time, many companies have struggled to implement TPM programs; nevertheless, less than ten percent of companies obtained TPM programs (Moradi et al., 2011). Prabowo (2018) emphasized that TPM cannot be implemented in the same way in all organizations. This is because of the differences in their culture, environment, and structure. With so many challenges and difficulties, it seems to be a very difficult task to carry all the eight pillars of a TPM program at one time. Particularly, the Canadian manufacturing industry faces many challenges in the implementation of TPM, for example (Robinson & Ginder, 1995):

- TPM is a complex, long-term process.
- Most North American companies focus on short-term profitability.
- Long-term employment is not guaranteed
- Teamwork and cooperation are not familiar to the North American worker

Furthermore, as mentioned in the literature review, the essential feature of TPM approach is that there is no need to implement the eight pillars at once; however, it is possible to adapt the total productive maintenance approach following the organization's culture, where the TPM pillars are selected according to the compatibility with the current circumstances of the organization. A survey was done in the automotive industry to determine the best TPM pillars practices. The conclusions show that Planned Maintenance and Autonomous Maintenance were statistically ranked as primary pillars in the implementation process (Guariente et al., 2017). Furthermore, Erin (2016) stated that to implement TPM successfully, it must be built on a foundation of a lean culture and supported by the 5S technique. Sharma & Singh (2015) study the relationship between 5S and the pillars of TPM in manufacturing. Their findings confirmed that all 5S principles affect TPM by providing a better way to reduce the equipment losses and therefore improve equipment performance. David (2018) emphasized that other TPM pillars will be implemented depending on the situation that the organization is facing and do not necessarily have to be implemented all at once. Also, other researchers had different observations and views on the TPM pillar implementation process.

Wherefore, many companies have moved away from the traditional eight-pillar implementation process. These days, companies do engage in TPM programs to have a general understanding, but the pillar implementation process is selected according to their needs. Firms' exercise has the option to select and implement pillars that will achieve the objectives and goals of TPM in their organization effectively and efficiently. Thus, several studies focus on specific TPM pillars to obtain effective implementation and have a positive impact on manufacturing performance. They can help to determine which specific TPM pillars will produce faster and quicker results in improving equipment performance and higher productivity for manufacturing companies.

Consequently, 5S is a useful tool that strongly supports the objectives of STTPM implementation (Ben Hassan & Abdul-Kader, 2016). This thesis highlights the short-term TPM focusing on autonomous and planned maintenance as the driver for high manufacturing performance and providing the framework to maximize the benefit of STTPM activities. In this thesis, "production operator" does not refer to unskilled production workers. Instead, it refers to operators that are skilled to set up and program the CNC machines. Although these operators are not maintenance technicians by trade, after training (that they need to undergo), they would be able to perform necessary maintenance tasks.

3.3 STTPM Methodology

The proposed STTPM methodology is based on a set of stages that form an integrated system of several elements to achieve the strategy and objectives of the STTPM.

The elements of the framework have been developed based on TPM literature. Each stage consists of some elements that must be executed to ensure successful implementation. All these elements improve the efficiency of the overall maintenance application by improving and developing the maintenance plan for small and medium enterprises in Canada. With cultural differences between Japanese and North American workers, it is not very easy to implement the TPM approach using the same method and behaviours. Therefore, the focus will be on some of the TPM pillars.

This STTPM approach is a process to help companies smoothly and quickly implement TPM to achieve a desired future state for the maintenance function. It is vital to have top management support because they can effectively remove barriers to STTPM implementation. During the initial stages, upper-level management should coordinate with the production and the maintenance departments to choose the appropriate team for STTPM implementation. The method is made up of a five-stage model: TPM initial Preparation, Training and Motivation, 5S, AM and PM elements and STTPM Auditing, as shown in Figure 3-1. The details of each stage and sub-step are described in the next sections.

3.4 The objective of the STTPM Methodology

- To provide a smooth transformation of the maintenance function from its current state to the desired future condition.
- To assist the company in comparing the effectiveness of STTPM implementation with JIPM guidelines.
- To find a better approach to help with the implementation of TPM in a short time.
- To facilitate the successful implementation of STTPM in SMEs.
- To minimize losses associated with equipment and production efficiency and have a positive impact on manufacturing performance.

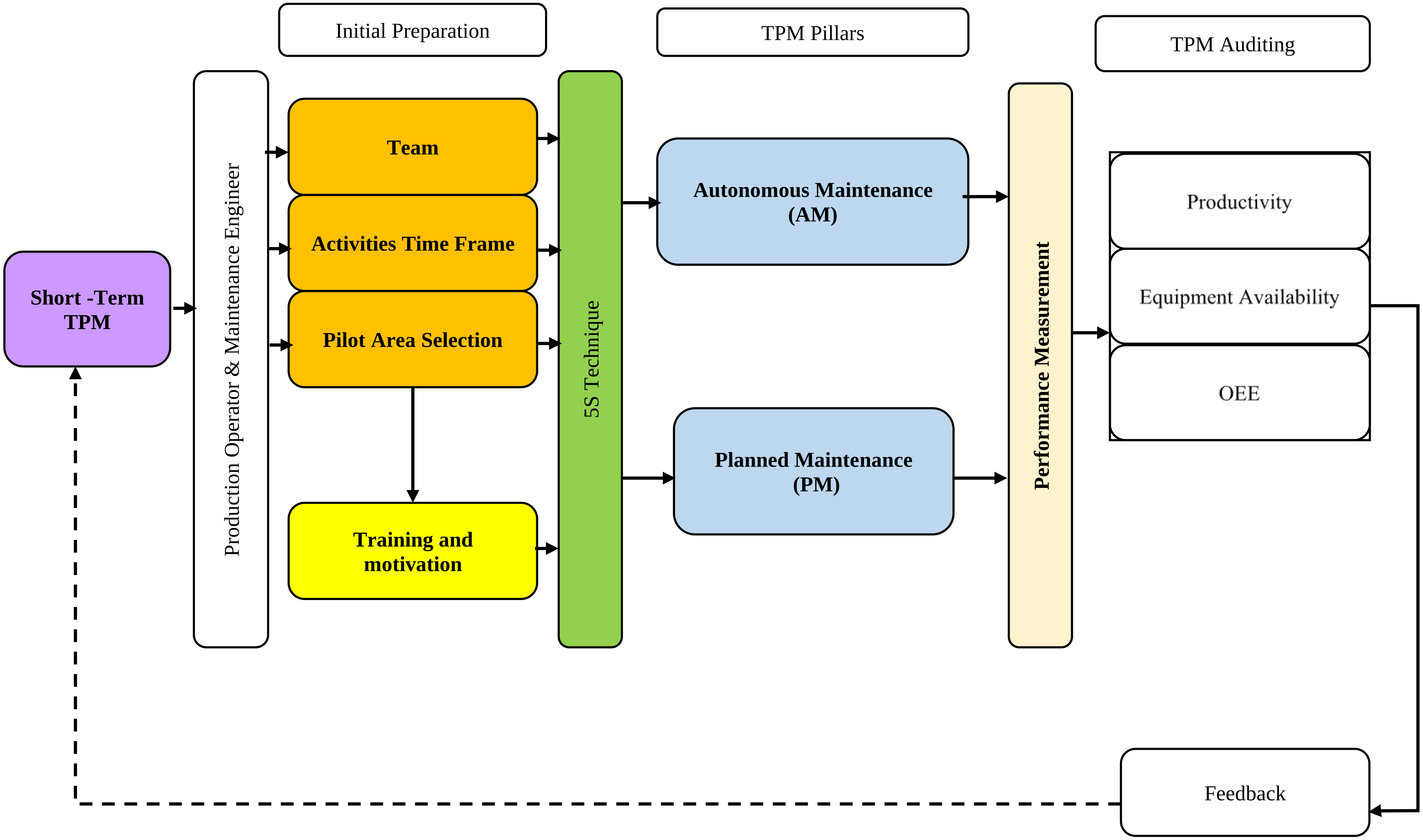


Figure 3-1. Short-Term TPM Framework.

3.5 The Five-Stage Approach of STTPM

3.5.1 Initial Preparation

The primary responsibility of preparing a suitable environment to introduce STTPM is with top management. The objective of this stage is to introduce STTPM concepts and fundamental principles to the STTPM team and obtain their commitment and support for the STTPM initiative. The initial preparation stage of the model that consists of the STTPM team formation, STTPM activities time frame and pilot project selection.

3.5.1.1 Team Formation

The most crucial step of the STTPM practice begins with the formation of the STTPM team. The STTPM teams are selected from the production operators and maintenance engineers. The STTPM team is led by a plant manager or a senior manager who defines the policies, supervises the procedures for the STTPM process, and manages the team to focus on eliminating the six major losses. Therefore, the team leader should monitor the progress of STTPM activities.

3.5.1.2 STTPM Activities Time Frame

The STTPM team is responsible for arranging the time frame for STTPM activities. Many different techniques can be used to track the activities and scheduling of projects such as the Program Evaluation and Review Technique (PERT) chart, Gantt chart and Product Breakdown Structure (PBS). A Gantt chart can be used to plan the STTPM activities, report on activities, or determine the progress of a project. Therefore, the team leader will be able to control the progress of the STTPM implementation through the Gantt chart and discern whether it is within the timeframe or not.

3.5.1.3 Pilot Project Selection

The STTPM journey starts with a pilot project selection, which can be a specific machine, piece of equipment or cell. Implementing the STTPM program in all the shop floor machines or equipment at once is a very challenging task. Consequently, the choice of the pilot project is made based on the critical level and areas of importance. After the selection of machines or equipment, the planned STTPM activities are carried out. Duffuaa et al., (2000) define the critical level of the machine or equipment in a plant, as those machines whose failure will shut down the production process or endanger human life and safety. For excellent results, the team must choose the right machines at the initial stages of STTPM implementation. The success of the pilot project will direct the company to implement the TPM program throughout the entire plant.

3.5.2 Training and Motivation

Training and motivation is the second stage of the STTPM framework. Implementing STTPM is a continuous learning process. Chlebus et al. (2015) indicate that training is the critical success factor in performing TPM in a manufacturing company. Operators and maintenance engineers receive training to improve their skills and knowledge. Thus, the training program is to be designed based on their needs. The training program aims to introduce STTPM and to train team members at the implementation level in the STTPM activities. Also, training allows the learner to become more familiar with the equipment they use, the frequency of oiling, daily maintenance activities required and the abnormalities that could occur in the machine and a way to identify the abnormalities. Also, they may propose methods to avoid failure from happening again.

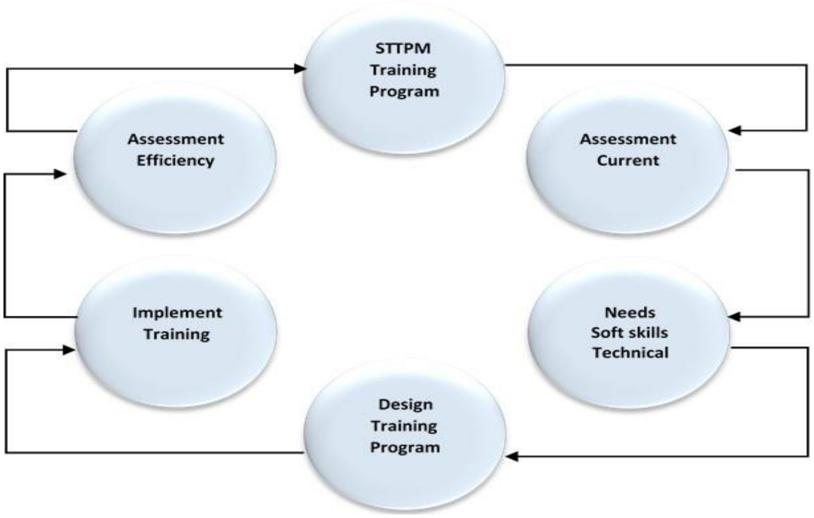


Figure 3-2. STTPM Training System.

The training program should be coupled with a motivational program for an increased opportunity for success. STTPM team motivation can be achieved through a rewards program and encourages continuous improvement. A training system can be considered in the form of a cycle, as shown in Figure 3-2. The company must have a well-defined training program for each employee (Haroun & Duffuaa 2009). The following provides guidelines for developing and assessing the effectiveness of the training program:

1) Evaluate current personnel performance.
2) Assess training needs analysis.
3) Design the training program.
4) Implement the program.
5) Evaluate program effectiveness.

3.5.3 5S Technique

The third stage of the STTPM framework is the 5S technique. Therefore, the 5S technique was considered as a first step towards the actual implementation of STTPM and adoption of lean manufacturing. 5S refers to five principles: Sort, Set in Order, Shine, Standardize, and Sustain. Table 3-1 lists the five original Japanese words of 5S and the equivalent terms in English. The 5S technique focuses on how the maintenance program will improve the performance of the equipment. The 5S is the backbone of any maintenance program implementation.

Table 3-1: Meaning of 5S.

Japanese Term	**Equivalent 'S' term**	**English translation**
Seiri	Sort (S1)	Organization
Seiton	Set in Order (S2)	Tidiness
Seiso	Shine (S3)	Cleaning
Seiketsu	Standardize (S4)	Standardization
Shitsuke	Sustain (S5)	Discipline

Sharma & Singh (2015) study the relationship between 5S and the pillars of TPM in manufacturing. Their findings confirmed that all 5S principles affect TPM by providing a better way to reduce the equipment losses and therefore improve equipment performance. Also, 5S promotes a collaborative culture in the organization to improve workers' Autonomous Maintenance practices. 5S is a five-step process in which each step is a prerequisite for the next. For instance, it is impossible to implement S2 if S1 has not been done first. Below are brief definitions and explanations of each step of the 5S process:

- ***Sort:*** Separating the needed from the unneeded. Sorting activities aim to eliminate unneeded items from the work area and to perform an initial cleaning.
- ***Set in Order:*** A place for everything and everything in its place, clean and ready for use. Simplifying arranges the workplace to ensure safety and efficiency.
- ***Shine:*** Cleaning for inspection. Systematic daily cleaning and inspection of work areas and equipment help to understand current conditions and determine if corrective action is required.

- ***Standardize:*** Developing standard methods for consistency and standardizing aims to make abnormal conditions noticeable and to document agreements to ensure consistency and sustainability.
- ***Sustain:*** Maintaining gains and improving. Sustaining is aimed at maintaining the improvements from the other 5S activities and improving further.

3.5.4 Autonomous Maintenance (AM) & Planned Maintenance (PM) Elements

The fourth stage of the STTPM framework includes both autonomous and planned maintenance elements. STTPM focuses on autonomous and planned maintenance activities to build the foundation soon for a successful implementation for all other TPM pillars, and to make a smooth transformation of the maintenance function from its current state to the desired future condition. The cost and time associated with AM and PM activities are unique for each company. For instance, the previous status of the machines and the maintenance strategy that was implemented play a significant role in determining the required cost and time for a new change.

- **AM Elements**

The main purpose of Autonomous Maintenance is to let machine operators address basic maintenance activities such as inspection, cleaning, lubrication, setup, and other preventive maintenance activities. These activities do not include accidental breakdown or non-basic maintenance activities. Therefore, skilled technicians must conduct these activities. Involving machine operators in these basic maintenance activities will result in good savings as maintenance technicians will not be called to fix some minor or basic maintenance tasks. Autonomous Maintenance (AM) is the most characteristic feature of TPM and, for many, the hardest to implement as it involves changes in culture, roles, and responsibilities. Operators perform AM, and their performance is the key to improve TPM performance and allow them to carry out preventive maintenance tasks. Generally, in this approach, the AM practice consists of four elements as required by JIPM (2017) for the TPM Excellence Award, Class B. Plants must have completed at minimum 76% of the fourth element for AM activity. Table 3-2 shows typical elements for the four steps of Autonomous Maintenance.

Table 3-2: The Elements of AM (JIPM 2017).

Step	AM Elements
1	Initial cleaning
2	Countermeasures for contamination sources and hard-to-access areas
3	Preparation of tentative standards for AM
4	General inspection

These four elements are needed to maintain the basic equipment conditions through inspections, lubrication, cleaning, and other simple preventive maintenance to be completed by production operators. Therefore, AM practices have two fundamental aims, the restoration and maintenance of equipment in optimum condition and the development of operation skills and engagement, leading to increased equipment reliability. AM activities requiring operators to become knowledgeable about their production activities as the Japan Institute of Plant Maintenance (JIPM) describes the critical operator autonomous maintenance skills to be (Pomorski, 2004):

1. Ability to discover abnormalities.
2. Ability to correct abnormalities and restore equipment functioning.
3. Ability to set optimal equipment conditions.
4. Ability to maintain optimal conditions.

- **PM Elements**

PM is one of the fundamental development activities that support the implementation of TPM. This type of maintenance differs from autonomous maintenance since it leads directly to the maintenance engineer. However, TPM encourages better PM and encourages its interaction with other pillars of TPM. Existing planned and scheduled maintenance needs to be evaluated and improved as part of STTPM implementation. According to JIPM (2017), plants must practice the PM activities for the TPM Excellence Award, Class A or B, which are shown in Table 3-3.

Table 3-3: The Elements of PM.

Steps	**PM Element**
1	Evaluation of Equipment and Understanding Current Conditions
2	Restoration of Deterioration and Improvement of Weak Points
3	Creation of an information Management system
4	Creation of a Periodic Maintenance system
5	Creation of a Predictive Maintenance system
6	Evaluation of Planned Maintenance

3.5.5 STTPM Auditing

Finally, Stage 5 is the STTPM audit, which serves as an essential benchmark to identify any discrepancies and to improve the application of the prior STTPM stages. At this step, the STTPM auditors could be a team leader or another production or department manager to manage and assess STTPM stages. They would use the auditing sheet as a score sheet to quantitatively record the progress of the STTPM implementation. The STTPM auditors can periodically review STTPM stages to assess the progress of the STTPM implementation.

3.5.6 Summary

This chapter presented the development of a conceptual framework for the STTPM implementation to show the essential relations between manufacturing performances. The STTPM methodology is based on selecting the well-established frameworks of the TPM pillars and the manufacturing performance. The formulation process followed various steps to implement STTPM approach. The chapter also discussed the selection of STTPM pillars of the conceptual framework for the performance measurement. The approach for assessing STTPM is also presented. This chapter presents the five-stage approach of STTPM that describes the development of an integrated STTPM methodology for reducing manufacturing losses.

CHAPTER 4 STTPM APPROACH IMPLEMENTATION

4.1 Introduction

In Chapter 4, we discuss how Small to Medium Enterprises (SMEs) could implement STTPM, which may be a preliminary step towards fully implementing a TPM program. As mentioned earlier, an SME is selected for the implementation of the developed STTPM approach. This section provides a step-by-step approach to implementing STTPM in SMEs. Successful implementation requires senior-level management support and commitment from day one. A five-stage implementation process is discussed in the subsequent subsections. The implementation process of the STTPM approach is shown in Figure 4-1.

4.2 STTPM Approach Implementation

4.2.1 Initial STTPM preparation

The first essential process of the STTPM approach is to form the STTPM team from among internal staff. The employees from the maintenance or production department with the most extensive knowledge and experience are appointed as the STTPM team leaders of each team. Figure 4-2 shows that each team has three members, one from the maintenance department and two from the operation department. The plant manager can determine the responsibilities and roles of each STTPM member. A Gantt chart can be used to have the time frame of STTPM implementation, as shown in Figure 4-3. STTPM Project Gantt chart acronyms are defined in Table 4-1. The critical machines can be identified for the STTPM approach implementation and are based on historical data analysis such as breakdown, set-up and adjustment, and yield loss.

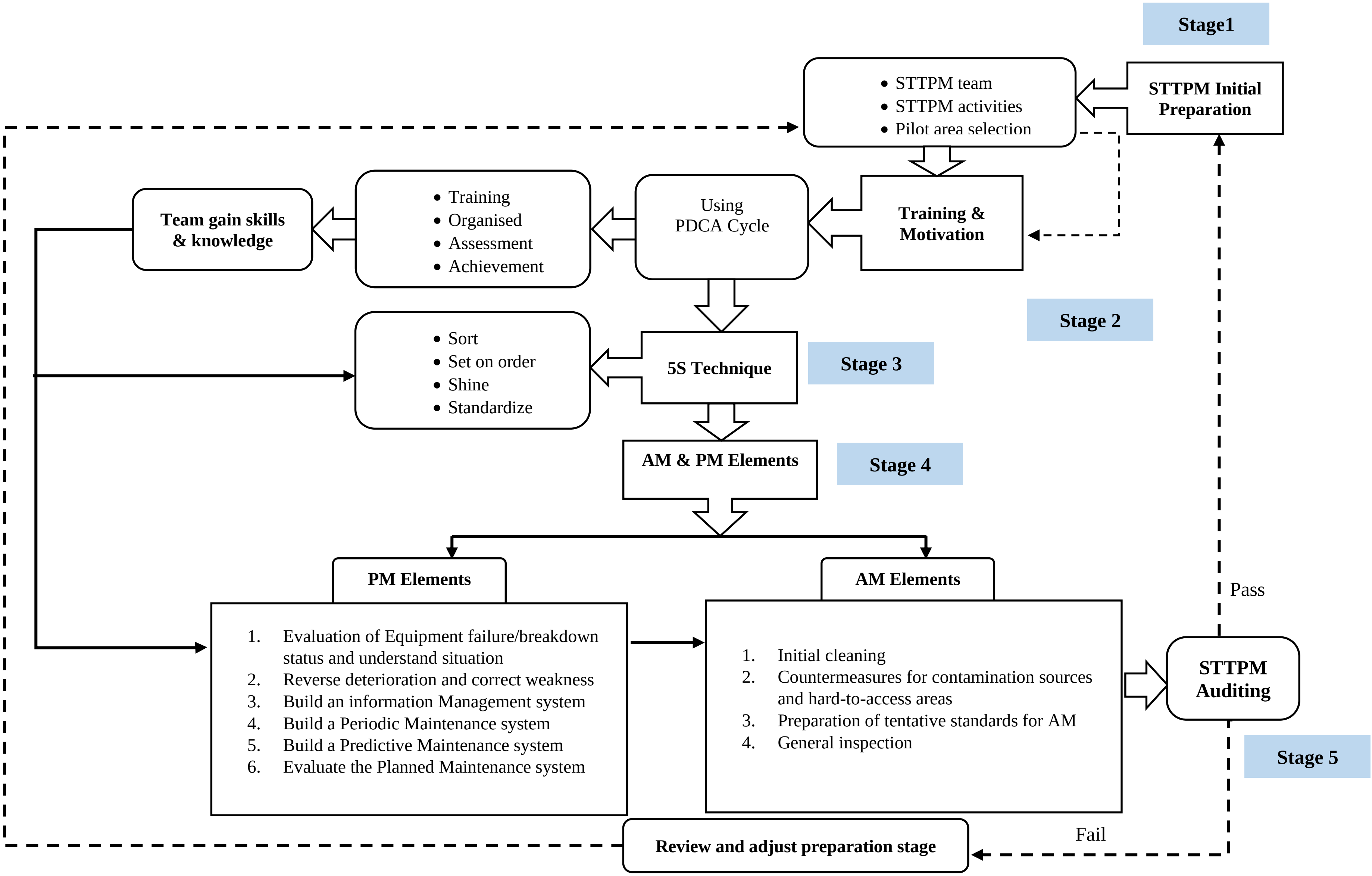


Figure 4-1. The Implementation Process of STTPM

Consequently, the data analysis result can indicate that the machines were not utilized effectively. Therefore, these machines would be selected as the first stage to adopt the STTPM program. Each machine can be studied thoroughly to identify its performance and to understand the working condition.

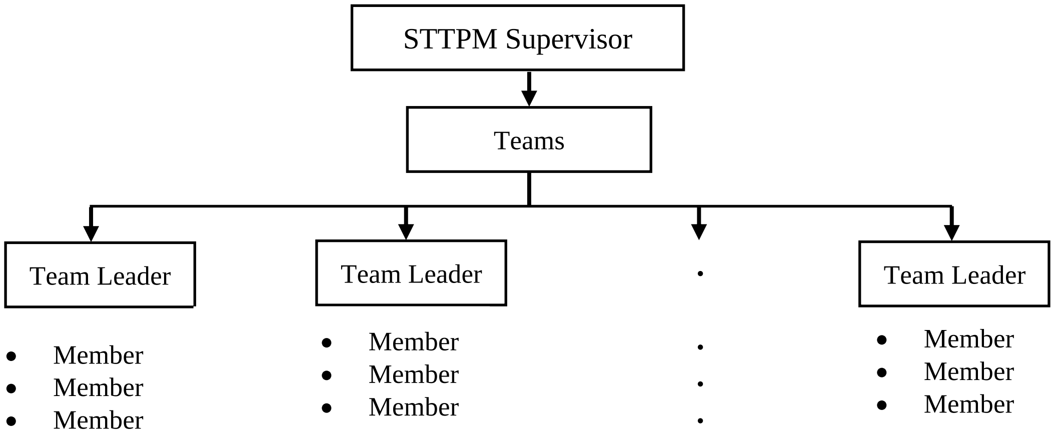


Figure 4-2. STTPM Team Members.

Table 4-1: STTPM Project (Gantt chart) Acronyms List of Abbreviations.

No	Task	Acronyms
1	**STTPM initial Preparation**	**IP**
2	STTPM Team Formation	IP1
3	STTPM Activities Time Frame	IP2
4	Pilot Project Selection	IP3
5	**Training and Motivation**	**TM**
6	Improving Skill, Knowledge	TM1
7	Technical Job Skills	TM2
8	Complying PDAC cycle	TM3
9	**5S Technique**	**5S**
10	Sort	S1
11	Set in Order	S2
12	Shine	S3
13	Standardize	S4
14	Sustain	S5
15	**AM Elements**	**AM**
16	Initial Cleaning	AM1
17	Countermeasures for Contamination Sources and Hard-To-Access Areas	AM2
18	Preparation of Tentative Standards For AM	AM3

19	General Inspection	AM4
20	**PM Elements**	**PM**
21	Evaluation of Equipment and Understanding Current Conditions	PM1
22	Restoration of Deterioration and Improvement of Weak Points	PM2
23	Creation of an Information Management System	PM3
24	Creation of a Periodic Maintenance System	PM4
25	Creation of a Predictive Maintenance System	PM5
26	Evaluate of Planned Maintenance	PM6
27	**STTPM approach audit**	**AU**

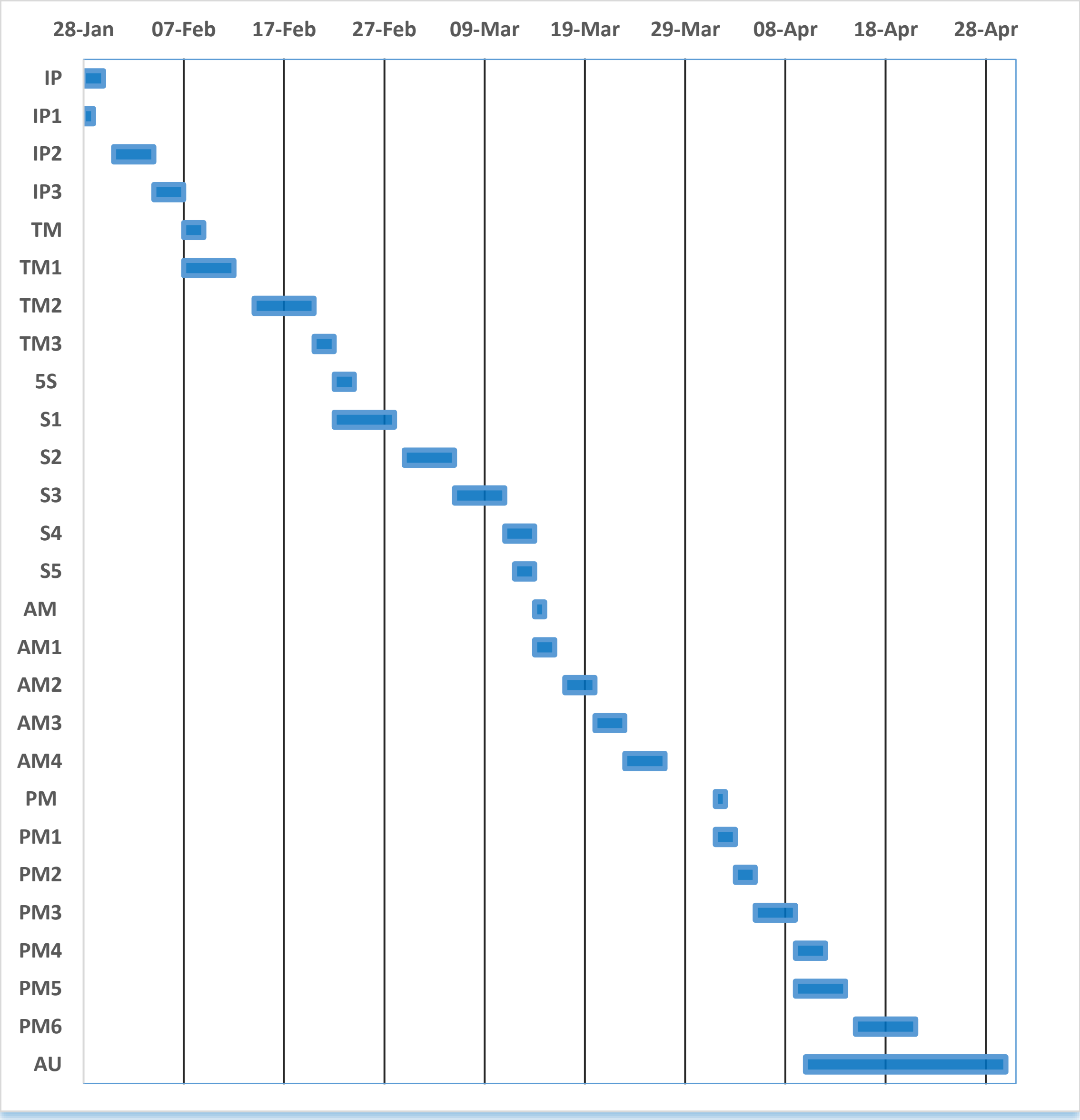


Figure 4-3. Gantt Chart of The STTPM Program, (the time frame for each step).

4.2.2 STTPM Training and Motivation

Proper training is necessary for the execution of STTPM implementation. Generally, training for STTPM implementation is carried out in a two-step method: classroom training to provide auditory and visual learning and hands-on training to incorporate this with physical learning. As suggested by Digalwar and Nayagam (2014), training is the TPM key to success for any lean manufacturing. Without proper training, the teams will not capture the STTPM implementation adequately and will not be able to standardize the STTPM activity. The team leaders must contribute in this regard by providing appropriate training for improving skills and knowledge towards implementing STTPM since the STTPM implementation is closely interlinked with the skill and knowledge base of team members.

The STTPM team must be provided with technical job skills such, as operating, maintaining and repairing equipment, preventive maintenance techniques, test equipment operation, and safety training. By learning how their machines function, and how to detect abnormal conditions, operators can more accurately control the factors affecting equipment performance. The process of STTPM training is conducted based on Plan-DO-Check-Act (PDCA) cycle as shown in Figure 4-4. The plant manager, as the operation owner, takes charge of the Lean Manufacturing, 5S, and technical maintenance training, which is required for STTPM implementation. 5S, autonomous, and planned maintenance training is taught to STTPM teams to raise an operator’s skill levels and ownership. Lectures, seminars, and workshops would be organized for the STTPM teams. Two methods mainly impart training: -

a) Classroom training: the training could be in training rooms. In classroom training, principal knowledge of TPM can be imparted by using PowerPoint presentations and handouts provided to the STTPM team leaders and team members.

b) Hands-on training: These types of training would be on shop floors. The objective is to enhance the skills of STTPM teams. The training program includes the following:

- Introduction of TPM
- Introduction and how to implement 5S
- OEE and its calculations
- Training for autonomous maintenance
- Introduction to planned maintenance
- TPM performance indicators

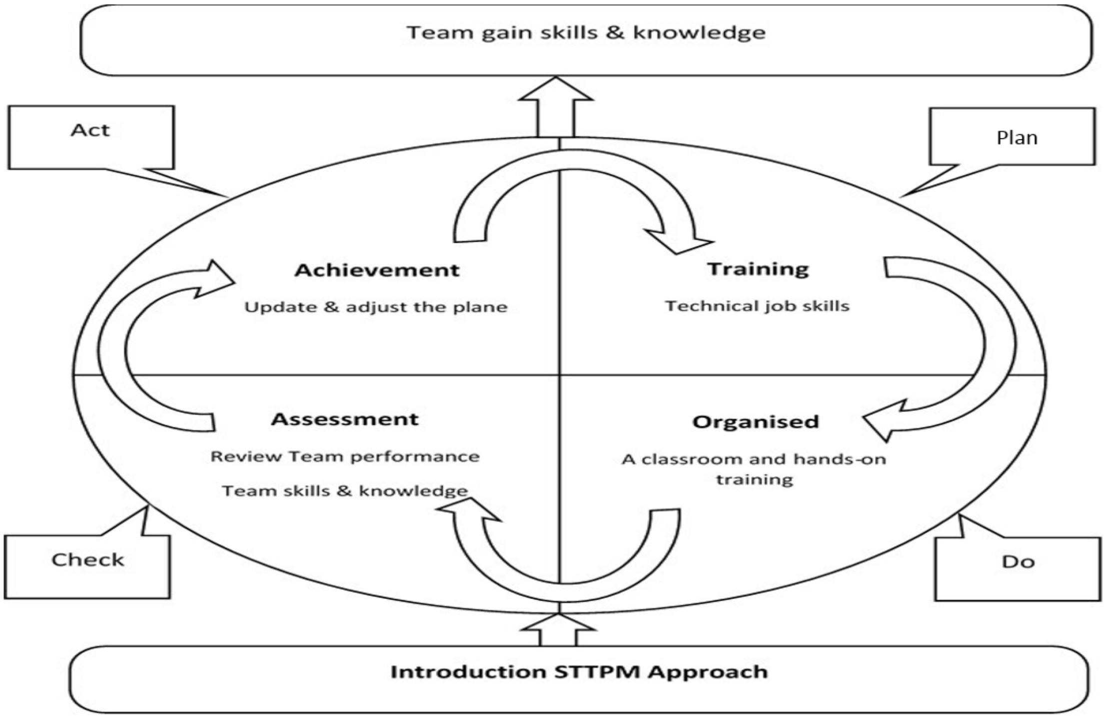


Figure 4-4. STTPM Training Process.

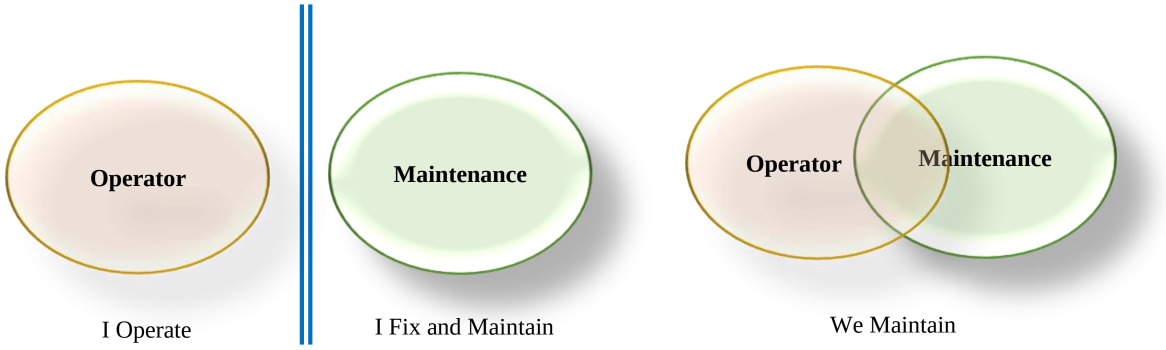
4.2.3 5S Implementation

The actual implementation of 5S practice is initiated by preparing and maintaining records of the jobs to be performed. The team leaders are responsible for implementing the 5S technique according to guidance designed for this purpose. 5S guidance is defined in (Appendix A). According to the recommendations of each team, the leader of the production line should set up an action plan for 5S implementation. After a month and as a first stage, the official kick-off of 5S implementation in the first production area would take place with a small ceremony to emphasize its importance. It would be a model for the rest of the production lines/areas. Indeed, the implementation of each item of 5S principles is considered an important step in contributing to the STTPM's successful implementation. The teams would focus on the key machines and soon realize improvements through identifying abnormal conditions and, consequently, a drop in the six big losses lead to an improvement in OEE. As a measure of the implementation of 5S, a follow-up document is developed to assess the progress level of all 5S elements. This 5S assessment form is defined in (Appendix B). 5S assists in changing the operators' attitudes and reveals hidden faults that are usually not noticed.

4.2.4 AM & PM Elements

4.2.4.1 AM Elements

After the training stage and 5S implementation, operators will learn the basic maintenance skills they need through AM program as required by JIPM (2017) to achieve the TPM Excellence Award, Class B. In general, there are seven elements to accomplish to gain the other TPM Award Class. Figure 4-5 shows the paradigm shift that addresses a change in the operator perception from “I run the equipment, maintenance fixes it,” to “we maintain”. The focus of the AM is on cleaning, inspecting, adjustment, lubricating and other simple preventive maintenance tasks. Furthermore, when the operator engages in routine maintenance, it will build a sense of responsibility, pride, and ownership. Four significant elements of the AM are discussed in further detail in this section. The autonomous maintenance (AM) elements were developed for a selected production line. AM’s objective is to train the production operators for handling the basic tasks of maintenance of their equipment through specialized training.



Old Attitude TPM Attitude

Figure 4-5. The Paradigm Shifts of TPM.

The implementation of autonomous maintenance takes place after conducting operator training to be able to perform some basic maintenance tasks for the equipment. The STTPM team must be provided with technical job skills training such as operating, maintaining equipment, preventive maintenance techniques, test equipment operation, and safety training.

- ***Initial cleaning.***

The first element of AM is cleaning equipment. This cleanliness helps with the early detection of defects such as the presence of leaking or cracking depending on the five senses of the operator. The focus of the initial cleaning is in the production line that is identified as the critical area. Also, this step is considered to determine hidden problems so that the equipment can be restored to its ideal condition. Abnormalities are recorded using a daily or weekly inspection sheet for each production line/area.

- ***Countermeasures for contamination sources and hard-to-access areas.***

This is the second element of AM. After the initial cleaning has been performed, this element tries to eliminate all possible contamination sources and improving accessibility for cleaning and maintenance. At this point, the operators start looking for the root causes of contamination, especially if they supported activities in element one by correcting the problems thoroughly by modifying either the equipment, the processes, the work areas or work practices aimed at reducing the time to clean, lubricate or inspect.

- ***Preparation of tentative standards for AM.***

From 5S element one and two practice, the operators would gain the experience to keep the level of cleanliness that was achieved, and the equipment improvements made to deal with contamination sources and hard-to-access areas. To do this, basic standards for cleaning, inspecting and lubricating must be formulated. Cleaning standards are established to include a description, method, cleaning tools, cleaning time and frequency. Lubrication standards include a lube diagram, type and amount, method, tools, and frequency. Equipment inspection includes daily startup and shutdown procedures. The main goal of these standards is to improve equipment reliability and maintainability.

- ***General inspection.***

This element aims to provide operators a wide understanding of the functions, principles, and structure of their equipment, and to develop their ability to perform basic maintenance including hydraulic systems, fasteners, leak prevention and seals, drives, gears, bearings, electrical devices, and lubrication.

4.2.4.2 PM Elements

AM is considered the first step toward PM implementation. Also, planned maintenance is commonly referred to as planned preventive maintenance. The STTPM team through this stage (AM and PM), helps to keep equipment up and running to avoid any unplanned downtime during daily operations. PM includes the repair, replacement, and maintenance of equipment in order to avoid unexpected failure. The main objective of PM is to achieve high reliability of equipment and minimize maintenance costs such as inspection and repair, and equipment downtime. The best way to carry out PM elements is the following (JIPM 2017) implementation of the PM phase as shown in (Appendix C).

4.2.5 STTPM Auditing

The purpose of an STTPM audit is to ensure the stage requirements of the STTPM approach are being fulfilled. The requirements have been referenced in the JIPM excellence award criteria. To follow up and monitor the STTPM implementation, auditing the stages of the STTPM approach is required. Therefore, in this approach, an STTPM stages audit sheet for the production line is established as presented in Table 4-2.

Table 4-2: STTPM Approach Audit Sheet.

No	Stages of STTPM Approach	Percentage of implementation	Recommend for improvement

		0 % - 25 %	26 %- 50 %	51 %- 75 %	76 %- 100 %	Yes	No
Stage 1	**Initial STTPM preparation**						
	STTPM Team Formation						
	STTPM Activities Time Frame						
	Pilot project selection						
Stage 2	**STTPM Training**						
	Improving Skill, Knowledge						
	Technical Job Skills						
	Complying PDCA Cycle						
Stage 3	5s Technique						
	Sort						
	Set in Order						
	Shine						
	Standardize						
	Sustain						
Stage 4	AM Elements						
	Initial Cleaning						
	Countermeasures for Contamination Sources and Hard-To-Access Areas						
	Preparation of Tentative Standards For AM						
	General Inspection						
Stage 5	PM Elements						
	Evaluation of Equipment and Understanding Current Conditions						
	Restoration of Deterioration and Improvement of Weak Points						
	Creation of an Information Management System						
	Creation of a Periodic Maintenance system						
	Creation of a Predictive Maintenance system						
	Evaluate of Planned Maintenance						
	Total score						
	The result						
	Comments						

The plant manager, quality inspector and team leader are selected as the STTPM committee. The STTPM audit is assessed based on the percentage approaches 0%-100%, in which 0% refers to ‘not implemented’ and 100% refers to ‘fully implemented’ as in

Table 4-2. Recommendation for improvement based on percentage approaches >75% implemented and looking for further improvement, 26%-51% minor implementation and <25% requires major modification to STTPM stages. The STTPM audit is carried out based on the check sheets and feedback of observations. The results of the STTPM audit are used for further improvement to achieve the objectives of the STTPM approach.

4.3 Cost of TPM Implementation

Marshall Institute, an asset management consulting and training company, has found that while TPM implementation has its benefits, there are financial expenses upon initial stages of application. Companies can expect an increase in training costs of 10% to 20%, plus another 15% to 20% for additional maintenance costs (Erin, 2016; Moradi et al., 2011; Oskar, 2017). Therefore, the cost of a TPM implementation depends on a set of components that are already in the factory (Moradi et al., 2011): 1) - Maintenance programs in place; 2) - Age of the equipment; and 3) - Skills of the workforce. In addition, it should be noted that most of the researchers agreed that the costs of the implementation of TPM are considered not significant when compared to the costs of not implementing TPM. The main TPM implementation cost will consist of:

- ***Training and Consultancy***. The TPM and lean manufacturing implementation fail without a good planning process for training and assistance from experienced professionals. According to the Association for Talent Development (2017) State of the Industry report, organizations spend an average of $1,273 per employee for direct learning expenditures. The SME spends more per employee and Larger Enterprises spend less per employee. The company must train the TPM team, which needs continuous support from senior management. Oskar, (2017) estimated that the annual training cost will increase by 10% to 20%, plus another 15% for additional maintenance costs. However, it requires some customized training in order to succeed.

- ***Increased initial maintenance costs.*** The elimination of manufacturing waste and the implementation of the TPM approach is likely to increase maintenance costs. Moradi et al., (2011) and Oskar, (2017) expected maintenance cost to increase up to 20% during the first year, but even before the second year, maintenance costs will be lesser than what it has today when it eventually stabilizes at a certain level as explained in maintenance cost analysis section below.
- ***Project team members*.** The company will need individuals to run the TPM project implementation. Project team leaders are equivalent to about one full-time coordinator per TPM team.

4.4 A contribution of STTPM Approach

There is some evidence to confirm that the 5S, autonomous maintenance and planned maintenance during the TPM implementation process has a direct and positive effect on manufacturing performance. Particularly, 5S implementation on the shop floor has played a significant role in improving the employee’s productivity. The case study result shows that production rate, equipment availability and cycle time and OEE were a significant improvement after the implementation of STTPM in the production line. Significant improvement can be evident within six months; however, expected tangible and beneficial results from applying all eight TPM pillars might be after three to five years

(David, 2018). Sharma and Singh (2015) concluded that the adoption of the TPM approach could reduce losses, which helps the company to increase profitability and image.

4.4.1 Maintenance Cost Analysis

In this section, we aim to explain the cost of maintenance when implementing STTPM. Autonomous maintenance essentially includes the operators doing some minor maintenance tasks on their equipment, such as inspection, lubrication, and cleaning. It is a unique feature of TPM that is done by the operators. The implementation of autonomous maintenance begins by training the operators to be able to perform basic maintenance tasks to keep the equipment in good operating condition, and to prevent any deterioration of the equipment. Nevertheless, selection and identification of maintenance tasks to be done by operators are agreed upon the production engineers and maintenance engineers.

Table 4-3: Operators and Technicians Acquire New Skills (Leflar, 2001).

Machine skill	Present	Future
Failure prevention Design improvement Rebuilding	Very Little Done	Technicians
Major repairs Troubleshooting Minor repairs Minor adjustments	Technicians	
Lubricating Inspecting Tightening Cleaning		Operators
Operating	Operators	

The STTPM approach does not eliminate the need for skilled maintenance technicians. However, by making machine operators responsible for the daily upkeep of their equipment, autonomous maintenance frees maintenance technicians from being occupied with basic maintenance activities. Therefore, it enables these technicians to focus on demanding technical repairs. Autonomous maintenance is a step-by-step improvement process, rather than production operators taking on maintenance tasks. Leflar (2001) indicates that acquiring new skills, operators and technicians can elevate their role in equipment care, which translates into improved equipment performance as shown above in Table 4-3. Borris (2006) reported that “Using highly skilled technicians or engineers to carry out very simple maintenance tasks is not cost-effective.”

This approach affects the cost of maintenance in two ways. First, the labour costs of maintenance can be reduced because the operators who run the machines can now (after TPM implementation) do basic maintenance activities such as lubrication, cleaning, tightening bolts and nuts, alignment, and adjustment. Training and involving machine operators in these basic maintenance activities (preventive maintenance) will result in significant savings, as maintenance technicians will not be called to fix some minor problems or perform basic maintenance tasks. Second, the time required for preventive maintenance is expected to increase compared to the regular time required by experienced technicians. However, as the operators are learning, the time of preventive maintenance is expected to decrease significantly. Maintenance activities vary in nature. It is indicated that individuals learn by experience (i.e., get increasingly better at the job by repeatedly carrying out the tasks). There is a learning effect as operators become more efficient as they gain experience with a preventive maintenance task. This leads to a decrease in cost; consequently, profit will increase. The preventive maintenance time can be measured by using the Learning Curve formula (Drury, 2013; Wright, 1936):

$$T(m) = am^b \qquad (4.1)$$

Where,

$m = PM\ Task\ number$

$T(m)$ =*Time required for the* m^{th} $task$.

a =*Time required by the trained operator to complete the first PM task.*

$$b = \frac{\ln(L)}{\ln(2)}\ (the\ learning\ curve\ factor\ ),$$

Where, (L) is the percentage rate of improvement, which is also known as the learning rate.

Maintenance activities look similar to general assembly activities. Lee and Strategos (2014) suggested that the learning rate of the general assembly is 80%. Using this learning rate, we calculate the time for maintenance. For instance, the minimum time required to perform a preventive maintenance task is 0.25 hours. The first measured duration for doing preventive maintenance will be assumed as a = 0.61 hours. This is also equal to *T(m*=1*)* = 0.61 hours. After 16 times (or for *m* =16) of executing these maintenance activities (or tasks) by applying the learning curve formula presented above (see Equation (4.1)), the preventive maintenance time (PMT) will decrease to 0.25 hours as shown in Table 4-4. Because no manufacturing job can keep increasing its efficiency incessantly, we will stop at the minimum time required to do this task. Assuming a learning rate is 80%, and the learning curve factor (*b*) is $\frac{\ln(0.8)}{\ln(2)} = -0.3219280949$.

Table 4-4: Learning Effect on Preventive Maintenance Tasks.

$T(m) = am^b$	*PMT* *hour*
$T(m = 1) = 0.61\ (1^{\mathrm{b}}) =$	**0.61**
$T(m = \ 2) = 0.61(2^{\mathrm{b}}) =$	0.488
$T(m = 3) = 0.61(3^{\mathrm{b}}) =$	0.428
$T(m = 4) = 0.61(4^{\mathrm{b}}) =$	0.390
$T(m = 5) = 0.61(5^{\mathrm{b}}) =$	0.363

$T(m = 6) = 0.61(6^{\mathrm{b}}) =$	0.343
$T(m = 7) = 0.61(7^{\mathrm{b}}) =$	0.326
$T(m = 8) = 0.61(8^{\mathrm{b}}) =$	0.312
$T(m = 9) = 0.61(9^{\mathrm{b}}) =$	0.301
$T(m = 10) = 0.61(10^{\mathrm{b}}) =$	**0.291**
$T(m = 11) = 0.61(11^{\mathrm{b}}) =$	0.282
$T(m = 12) = 0.61(12^{\mathrm{b}}) =$	0.274
$T(m = 13) = 0.61(13^{\mathrm{b}}) =$	0.267
$T(m = 14) = 0.61(14^{\mathrm{b}}) =$	0.261
$T(m = 15) = 0.61(15^{\mathrm{b}}) =$	0.255
$T(m = 16) = 0.61(16^{\mathrm{b}}) =$	**0.250**

4.4.2 The expected profit

In this section, we aim to explain the potential improvement in expected profit after implementing STTPM. Also, it can be improving profit by preventing equipment breakdown, improving the quality of the equipment and productivity. For simplicity, let us assume that all the production operations are done on only one machine. This means that the product does not need to be moved to another machine for additional operations. The units that are produced are naturally categorized as good units (G) and reject units (J). Here, we consider a discrete random variable that counts the number of successes in n independent trials of a procedure that always results in either of two outcomes, “good” or “bad” and in which the probability of success on each trial is the same number p. It is called the binomial distribution with parameters n and p. The expected value of the random variable (X), denoted by $E(X)$ of a binomial distribution is defined as follows:

$$E(X) = \sum_{x=0}^{n} x\, p(x) \qquad (4.2)$$

Moreover, the probability mass function of the binomial distribution $p(x)$, is given by the following:

$$p(x) = \binom{n}{x} P^x \, (1 - P)^{n-x}$$

Therefore, the expectation, *E(X)* can be measured using Equation (4.2). In general, the expected profit for producing Q_p units can be determined as follows:

$$E\left[P\left(Q_p\right)\right] = \left[R\left(Q_p\right) - C\left(Q_p\right)\right] p(x) \qquad (4.3)$$

where

Q_p = *Quantity of production*

$E\left[P\left(Q_p\right)\right]$ = *Expected profit when* Q_p *units are produced*

$R(Q_p)$ = *Revenue from producing* Q_p *units*

$C(Q_p)$ = *Cost of producing* Q_p *units*

p(x)= *Probability of accepting the sample n*

The cost per unit is derived from the variable costs and fixed costs incurred by a production process divided by the number of units produced. The variable costs include labour, material, and delivery costs. Fixed costs could include rent, utilities, and administrative costs. Tompkins et al. (2010) emphasis on using Equation (4.3) is to calculate the expected profit in the case of a production process producing custom-made products. The example below shows how Equation (4.3) can be extended to include preventive maintenance costs explicitly.

4.4.3 An Illustrative Example:

To illustrate the expected profit analysis, we have taken an example of a company that produces conveyor rollers. We chose to take a single machine that produces one component of a conveyor roller (roller shaft) with an average defect rate of 1%. Also, the processing time to complete the production of only one component of a conveyor roller is (PT = 2.5 minutes). The steps to calculate the expected profit per shift are as follows:

- Firstly, we assume that every day, a random sample size *n* is taken from a lot, and each component is classified just as acceptable or unacceptable. If the sample has more than one defect, then the lot is rejected. The sampling process is *n*= 50 with *p*= 0.01. The probability that the lot will be accepted can be calculated as follows:

  $$p(x) = \begin{Bmatrix} \binom{n}{x} p^x \, (1-p)^{n-x}, x = 0,1,2, \dots, 50 \\ 0, otherwise \end{Bmatrix}$$

  The probability $P(X \leq 1)$ is calculated from

  $$P(X \leq 1) = \sum_{x=0}^{1} \binom{n}{x} p^x \, (1-p)^{n-x}$$

  $$= \binom{50}{0} (0.01)^0 \, (0.99)^{50} + \binom{50}{1} (0.01)^1 \, (0.99)^{49} = 0.605 + 0.305 = 0.91$$

  Thus, the probability that accepting the lot is 0.91.

- ***Preventive Maintenance Cost (PMC)**:* The preventive maintenance cost for the machine is calculated for the first task as follows:

  $$PMC = T(m) \times (PMOc + MIC)$$

  where

PMC	*Preventive maintenance cost*
T(*m*)	*Preventive Maintenance Time*
PMO_C	*Preventive Maintenance Operator Cost, this is equal to* \$50 *per hour in the example*
MIC	*Machine idle cost, this is equal to* \$100 *per hour in the example*

  As indicated above, *T (m =*1*)* = 0.61 hours, the preventive maintenance cost would be: $PMC = 0.61 \times (\$50 + \$100) = \$91.5$

Similarly, by substituting $T(m=10)=0.291$ hours, the preventive maintenance cost:

$PMC = 0.291 \times (\$50 + \$100) = \$43.65$

Figure 4-6 below shows the preventive maintenance cost by considering the maintenance time of Task 1 to Task 16, see Table 4-4, above. Accordingly, preventive maintenance costs will decrease, as shown in Figure 4-6. The PMC is related to preventive maintenance time because the cost of preventive maintenance tasks decreases gradually to the regular cost incurred by the technician (see dashed line). Therefore, there is no significant decrease in the cost of PM after reaching the minimum time required to perform these tasks. The dashed line represents the cost of maintenance before implementing any autonomous maintenance training/program. The solid line curve represents the decrease in maintenance cost as the trained operator gains experience in performing the basic maintenance activities.

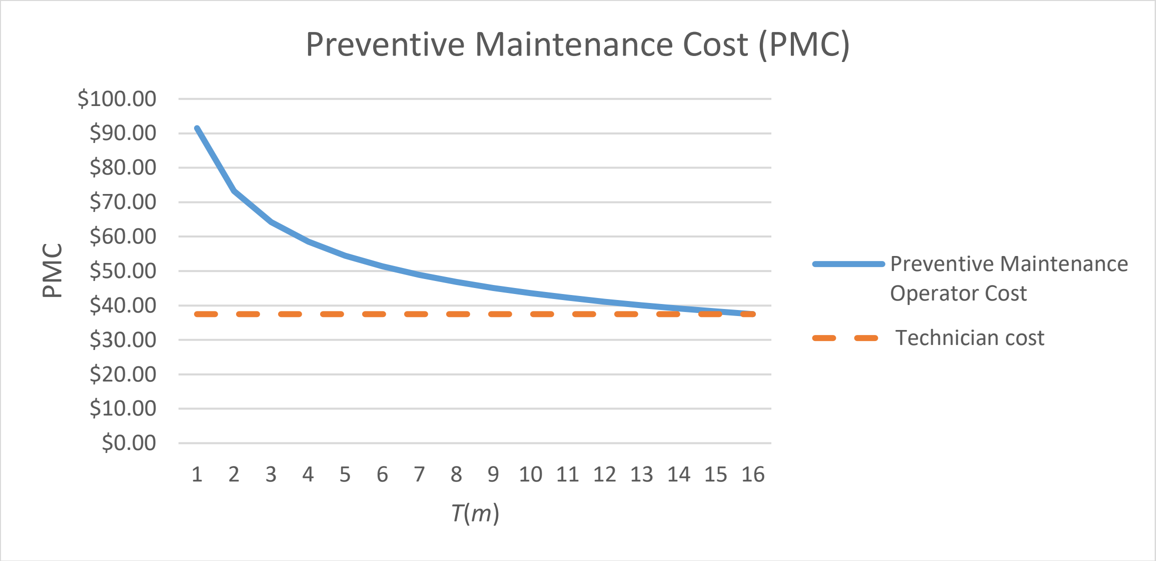


Figure 4-6. Preventive Maintenance Cost.

- ***Machine Available Time (MVT):*** In machine available time calculation, shift time (SFt), break time (Br), setup time (STp), and preventive maintenance time $T(m)$ are considered. The time for all (Br+STp = constant = 1 hour), (SFt = 8 hours), and ($T(m)$= 0.61 hours), for the first trial is as reported earlier. The available machine time will increase as preventive maintenance time is gradually reduced. Therefore, the increasing machine available time for each shift allows more components to be produced. The available machine time can be calculated using the following relation:

  $$MVT = SFt - (STp + Br + T(m))$$

  For the shift (1),

  $$MVT = 8 - (1 + 0.61) = 6.39\ hours$$

  Number of components $= \frac{Machine\ available\ time\ (MVT)}{Processing\ Time\ (PT)} = \frac{6.39\times 60}{2.5} \cong 153$

  For the shift (10),

  $MVT = 8 - (1 + 0.291) = 6.709\ hours$

  Number of components $= \frac{6.709\times 60}{2.5} \cong 161$

  Therefore, after the tenth shift, the preventive maintenance time $T(m)$ becomes more stable, and then the machine available time increase becomes negligible.

- ***Cost of inspection***: The expected cost per manufactured item as a consequence of sampling inspection $E(C_{SI})$ can be calculated as follows:

  $$E(C_{SI}) = C_A \times \frac{n}{N}$$

Where,

C_{SI} *Cost per manufactured item as a result of sampling inspection*

C_A *Cost of inspecting a single item*

n *Sample size*

N *Lot Size*

For the tenth shift, the cost of sampling inspection is considered \$2.00 per item, *n*=50, *N*=161:

$$E(C_{SI}) = C_A \times \frac{n}{N}$$

$$E(C_{SI}) = \$2.00 \times \frac{50}{161} = \$0.621$$

- ***Expected profit:*** Assuming that the cost of materials, equipment, and labour, per component (CO), is \$15 and the selling price of one component (SP) = \$25, the expected profit can be calculated using Equation (4.3) and by incorporating the expected cost of sampling inspection $E(C_{SI})$ and the cost of preventive maintenance as follows:

$$E\left[P\left(Q_p\right)\right] = \left[R\left(Q_p\right) - C\left(Q_p\right)\right] p(x) - \left(E(C_{SI}) \times Q_p\right) - PMC$$

The revenue of producing $Q_p$components for the tenth shift is:

$$R\left(Q_p\right) = \left(Q_p \times SP\right)$$

$$R\left(Q_p\right) = (161 \times 25) = \$4{,}025$$

And the cost of producing $Q_p$components are:

$$C\left(Q_p\right) = \left(Q_p \times CO\right)$$

$$C\left(Q_p\right) = (161\times 15) = \$2{,}415$$

Once the probability of accepting the lot $p(x) = 0.91$, and $PMC = \$43.65$, the expected profit is calculated as shown below:

$$E\left[P\left(Q_p\right)\right] = [4{,}025\ - 2{,}415]\ \times 0.91 - (\$0.621 \times 161) - 43.65 = \$1{,}321.469$$

Therefore, in the tenth shift, the expected profit is calculated and reflected here. The cost model can explicitly consider preventive maintenance costs while calculating the expected profit. The costs of preventive maintenance will decrease, and machine available time will increase, which allows more quantity of components to be produced. The purpose of this example is to demonstrate how expected profit can be improved by gradually reducing preventive maintenance costs. It can also help persuade decision-makers to reconsider maintenance strategies and implement TPM.

4.4.4 New View of Maintenance Cost

Gosavi et al., (2011) emphasized that production managers should consider preventive maintenance costs with the need to reduce lost production costs due to equipment breakdowns. Fredendall et al., (1997) discussed two types' views of maintenance costs as shown in Figure 4-7 and Figure 4-8: the traditional view and TPM maintenance view. The traditional view of maintenance costs is that all maintenance is performed by a set of maintenance engineers or technicians. In this view, the optimal level of maintenance cost occurs at the point of minimal total maintenance costs where the sum of the cost of equipment losses and maintenance activity costs is minimized, shown as (P) in Figure 4-8. On the other hand, TPM is a new approach to maintenance that decreases equipment losses and at the same time reduces maintenance costs**.** The cost of the maintenance activities is lower since the firm performs its maintenance tasks differently. Therefore, it is apparent that contributing to the efforts of the machine operators to maintenance, the total hours of maintenance activities was decreased, as the machine operators became responsible for much of the routine maintenance.

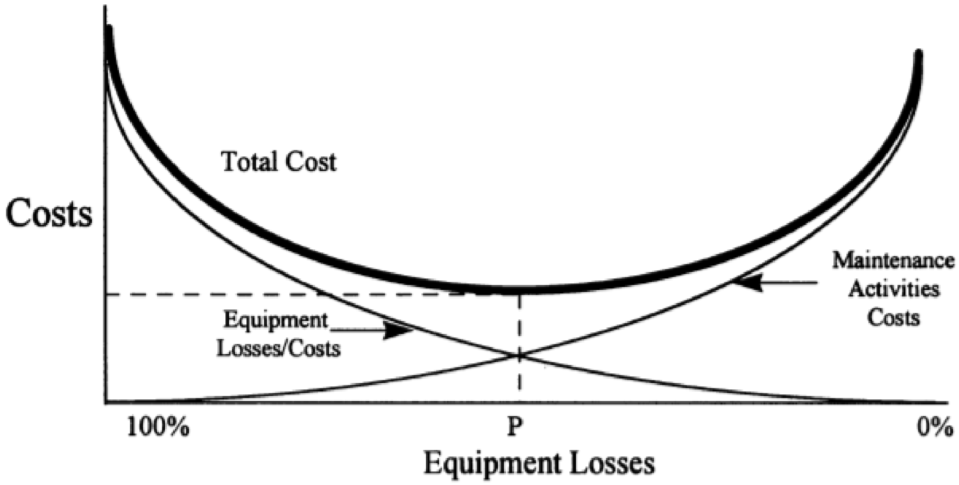


Figure 4-7. The Traditional View of Maintenance Cost.

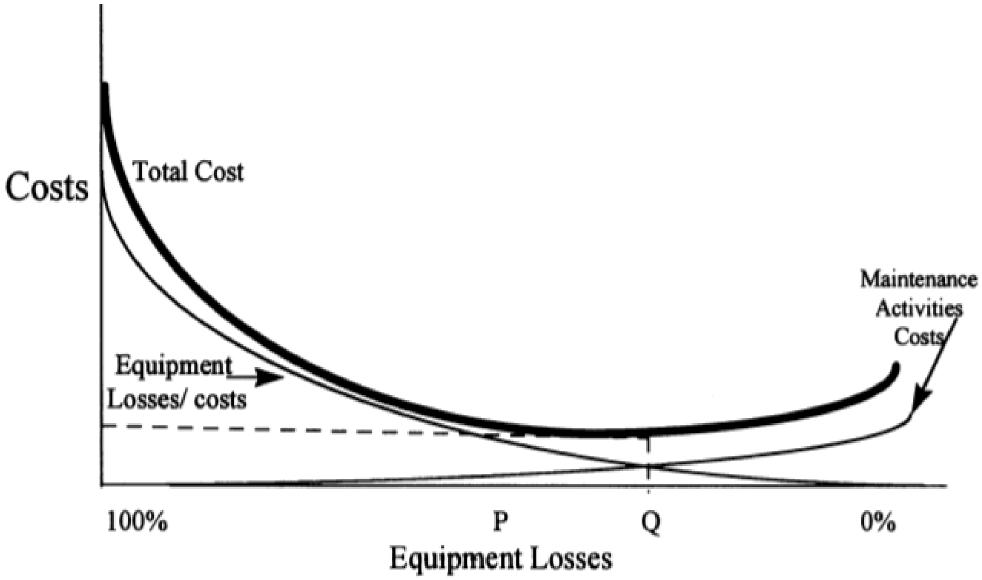


Figure 4-8. TPM Approach View.

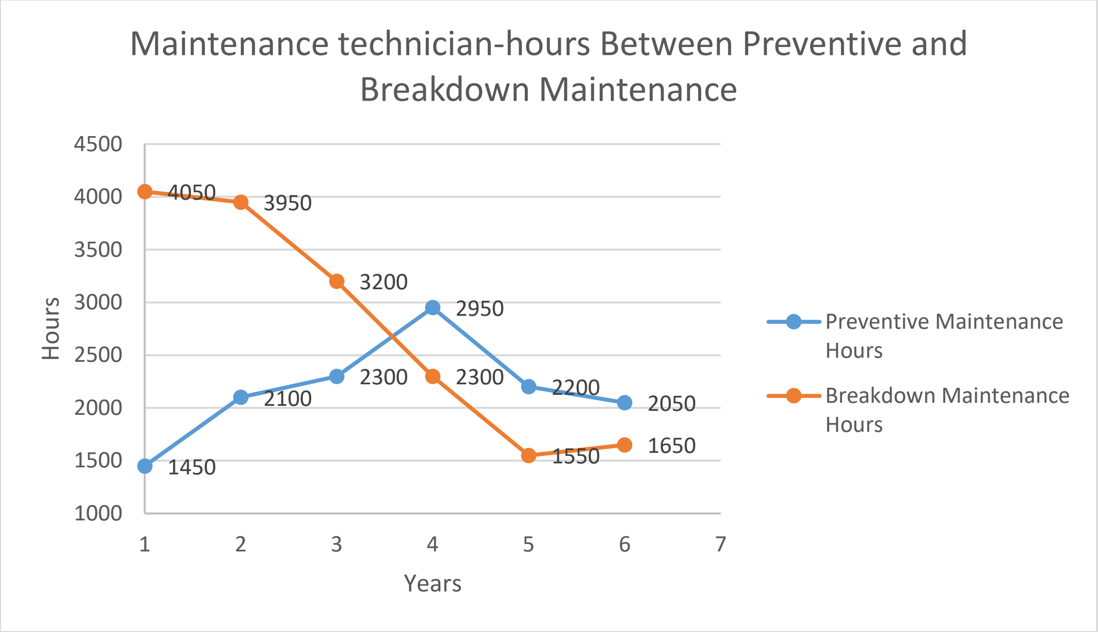


Figure 4-9. Maintenance Technician -Hours between Preventive and Breakdown Maintenance (Adapted from Patterson et al., 1996).

The TPM approach for Asten, Inc. was implemented in the 1990s and tracked hours of maintenance time spent on preventive and breakdown maintenance for six years (Patterson et al., 1996). Figure 4-9 shows the total hours of breakdown maintenance declined from 4,050 in year 1 to 1,650 in year 6, while the total hours of preventive maintenance increased from 1,450 in year 1 to a high of 2,950 in year 4 and decreased to 2,050 in year 6. Accordingly, this increased number of maintenance tasks will reduce the number of equipment breakdowns. The costs of maintenance activities have been reduced and its minimum cost point moved to the right of point (*P*) to the point (*Q*) in Figure 4-8.

4.5 Overall Line Effectiveness (OLE)

This section aims to determine the OLE using the OEE matrix. As originally defined by Nakajima (1988), the purpose of OEE is to evaluate the progress of the TPM approach through the measure of individual equipment. OEE improves the effectiveness of individual equipment. However, for improving the effectiveness of a production line OLE provides an appropriate explanation. In a production line, OLE provides a useful production monitor and a guide to aspects of the production process through which inefficiencies can be targeted.

OEE calculation is more relevant to measure individual equipment effectiveness. In the case of a production line with machines having a different level of importance (weight factor), OEE alone is insufficient (Oechsner et al., 2002). This is because the production line has relationships between two or more machines which leads to an impact on availability, performance and quality loss throughout the system. In fact, in most manufacturing scenarios this will be the case, with different processing stages having different weights. When implementing the STTPM approach, it is more important to maximize the overall effectiveness of the total production line than to focus on individual equipment only. Therefore, OLE based on OEE metrics is analyzed with two production line configurations.

4.5.1 OLE Calculation

For illustration purposes, two different configurations are discussed in this section. To calculate OLE for these configurations and to control the production line, there is no intermediate buffer between the consecutive machines as shown in Figure (4-10), (4-11) and (4-12). However, in a real manufacturing context, a buffer can be used to help make the machines less dependent so that each machine will not be directly or instantaneously affected by the unreliability of other machines.

First, consider a production line composed of three machines connected in series as shown in Figure 4-10:

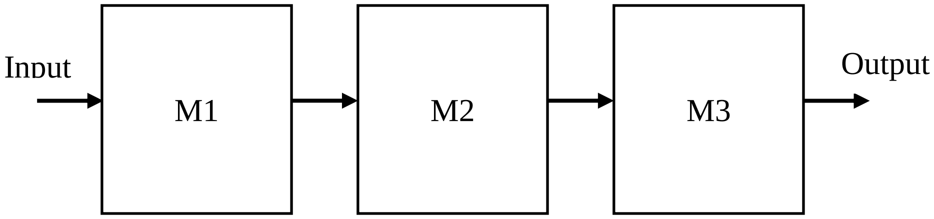


Figure 4-10. Production Line with a Series Arrangement of Machines.

Assume that M1, M2, and M3 machines have the same level of importance (weight factor). By using the following Equation (4.7) (Oechsner et al., 2002), the overall line effectiveness OLE can be calculated:

$$OLE = LEV \times LPR \times LQR \tag{4.7}$$

Where

$LEV = line\ Equipment\ Availability$

$LPR = line\ Performance\ Rate$

$LQR = line\ Quality\ Rate$

LEV, LPE, and LQR are calculated individually and then multiplied to determine OLE as shown in Equation (4.7). In this case, the OLE calculation on those three machines would be as follows:

$$LEV = \frac{EV_{M1} + EV_{M2} + EV_{M3}}{n} \tag{4.8}$$

$$LPR = \frac{PR_{M1} + PR_{M2} + PR_{M3}}{n} \tag{4.9}$$

$$LQR = \frac{QR_{M1} + QR_{M2} + QR_{M3}}{n} \tag{4.10}$$

Where *n*=3 machines in this case.

$EV_M = \ Equipment\ Availability$

$PR_M = Performance\ Rate$

$QR_M = Quality\ Rate$

By using a simple average, the mean value of the different machines will not reflect the real bottleneck machine. However, if the machines have different weight values, which can be any factor that assigns relative importance such as operating times, OLE calculation is more complex.

For the same production line as shown above, if M1, M2, and M3 machines have different weight values, EV_M of the individual machines is calculated and then the result is multiplied by the weight (w) of the corresponding machines. LEV can be obtained as shown in the expression given below. Similarly, the same method would apply for LPR and LQR of the production line as follows:

$$LEV = \frac{(EV_{M1} \times w_1) + (EV_{M2} \times w_2) + (EV_{M3} \times w_3)}{(w_1 + w_2 + w_3)}$$

$$LPR = \frac{(PR_{M1} \times w_1) + (PR_{M2} \times w_2) + (PR_{M3} \times w_3)}{(w_1 + w_2 + w_3)}$$

$$LQR = \frac{(QR_{M1} \times w_1) + (QR_{M2} \times w_2) + (QR_{M3} \times w_3)}{(w_1 + w_2 + w_3)}$$

The three factors would then be multiplied together to get OLE as in Equation (4.7). Determining LQR for the production line through this equation is inaccurate. This is because by going from M1 to M2 and M3, as per the sequence of the process, the LQR value is reduced due to the potential presence of defects in each stage of the production line. Thus, if the machines are connected in series as per Figure (4-10), Nachiappan and Anantharam (2006) propose the following as the appropriate way to determine LEV, LPR, and LQR:

$$LEV = EV_{M1} \times EV_{M2} \times EV_{M3}$$

$LPR = PR_{M1} \times PR_{M2} \times PR_{M3}$

$LQR = QR_{M1} \times QR_{M2} \times QR_{M3}$

In the case of a series configuration, OLE calculations using a straight or a weighted average are both reasonable options, in the case of a comparison of different production lines that are running identical products on identical equipment under identical conditions. However, by using a straight average, the mean of the different machine’s parameter will not reflect the real bottleneck machine and contributing parameter. Therefore, in the case of a weighted average calculation by testing the quality of a product from M1, M2, and M3, the quality is reduced in value because defect can be present in each machine. Consequently, LQR, LEV and LPR calculated by a weighted average will not reflect the actual OLE. Further, OLE calculated by both methods will not be useful for understanding the status of manufacturing to improve the production line. Nachiappan and Anantharam's method of calculating OLE provides good results only if applied to a continuous production line. However, when buffers are displaced between machines, a straight application of LEV, LPR and, LQR would underestimate the actual efficiency of the line (Braglia et al., 2009).

For the second configuration shown in Figure 4-11, consider a series-parallel configuration in which the second stage of the production line is composed of three machines in parallel. These machines in parallel along with the other two machines in series, M1 and M4, are either identical machines or have the same function or have different levels of weights.

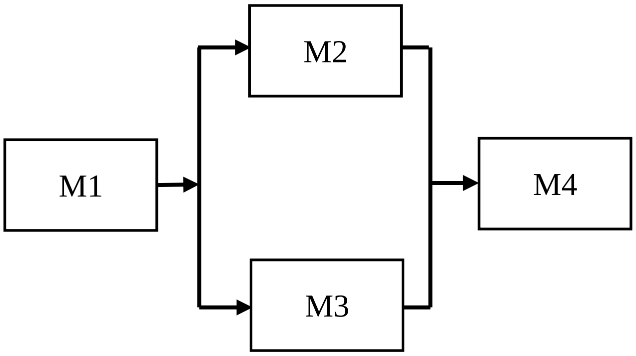


Figure 4-11. Production Line Has Parallel Machines with Other Series Machines.

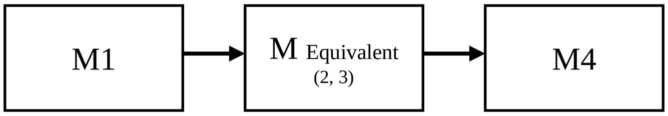


Figure 4-12. Equivalent Machine in Series.

Patchong and Willaeys (2001) proposed replacing the machines in parallel by considering a single equivalent machine as shown in Figure 4-12.

4.5.2 Equipment Availability

In the second configuration (see Figure 4-11, above), Oskar (2017) presented a procedure to calculate the Equivalent Equipment Availability (EV_{eq}), using Mean Time Between Failure (MTBF) and Mean Time to Repair (MTTR), as follows:

$$EV_{eq} = \frac{MTBF_{eq}}{MTBF_{eq} + MTTR_{eq}} \tag{4.11}$$

Where

$$MTBF_{eq} = \frac{1}{\lambda_{eq}}$$

$$MTTR_{eq} = \frac{1}{\mu_{eq}}$$

Where

$\lambda_{eq} = Equivalent\ failure\ rate$

$\mu_{eq} = Equivalent\ repair\ rate$

The average processing rate of the equivalent machine (u_{eq}) shown in Figure 4-12, above is calculated by adding the average processing rate of all individual parallel machines (u_j) or as it follows:

$$u_{eq} = \sum_{j=1}^{n} u_j \tag{4.12}$$

Where

u_{eq} - The average processing rate of the equivalent machine

n - The number of machines in parallel

u_j – The processing rate of individual parallel machine j = {1, 2, 3…. n}

The failure rate of the equivalent machine (λ_{eq}) can be determined using the following (Patchong and Willaeys, 2001):

$$\lambda_{eq} = \frac{\sum_{j=1}^{n} \lambda_j P_{Wj} \ \ \sum_{k=1}^{k=n}(1 - P_{Dk})}{P_W} \tag{4.13}$$

(P_W) is the probability that the equivalent machine is working, which can be calculated using Equation (4.14):

$$P_W = \frac{\sum_{j=1}^{n} u_j P_{Wj}}{u_{eq}} \tag{4.14}$$

(P_{dk}) is the probability that the individual parallel machine is down. The probability that the equivalent machine is down (P_d) can be obtained as follows:

$$P_D = \frac{\sum_{j=1}^{n} u_j P_{Dj}}{u_{eq}} \tag{4.15}$$

To determine the repair rate of the equivalent machine (μ_{eq}), one may use the following:

$$\mu_{eq} = \frac{\sum_{j=1}^{n} \lambda_j P_{Wj} \ \ \sum_{k=1}^{k=n} (1 - P_{Dk})}{P_D} \qquad (4.16)$$

At any time, machine M_j is either working P_{Wj}, down P_{Dj}, or idle P_{Ij}. That can be related as follows:

$$P_{Wj} + P_{Dj} + P_{Ij} = 1 \qquad (4.17)$$

Consequently, Line Availability, LEV, is obtained as follows:

$$LEV = EV_{M1} \times EV_{eq} \times EV_{M4}$$

4.5.3 Performance Rate

Performance rate is one of the three OEE factors that consider performance loss including both slow speed and minor stoppages. The entire production line will be controlled by a machine with a low-performance rate. The minimum performance rate of that machine is taken as the performance rate of the production line using the following Equation(4.18):

$$PR = \frac{(\text{ ICT} \times \text{TP })}{\text{OT}} \qquad (4.18)$$

Where

ICT = Ideal Cycle Time

TP= Total Pieces per Shift by Bottleneck Machine

OT= Operating Time

Ideal Cycle Time is the minimum cycle time that a process can be expected to achieve in optimal circumstances.

4.5.4 Quality Rate

The quality rate considers quality loss, which factors out manufactured pieces that do not meet quality standards, including pieces that would be later reworked. After the completion of the process on only one machine, we would have a univariate parameter. If more than one parameter is measured the parameter is called multivariate (Wang & Du, 2000). The quality rate is calculated as the ratio of good pieces to total manufactured pieces:

$$QR = \frac{\mathrm{GP}}{\mathrm{TP}} \tag{4.19}$$

Where

$$\mathrm{GP} = \text{Good Pieces}$$

$$\mathrm{TP} = \text{Total Pieces}$$

In this case, the LQR calculation on the single production line with n machines connected in series (univariate data), is as follows:

$$LQR = QR_{M1} \times QR_{M2} \times \ldots \times QR_{Mn}$$

However, in the case of multivariate type, Principal Component Analysis (PCA) can be used (Ringner, 2008). Moreover, Jolliffe and Cadima (2016) define PCA as a dimension-reduction tool that can be used to reduce a large set of variables to a small set that still contains most of the information in the large set. While PCA is performed with many dimensions, a data set of two independent variables (X, Y) will make it simple to follow the analysis steps, PCA is applied to determine the principal components as the following steps:

1. The mean for X and Y is simply calculated for n observations:

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}$$

$$\bar{Y} = \frac{\sum_{j=1}^{n} Y_j}{n}$$

2. Find Covariance for both variables (X, Y);

$$Cov(X, X) = Var_X = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}$$

$$Cov(Y, Y) = Var_Y = \frac{\sum_{j=1}^{n}(Y_j - \bar{Y})^2}{n-1}$$

$$Cov_{XY} = \frac{\sum_{i=1,j=1}^{n}(X_i - \bar{X})(Y_j - \bar{Y})}{n-1}$$

3. Covariance values have to be written in the form of a matrix, or as follows:

$$A = \begin{bmatrix} Var_X & Cov_{XY} \\ Cov_{YX} & Var_Y \end{bmatrix}$$

4. To find the eigenvalues of the matrix A (Morosanu, 2019):

   Ax = λx

   (A − λI) x = 0

   Where, I and A matrices have the same order, and $Cov_{YX} = Cov_{XY}$.

   Ax = λx has nonzero solutions for the vector x

   The eigenvalues are those λ for which (A − λI) = 0. Now

   $$(\text{A} - \lambda\text{I}) = \begin{bmatrix} Var_X & Cov_{XY} \\ Cov_{YX} & Var_Y \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} Var_X - \lambda & Cov_{XY} \\ Cov_{YX} & Var_Y - \lambda \end{bmatrix} = 0$$

   Find the matrix determinant:

   $$= (Var_X - \lambda) \times (Var_Y - \lambda) - (Cov_{XY})^2 = 0$$

   $$= \lambda^2 - (Var_X + Var_Y)\lambda + (Var_X \times Var_Y) - (Cov_{XY})^2 = 0$$

The eigenvalues of A are the solutions of the quadratic equation, $\lambda_1 = \mathrm{v}_{\mathrm{e1}}$ and $\lambda_2 = \mathrm{v}_{\mathrm{e2}}$

5. Eigenvectors are calculated as follows:

   By multiplying (λI – A) by $\vec{v} = \begin{bmatrix} x \\ y \end{bmatrix}$, which satisfy $(\lambda\mathrm{I} - \mathrm{A})\vec{v} = 0$, by substituting $\lambda_1 = \mathrm{v}_{\mathrm{e1}}$ as follows:

$$\begin{bmatrix} \mathrm{v}_{\mathrm{e1}} - Var_X & -Cov_{XY} \\ -Cov_{XY} & \mathrm{v}_{\mathrm{e1}} - Var_Y \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} (\mathrm{v}_{\mathrm{e1}} - Var_X) \times x & (-Cov_{XY}) \times y \\ (-Cov_{XY}) \times x & (\mathrm{v}_{\mathrm{e1}} - Var_Y) \times y \end{bmatrix} = 0$$

$$(\mathrm{v}_{\mathrm{e1}} - Var_X) \times x - (Cov_{XY}) \times y = 0$$

$$(\mathrm{v}_{\mathrm{e1}} - Var_Y) \times y - (Cov_{XY}) \times x = 0$$

   Using any one of the equations, *x* can be written in terms of *y*, to obtain the Principal Component (*PC1*) for both (*x*, *y*) values:

$$PC1_X = \frac{x}{\sqrt{x^2 + y^2}}$$

$$PC1_Y = \frac{y}{\sqrt{x^2 + y^2}}$$

   Also, substituting the other eigenvalue $\lambda_2 = \mathrm{v}_{\mathrm{e2}}$

$$\begin{bmatrix} (\mathrm{v}_{\mathrm{e2}} - Var_X) \times x & (-Cov_{XY}) \times y \\ (-Cov_{XY}) \times x & (\mathrm{v}_{\mathrm{e2}} - Var_Y) \times y \end{bmatrix} = 0$$

$$(\mathrm{v}_{\mathrm{e2}} - Var_X) \times x - (Cov_{XY}) \times y = 0$$

$$(\mathrm{v}_{\mathrm{e2}} - Var_Y) \times y - (Cov_{XY}) \times x = 0$$

   Using any one of the equations, *x* can be written in terms of *y* to obtain the Principal Component (*PC2*) for both (*x*, *y*) values:

$$PC2_X = \frac{x}{\sqrt{x^2 + y^2}}$$

$$PC2_Y = \frac{y}{\sqrt{x^2 + y^2}}$$

$$\begin{array}{c} X \\ Y \end{array} \begin{bmatrix} PC1_X & PC2_X \\ PC1_Y & PC2_Y \end{bmatrix}$$

6. To determine Proportion of Conformance of Principal Components:

$$P_{PCi} = pr(Z_{1PCi} \leq Z \leq Z_{2PCi})$$

$$Z_{2PCi} = \left(\frac{USL_{PC_i} - T_{PC_i}}{\sigma}\right)$$

$$Z_{1PCi} = \left(\frac{LSL_{PC_i} - T_{PC_i}}{\sigma}\right)$$

Where,

P_{PCi} = Proportion of Conformance of Principal Components

$\sigma = \sqrt{\lambda}$, The square root of Eigenvalue

USL_{PC_i}= Upper Specification Limit for Principal Components

LSL_{PC_i}= Lower Specification Limit for Principal Components

T_{PC_i} = Target values for Principal Components

7. The next step is to determine the quality rate which is calculated using Equation (4.20):

$$QR_i = \left(\prod_{i=1}^{m} P_{PCi}{}^{\frac{1}{m}}\right) \tag{4.20}$$

Where,

m = Number of Principal Components

QR_i = Quality rate of the i^{th} machine *i* = [1, 2, 3...n]

The model of determining the production specifications of Principal Components and their Target values (T_{PC_i}) and the transpose matrix (U_i) as used by Wang & Du, (2000) are as follows:

$$LSL_{PC_i} = U_i\, LSL, \qquad USL_{PC_i} = U_i\, USL \qquad T_{PC_i} = U_i\, T$$

The transpose matrix, U_i is a new matrix whose rows are the columns of the original matrix A and the columns of the new matrix are the rows of the matrix A. PCA is calculated from the collected data of a process and can be used to evaluate the Quality rate for the production line. PCA is an important tool for applications involving multivariate process data, especially when the product quality should be measured in terms of several characteristics.

In the second configuration of the production line, as shown in Figure 4-13, parallel machines (M2a and M2b) along with the other two machines, M1 and M3, PCA is used to convert the parallel machines to an equivalent machine. The Quality rate of the equivalent machine (QR_{eq}) is obtained using Equation (4.21):

$$QR_{eq} = 1 - \frac{(P_{c1} \times P_{nc1}) + (P_{C2} \times P_{nc2})}{P_{c1} + P_{c2}} \tag{4.21}$$

Where,

P_{c1} = Proportion of Conformance of Machine M2a

P_{nc1} = Proportion of Non-conformance of Machine M2a

P_{c2} = Proportion of Conformance of Machine M2b

P_{nc2} = Proportion of Non-conformance of Machine M2b

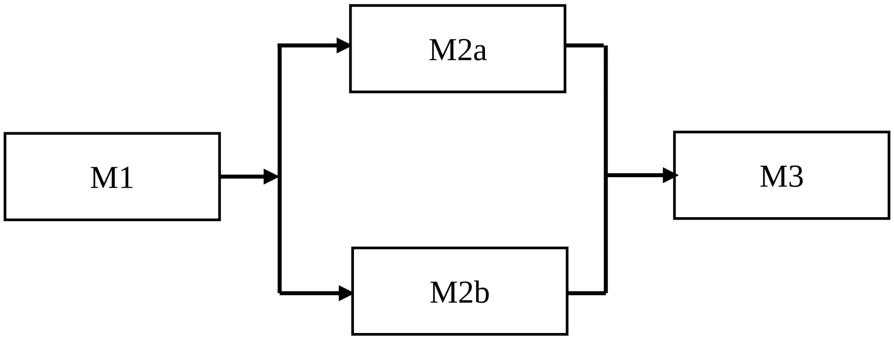


Figure 4-13. Parallel Machines with Other Series Machines.

As per Patchong and Willaeys (2001), all the parallel machines are considered as a single equivalent machine. The Line quality rate, LQR is calculated using the following Equation:

$$LQR = QR_{M1} \times QR_{eqM2ab} \times QR_{M3}$$

So, the OLE calculation of the second configuration using Equation (4.15):

$$OLE = LEV \times LPE \times LQR \qquad (4.15)$$

The PCA is performed to reduce the number of variables to make the data easier to analyze. Therefore, several Principal Components will be chosen that account for a high percentage of the total variance. Therefore, the decision-makers would be able to decide which components to analyze to improve product specifications. They would have enough components to explain at least 90% of the variation in the data.

Besides, the PCA technique can significantly contribute to improving maintenance planning to maintain high machine performance. The integration of the PCA technique and OLE can facilitate decision-making related to improving product quality and planning for maintenance. In a production line, there is a positive correlation between the quality of a product and maintenance. Improving the production line to where the production of defective parts is reduced will lead to a decrease in rework and returned products.

4.5.5 Illustrated Example.

To calculate OLE for three machines connected in series, we chose a shaft (spindle) used for the roller (ROLLER PSV/1-FHD- Ø 63 N). The steel bar for this shaft machined, as shown in Figure 4.14.

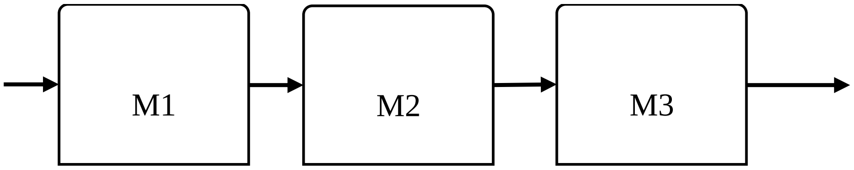


Figure 4-14. Machines Connected in Series.

M1 PLC Based Cutting Bandsaw.

M2 CNC Polygon Turning (for flat ends).

M3 CNC Turning Machine (for groove).

4.5.5.1 Equipment Availability Calculation.

For equipment availability calculation, we assume that the downtime of the machines in the line for one month. Therefore, MTBF and MTTR are calculated for each machine from their total downtime, total repair time and the number of times the machine was down. From MTBF and MTTR, the equipment availability of the machines is calculated by using Equation (4.11). For machine M1, the equipment availability is calculated using the data given in Table 4-5 below.

$$EV_1 = \frac{MTBF}{MTBF + MTTR} \tag{4.11}$$

$$MTBF = \frac{175}{3} = 58.33$$

$$MTTR = \frac{5.05}{3} = 1.68$$

Therefore, $EV_1 = \frac{58.33}{58.33+1.683} = 0.971$

Likewise, the *EV* for the other machines is calculated and tabulated in Table 4-5. By multiplying individual machine availabilities from Table 4-5, the Line Equipment Availability can be obtained, *LEV* =0.8967.

Table 4-5: Equipment Availability Data.

Machines	**Total time of operation hr**	**Number of Occurrences**	**Total Repair Time hr**	**MTBF**	**MTTR**	**EV**
M1	175	3	5.05	58.33	1.68	0.971
M2	172.64	5	7.36	34.52	1.47	0.959
M3	173.5	4	6.5	43.37	1.625	0.963

4.5.5.2 Performance Rate Calculation.

A machine with a minimum-performance rate will control the production line. Therefore, Planned Production Time= Scheduled Time- Break Time = 480 - 60 = 420 minutes, and Operating Time,(OT) = Planned Production Time- Breakdown= 420 - 60 = 360 minutes. The total number of products produced by a bottleneck machine (TP) is 150 per shift. The performance rate can be obtained by using the following Equation (4.18):

$$PR = \frac{(\text{ ICT} \times \text{TP })}{\text{OT}} \qquad (4.18)$$

Where,

ICT = Ideal Cycle Time

TP= Total Pieces per Shift by Bottleneck Machine

From Table 4-6 values and using Equation (4.18) to calculate performance rate for M1,

$$PR = \frac{(\,1.25 \times 150)}{360} = 0.520$$

Similarly, the performance rate for the other machines is also calculated and tabulated in Table 4-6. After the performance rate is calculated, the machine with the minimum-performance rate is chosen as Line Performance Rate *LPR*= 0.445.

Table 4-6: Performance Rate of Machines.

Machine	Ideal Cycle Time (minutes)	The actual output of the bottleneck machine	Performance rate
M1	1.25	150	0.520
M2	1.07	150	0.445
M3	2.1	150	0.875

4.5.5.3 Quality Rate Calculation.

To illustrate the PCA technique, the quality rate is analyzed in a production line. According to the Rulmeca Company catalog (Pages 96-97), we generated a random number for all the shaft quality characteristics for all three machines (Rulmeca, 2019). The quality characteristics of the products have acceptable level of variation and they remain within their tolerance limits. In machine M1, after cutting a steel bar, Length (A) is measured as one quality characteristic. Table 4-7 shows these measurements.

Table 4-7: Quality Characteristics Machine M1.

Sample No.	1	2	3	4	5	6	7	8	9	10
A (mm)	525.93	522.60	529.46	523.03	528.70	526.77	524.18	526.33	525.67	529.38

USL=529.46, LSL=522.6, Target value =526.2

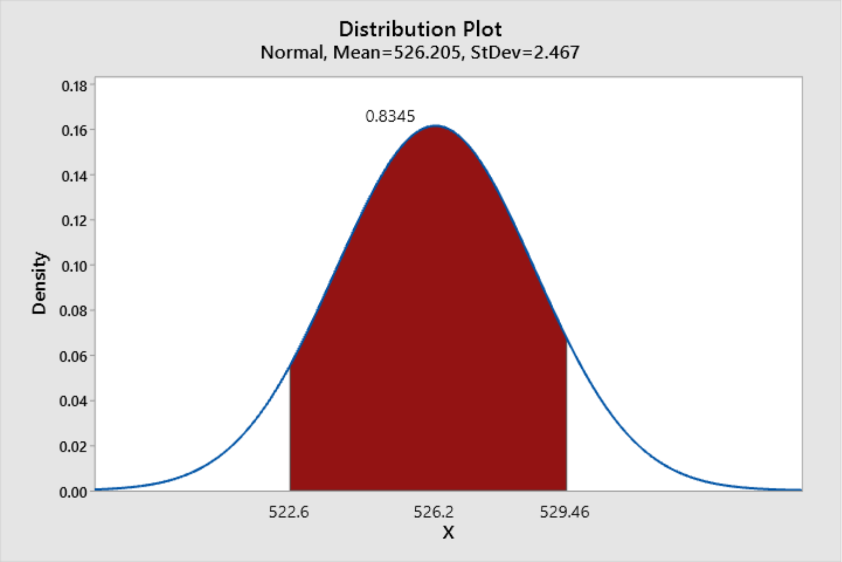


Figure 4-15. Normal Distribution Curve.

The quality rate (QR_1) is obtained from the proportion of conformance by MINITAB 19 software, drawing the normal distribution curve as shown in Figure 4-15. USL, LSL, Target value and standard deviation were used to obtain the quality rate of this machine (QR_1= **0.8345**).

In the machine M2, Figure 4-16 shows Roller PSV Measurements. Four quality characteristics of roller shaft product are measured for 10 samples as listed in Table 4-8, assuming that the process is in control.

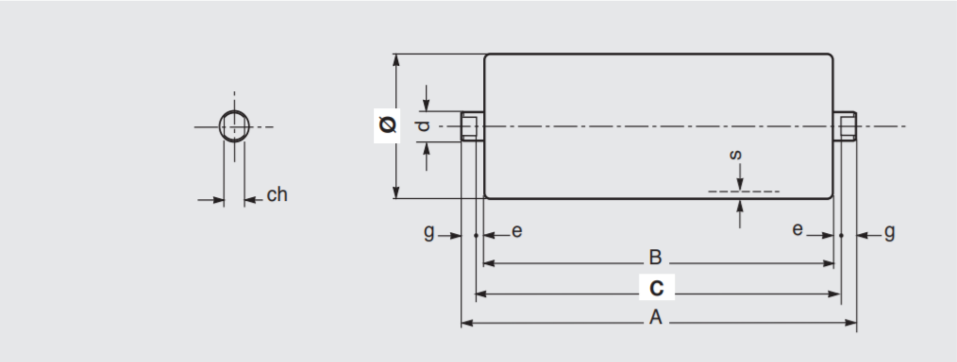


Figure 4-16. Roller PSV Measurements (Rulmeca, 2019, Pages 96-97).

Table 4-8: Quality Characteristics for M2.

Sample No	Diameter (d) mm	Length (C) mm	Dimension (ch) mm	Dimension (g) mm
1	19.90	509.25	13.92	8.95
2	20.09	505.28	13.93	9.03
3	19.87	506.05	13.98	8.95
4	20.02	510.58	14.08	8.96
5	20.11	510.18	14.09	9.03
6	20.04	504.77	13.97	9.04
7	19.99	509.75	13.99	8.95
8	19.86	511.06	14.07	8.98
9	20.07	505.01	14.04	8.98
10	20.07	509.22	13.99	8.99

Table 4-9: The Specifications and Target Values for M2.

Quality Characteristic	**LSL**	**USL**	**Target**
d	19.86	20.11	20.00
C	504.77	511.06	508.115
ch	13.90	14.11	14
g	8.93	9.07	9

The Principal Components loading matrix calculated from the above set of observations is shown in Table 4-8. Therefore, it is calculated using MINITAB 19 software and the results are shown in Table 4-10.

Table 4-10: Principal Components Loading Matrix for M2.

	PC1	**PC2**	**PC3**	**PC4**
Characteristic 1	0.009	-0.942	-0.241	-0.235
Characteristic 2	-1.000	-0.007	-0.014	0.003
Characteristic 3	-0.012	-0.238	0.970	-0.041
Characteristic 4	0.005	-0.238	-0.017	0.971

	$\boldsymbol{\lambda_1}$	$\boldsymbol{\lambda_2}$	$\boldsymbol{\lambda_3}$	$\boldsymbol{\lambda_4}$
Eigenvalue	6.3713	0.0090	0.0024	0.0006

To determine the production specifications of Principal Components and their Target values and the transpose matrix as shown below:

$LSL_{PC_1} = U_1\, LSL$

$$LSL_{PC1} = |0.009 \quad -1.000 \quad -0.012 \quad 0.005| \times \begin{pmatrix} 19.86 \\ 504.77 \\ 13.90 \\ 8.93 \end{pmatrix}$$

$$LSL_{PC1} = |0.17874 - 504.77 - 0.1668 + 0.04465| = 504.71341$$

$USL_{PC_1} = U_1\, USL$

$$USL_{PC1} = |0.009 \quad -1.000 \quad -0.012 \quad 0.005| \times \begin{pmatrix} 20.11 \\ 511.06 \\ 14.11 \\ 9.07 \end{pmatrix}$$

$$USL_{PC1} = |0.18199 - 511.06 - 0.16932 + 0.04535| = 511.00198$$

$T_{PC_1} = U_1\, T$

$$T_{PC_i} = |0.009 \quad -1.000 \quad -0.012 \quad 0.005| \times \begin{pmatrix} 20.00 \\ 508.115 \\ 14 \\ 9 \end{pmatrix}$$

$$T_{PC_i} = |0.18 - 508.115 - 0.168 + 0.045| = 507.058$$

The same procedure is used to find the corresponding values for PC2, PC3, and PC4. The proportion of conformance of principal components are calculated and tabulated in Table 4-11 (see Appendix J).

Table 4-11: Proportion of Conformance for M2.

	PC1	**PC2**	**PC3**	**PC4**
LSL_{PC_i}	504.71341	27.67556	1.47815	4.94834
USL_{PC_i}	511.00198	28.03582	1.53116	5.03579
T_{PC_i}	507.058	27.870805	1.49339	4.989345
Proportion of Conformance	0.75656	0.938003	0.379756	0.923161

Then, the next step is to determine the quality rate of M2 which is calculated using this Equation (4.20):

$$QR_i = \left(\prod_{i=1}^{m} P_{PCi}^{\frac{1}{m}} \right) \qquad (4.20)$$

$$QR_2 = (0.75656 \times 0.938003 \times 0.379756 \times 0.923161)^{\frac{1}{4}} = 0.706248$$

Finally, in machine M3, the groove for both shaft ends are processed. So, two quality characteristics are measured. The measurements are tabulated in Table 4-12.

Table 4-12: Quality Characteristics for M3.

Sample No	**Width-1 mm**	**Depth-1 mm**
1	1.425	2.090
2	1.429	2.078
3	1.429	2.090
4	1.427	2.067
5	1.428	2.077

6	1.422	2.072
7	1.429	2.085
8	1.427	2.086
9	1.419	2.077
10	1.423	2.066

Table 4-13: The Specifications and Target Values for M3.

Quality Characteristic	**LSL**	**USL**	**Target**
Width-1	1.419	1.429	1.4258
Depth-1	2.066	2.09	2.0788

The principal components loading matrix calculated and the values are tabulated in Table 4-14.

Table 4-14: Principal Components Loading Matrix for M3.

	PC1	**PC2**
Characteristic 1	0.175	0.984
Characteristic 2	0.984	-0.175

	λ_1	λ_2
Eigenvalue	0.000079662	0.000009805

The(LSL_{PC_i},USL_{PC_i}, T_{PC_i}) and the proportion of conformance of principal components are calculated and tabulated in Table 4-15 (see Appendix J).

Table 4-15: Proportion of Conformance for M3.

	PC1	**PC2**
LSL_{PC_i}	2.281269	1.034746
USL_{PC_i}	2.306635	1.040386
T_{PC_i}	2.2950542	1.0391972
Proportion of Conformance	0.839694	0.566899

The next step is to determine the quality rate of M3 which is calculated using this Equation (4.20):

$$QR_i = \left(\prod_{i=1}^{m} P_{PCi} \right)^{\frac{1}{m}} \qquad (4.20)$$

$$QR_3 = (0.839694 \times 0.566899)^{\frac{1}{2}} = \mathbf{0.6899}$$

Machine	**EV**	**PR**	**QR**
M1	0.971	0.520	0.8345
M2	0.959	0.445	0.706248
M3	0.963	0.875	0.6899

OLE calculation

- The line equipment availability can be obtained by multiplying Equipment Availability of all machines: $LEV = EV_{M1} \times EV_{M2} \times EV_{M3} = 0.971 \times$ 0.959 ×0.963=0.8967.
- The line performance rate is obtained by taking the minimum of performance rate of all machines: LPR =0.445
- The Line quality rate, LQR can be obtained by multiplying the quality rate of all machines: $LQR = QR_{M1} \times QR_{M2} \times QR_{M3} = 0.8345 \times 0.706248 \times 0.6899$ =0.4066
- So, the OLE is calculated as shown below:

$$OLE = LEV \times LPE \times LQR$$

$$OLE = 0.8967 \times 0.445 \times 0.4066 = 0.1622 = 16.22\%$$

The example results show that an OLE calculation is very effective to identify the production line problems and what improvements should be made to increase the effectiveness of the product line. The PCA is used to convert multivariate quality characteristics measured in one machine into a univariate form.

The next chapter is on discussing a case study conducted in one of Canada’s manufacturers of heavy-duty equipment for quarries and mining applications. Quantitative method has been used to test hypotheses by using statistical analysis and to assess the effect of STTPM implementation on MP.

CHAPTER 5 PILOT CASE STUDY

5.1 Introduction

This chapter assessing how short-term TPM implementing in SMEs by presenting the five-stage model. A pilot case was conducted after visiting Rulmeca Canada Limited and discussing it with the company's administration. Production Lines (PL) were selected on the shop floor, which is considered as a key production area to implement STTPM. The production lines data were provided from daily company records. The company's production lines data were statistically analyzed. The statistical analysis presented in the study was obtained from data collected from a real manufacturing environment, and detailed personal observations during site visits. The data collected from daily production lines included production, downtime, cycle time, and defects. There was a case study using production line dataset that was collected to investigate if the STTPM approach can impact manufacturing performance.

The production lines chosen for the study were: (a) Celoria FM650. CNC referred to as PL1, (b) Doosan TT1800SY. CNC referred to as PL2, (c) Borsatto P180/4U.CN. CNC referred to as PL3, and (d) Bardons and Oliver RH900 referred to as PL4. The machines were selected based on the criticality of high breakdown and maintenance costs. The study was performed to compare each production line performance (Production Rate ($P_r R$), Equipment Availability (EV) and Cycle Time (CT)) before and after STTPM implementation using t-tests analysis to see how their means compare when implementing the STTPM approach and if it is significant or not.

The study was performed using the Minitab 19 software to identify the effect of STTPM on MP. The paired t-test analysis was performed to identify the effect of STTPM on manufacturing performance. The dataset collected from daily operations records for each variable according to its unit during February over May of 2016 (Appendix D). Daily operation data was used to test these hypotheses. Figure 5-1 shows the STTPM approach with hypotheses. The data was derived from the ratio to implement STTPM stages that were obtained during the time of the study. The dataset from the daily production was measured by the following methods:

- *Production Rate*: the number of products manufactured in the production line for each shift.
- *Equipment Availability*: the percentage of time during which an equipment is available to run.
- *Cycle Time*: the total time needed to process products divided by the number of products produced perf shift. Therefore, cycle time is the average amount of time to produce one unit. It includes processing time, set-up time, break times, and breakdown.

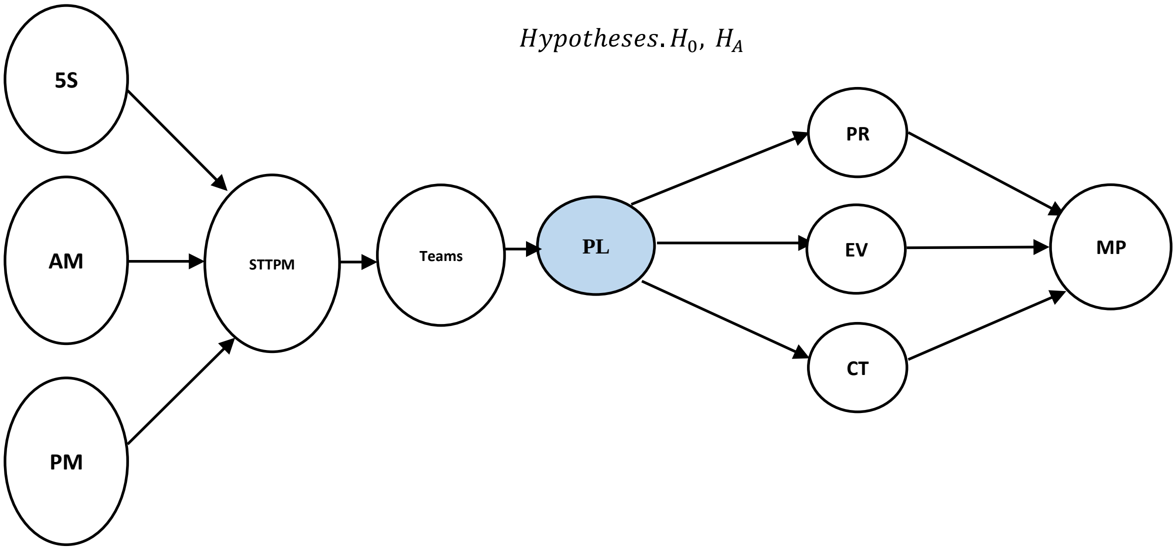


Figure 5-1. The STTPM Approach with Hypotheses.

5.2 Profile of the company

Rulmeca Canada Limited is one of Canada's manufacturers of heavy-duty equipment for quarries and mining applications. The Company is an SME industry located in Wallaceburg, Ontario. They have been dealing with manufacturing all types of rollers, idlers, and motorized pulleys for heavy-duty conveyors for quarries and mining applications for the last 35 years. The Company was selected to establish if the STTPM approach had an impact to facilitate the successful TPM implementation and if it had directly contributed to increasing the production rate, increasing equipment availability and decreasing cycle time. Rulli Rulmeca is the headquarter and mother company of Rulmeca Group located in Bergamo, Italy. The study examined two production lines that were part of a larger supplier group of rollers, idlers and motorized pulleys consisting of twenty-two production and sales companies all around the globe as shown in Figure 5-2. In this study, the STTPM approach has been applied on the shop floor of the plant. After establishing a framework for STTPM implementation and achieving the results in each production line, the plant could start looking forward to implementing full TPM.

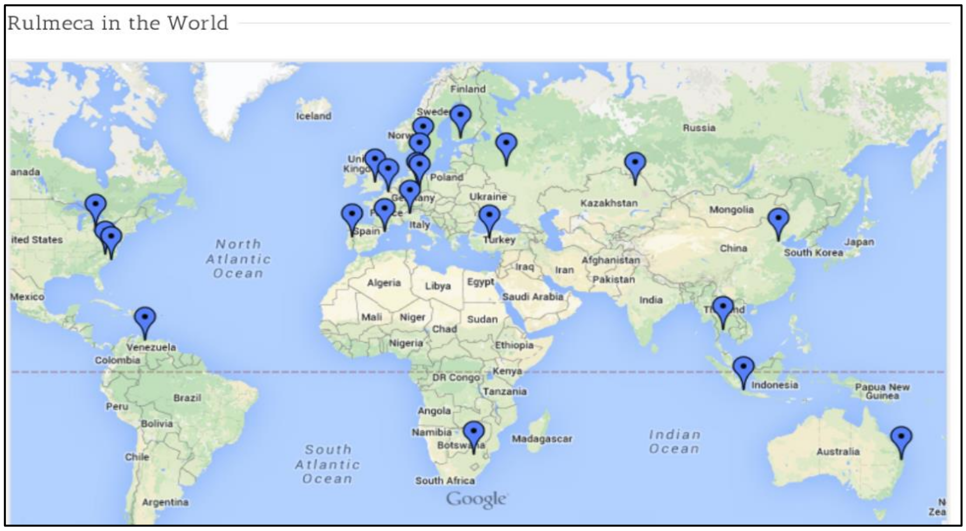


Figure 5-2. Map of Rulmeca in the World (www.rulmeca.ca/group).

In the course of this case study, this is a summary of what the researcher has done: Design data collection sheet; in the case study, the data collection sheet was developed. It covers information regarding machines and their production (i.e., the setup time, defect parts, waiting time for the repair, and comments) (See Appendix G). The on-site visits included giving presentations on various aspects of the TPM approach we were conducting, touring production and maintenance facilities as well as discussions with the production manager (STTPM supervisor). Also, there were meetings every two weeks, to discuss and evaluate the TPM implementation. The focus of these meetings was on 5S implementation and short-term TPM approach, training procedures and OEE assessment. The researcher communicated the 5S and lean manufacturing training recommendations, and also, added the STTPM approach related forms and guidelines. The researcher recommended some material training for the TPM team members that would help to implement the STTPM approach. The researcher could easily see the effect of the training after it was complete. The senior management permitted us to use data collected during the TPM implementation for production lines (See Appendix I).

5.3 Description of the Production Lines

As stated in the previous section, the company selected for this study manufactures heavy-duty equipment for quarries and mining applications. Table 5-1 shows the first two production lines (PL1 and PL2) both of which produce shafts with different specifications and why we will treat them as one production line (PL1, 2). The next two production lines (PL3 and PL4) manufacture roller shells with different specifications as shown in Table 5-2. Multi-products with specific descriptions are produced separately in the production lines, and then they are assembled as a final product. The overview of the production lines is shown in Figure 5-3.

Table 5-1: The Descriptions of the Production Lines (PL1, 2).

Production Lines	Name	Shaft Diameter Capacity	Maximum Length	Length Bar Feed
PL1,2	Celoria FM650	(25-45) mm	1.7 m	6 m
	Doosan TT1800SY	(25-67) mm	1.8 m	6 m

Table 5-2: The Descriptions of The Production Lines (PL3, 4).

Production Lines	Name	Tube Diameter Capacity	Maximum Length	Maximum Wall Thickness
PL3,4	Borsatto P180/4U.CN	(76-177) mm	2.3 m	6.35 mm
	Bardons and Oliver RH900	(63-229) mm	3 m	32 mm

5.4 Data Analysis Method for STTPM Approach

Quantitative methods deal with numbers and anything measurable in a systematic way of investigation of phenomena. In this approach, the collected data needs to be analyzed by numerical means. In contrast, the qualitative method examines the perceptions of human and social issues to gain insight (Thinagaran, 2014). In this study, the quantitative method was found to be more appropriate since it contains operational data from the production line. Implementation of STTPM as an integral part of the TPM approach can be measured by the results associated with performing a manufacturing performance assessment of the production line process. Therefore, the STTPM approach with hypotheses in Figure 5-1 is to support the objectives of the study, which was to determine whether the STTPM approach, based on two TPM pillars can minimize losses in the production process and have a positive impact on Manufacturing Performance (MP). The study compared the production lines using t-test analysis to identify the effect of STTPM on manufacturing performance.

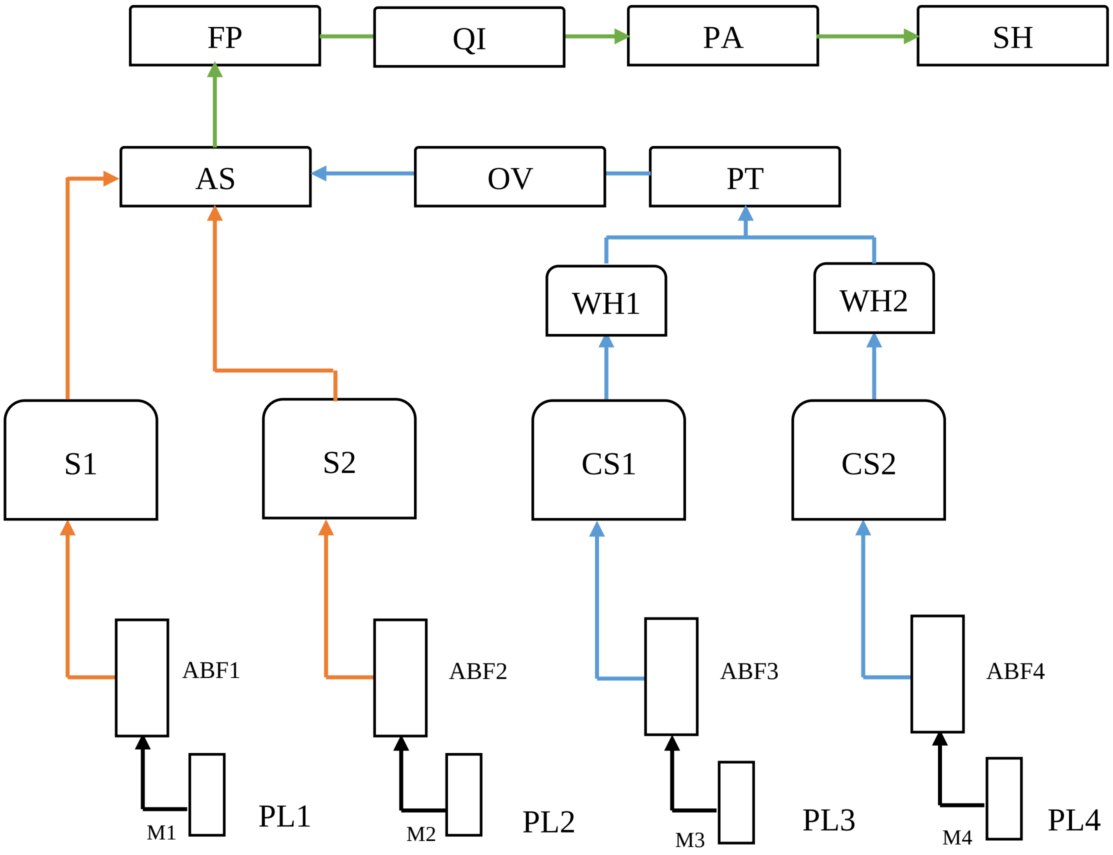


Figure 5-3. The Outline of the Production Lines.

PL1, PL2, PL3, PL4 : Production Lines
M1, M2, M3, M4 : Materials
ABF1, ABF2, ABF3, ABF4 : Automatic Bar Feed
CS1, CS2 : Cut Shell
S1, S2 : Shaft
WH1, WH2 : Welding Housing
PT : Paint

OV : Oven
AS : Assembly
FP : Final Product
QI : Quality Inspection
PA : Package
SH : Shipping

5.5 The t-test Analysis

Allen (2006) stated that paired t-testing is relevant when there is a natural pairing between observations. Therefore, when two samples are involved, and the values for each sample collected from the same individuals, then a paired t-test may be an appropriate statistic to use. He also emphasized that paired t-testing usually offers higher statistical power but is only relevant if there is a natural pairing between observations at different levels.

Since the sample data obtained from the same machines and the population standard deviation is unknown, the z-test was not considered. Even though the sample size is over 30, the t-distribution and z-distribution look very similar. Because of these factors, we will use the paired samples t-test. A paired t-test used to test the hypotheses. If there is a difference in the performance of the production line before and after implementing the STTPM approach; therefore, the null hypothesis is that the difference is zero, and the alternative hypothesis is not zero. The level of significance $\alpha = 0.05$ is used.

5.5.1 Procedure for a Paired t-test

Let $\boldsymbol{x}$ = test score before the STTPM implementation, $\boldsymbol{y}$ = test score after the STTPM implementation for each production line. To test the null hypothesis that the true mean difference is zero, the procedure is as follows:

1. Calculate the difference $(\boldsymbol{d_i} = \boldsymbol{y_i} - \boldsymbol{x_i})$ between the two observations on each pair.
2. Calculate the mean difference, $\overline{\boldsymbol{d}}$.

3. Calculate the standard deviation of the differences, $\boldsymbol{S_d}$, and use this to calculate the standard error of the mean difference, $\boldsymbol{SE(\bar{d})} = \frac{\boldsymbol{S_d}}{\sqrt{\boldsymbol{n}}}$
4. Calculate the t-statistic, which is given by $\mathbf{T} = \frac{\bar{\boldsymbol{d}}}{\boldsymbol{SE(\bar{d})}}$. Under the null hypothesis, this statistic follows a t-distribution with $\boldsymbol{n-1}$ degrees of freedom.
5. Use the table of the t-distribution to compare the value of $\mathbf{T}$ to the $\boldsymbol{t_{n-1,\propto}}$ distribution, (see Appendix E).

The paired t-tests were conducted on each production line separately with the following hypotheses:

- ***Production Rate***

H_0 : There is no significant difference in the production rate produced before and after the implementation of STTPM (STTPM implementation has no positive effect).

H_A : There is a significant difference in the production rate produced before and after the implementation of STTPM (STTPM implementation has a positive effect). The mathematical representation of the null and alternative hypotheses is defined below:

$H_0 : \mu d = 0$

$H_A : \mu d < 0$

- ***Equipment Availability***

H_0 : There is no significant difference in the equipment availability before and after the implementation of STTPM (STTPM implementation has no positive effect).

H_A : There is a significant difference in the equipment availability before and after the implementation of STTPM (STTPM implementation has a positive effect). The mathematical representation of the null and alternative hypotheses is defined below:

$H_0 : \mu d = 0$

$H_A : \mu d < 0$

- ***Cycle Time***

H_0 : There is no significant difference in the C before and after the implementation of STTPM (STTPM implementation has no negative effect).

H_A : There is a significant difference in the cycle time before and after the implementation of STTPM (STTPM implementation has a negative effect). The mathematical representation of the null and alternative hypotheses is defined below:

$H_0 : \mu d = 0$

$H_A : \mu d > 0$

5.5.2 OEE Assessment

According to Ahmad et al., (2018) OEE is a metric for the evaluation of equipment effectiveness and often used as a driver for improving equipment performance. OEE is a metric to monitor and assess the effectiveness of equipment, operation or the manufacturing process. As indicated in the STTPM framework, OEE was the tool to assess the success of STTPM implementation. The overall goal of STTPM is to raise overall equipment effectiveness. OEE is the product of the equipment availability rate, performance rate and quality rate (Nakajima, 1989). The paired t-test analysis was performed using Minitab 19 software to identify the effect of STTPM on OEE. The same data set collected from daily operations was used to test these hypotheses.

H_0 : There is no significant difference in OEE before and after the implementation of STTPM (STTPM implementation has no positive effect).

H_A : There is a significant difference in OEE before and after the implementation of STTPM (STTPM implementation has a positive effect). The mathematical representations of the null and alternative hypotheses are defined below:

$H_0 : \mu d = 0$

$H_A : \mu d < 0$

In the next chapter, we will present analyses of the different results for Production Lines (PL) selected on the shop floor and is considered as key production area (s) to implement the STTPM approaches. The hypotheses' tests were conducted to assess the effect of STTPM approach on Production Rate, Equipment Availability, Cycle Time and Overall Equipment Effectiveness.

CHAPTER 6 RESULTS AND ANALYSIS

6.1 Introduction

This chapter presents the data and statistical analysis for the t-test. The paired t-test analysis is performed to identify the effect of STTPM implementation on manufacturing performance. The data for the production line was demonstrated in the production rate (P_rR), equipment availability (EV), and cycle time (CT) metrics. This is followed by the paired t-test analysis for OEE and OEE calculation and contributions.

6.2 The t-test analysis for PL 1, 2

This section consists of an analysis of the manufacturing performance variables (P_rR, EV & CT) before and after STTPM implementation using paired t-tests analysis to see how their means compare when implementing the STTPM approach. The paired t-test analysis was performed using Minitab 19 software. The data set collected from daily operations for February over May of 2016 was used to test these hypotheses. In a paired sample t-test, the observations are defined as the differences between two sets of values, and each assumption refers to these differences, not the original data values. The paired sample t-test has four main assumptions:

- The dependent variable must be continuous (production rate, equipment availability & cycle time) (interval/ratio).
- The observations are independent of one another (Time 1, Time 2).
- The dependent variable should be approximately normally distributed.
- The dependent variable should not contain any outliers.

For (P_rR), daily operation data were produced from the same machines, in this case, the PL1, 2 do produce continuous data so it has met that assumption. It also needs independent observations, so for each time it needs to have two values and the values are paired, also it has met that assumption. The differences between the dependent variables should be approximately normally distributed and should not contain any outliers. From Figure 6-1, the histogram is not a perfect Normal distribution; but generally, the bell-shaped curve can be noticed in this histogram. Figure 6-2 presents the Probability plot of differences where the points are close or on a straight line. So, we would suggest that these data are normally distributed, and the assumption of normality is satisfied. Figure 6-3 shows the boxplots of differences. It is noticed that there are no points plotted above the top whisker or below the bottom whisker, so there are no outliers in this distribution. For other manufacturing performance variables EV and CT, see Appendix F.

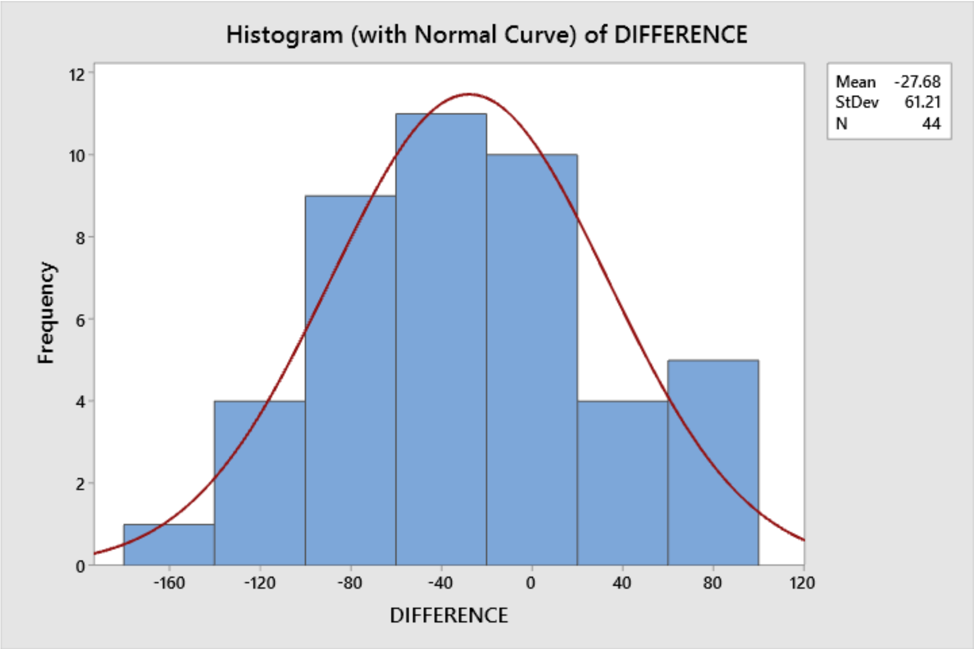


Figure 6-1. Plot Histogram.

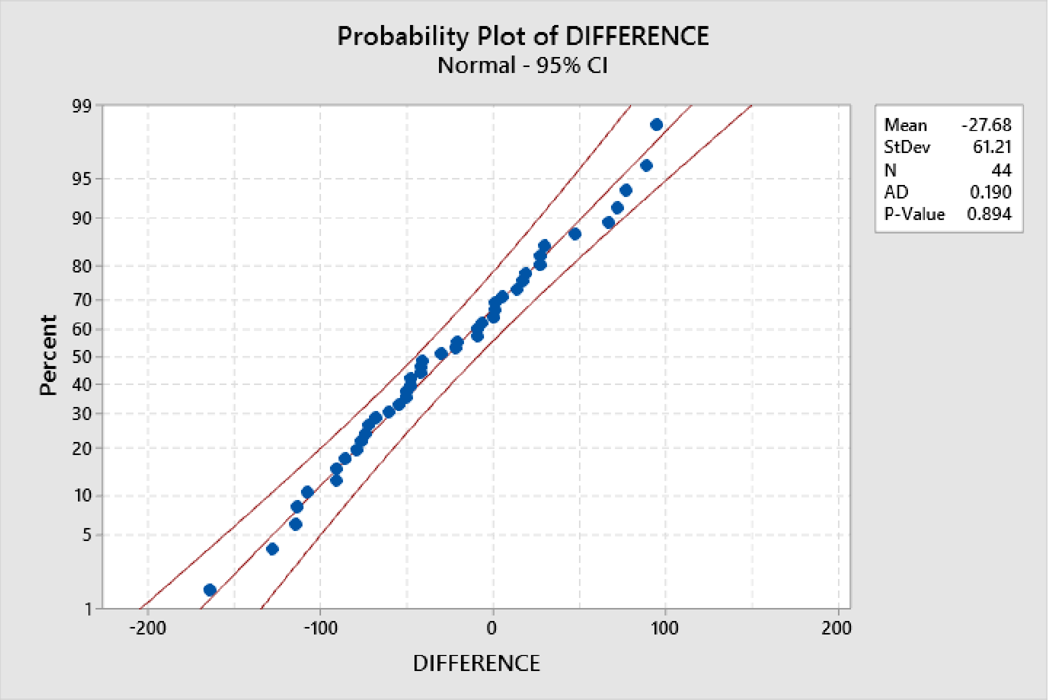


Figure 6-2. Probability Plot of Differences.

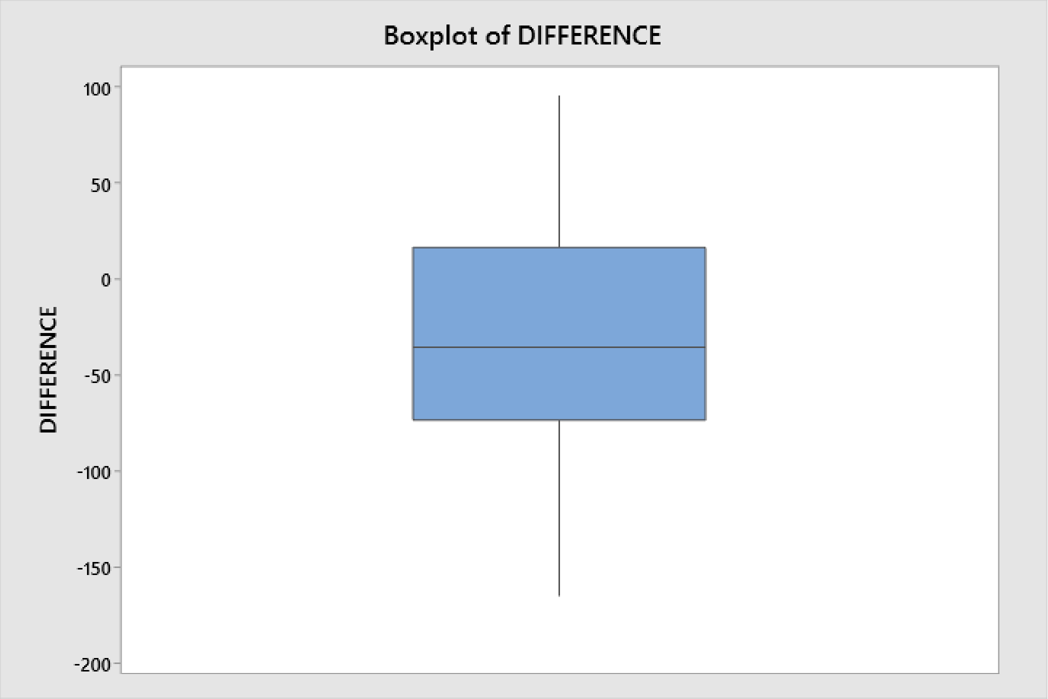


Figure 6-3. Plot Boxplot.

6.2.1 Production Rate

In Table 6-1 and Table 6-2, the results showed production rate made a larger amount after STTPM implementation (mean= 150.7955, StDev = 56.688) than before (mean = 123.1136, StDev = 62.968). The critical value for *t* distribution, at the significance level α = 0.05, and 43 degrees of freedom is: t = -1.681, and the computed value is: T-statistic = -3.00. The null hypothesis of no significant difference in the production rate produced before and after the implementation of STTPM can be rejected. The alternative hypothesis is that there is a significant difference in the production rate produced before and after the implementation of STTPM.

Table 6-1: Paired Statistics Results for Production Rate Before and After STTPM Implementation.

Sample	N	Mean	StDev	SE Mean
P_rR _BEFORE_STTPM	44	123.11	62.97	9.49
P_rR _AFTER_STTPM	44	150.80	56.69	8.55

Table 6-2: t-test Results Production Rate Before and After STTPM Implementation.

Mean	StDev	SE Mean	95% Upper Bound for µ_difference
-27.68	61.21	9.23	-12.17

µ_difference: mean of (P_rR _BEFORE_STTPM - P_rR _AFTER_STTPM)

Null hypothesis	H_0: µ_difference = 0
Alternative hypothesis	H_1: µ_difference < 0

T-Value	**P-Value**
-3.00	0.002

6.2.2 **Equipment Availability**

The results show that equipment was more available after STTPM implementation (mean= 0.8411, StDev = 0.17263) than before (mean = 0.7502, StDev = 0.19355). The critical value for t distribution, at the significance level $\alpha = 0.05$ and 43 degrees of freedom is $t = -1.681$, and the computed value is T-statistic = -2.10. Paired t-test found this difference to be significant, $(T < t)$ lower-tailed test. The null hypothesis can be rejected, since $p < 0.025$, (p-value = 0.021). There is a significant difference in the equipment availability before and after the implementation of STTPM as in Table 6-3 and Table 6-4.

Table 6-3: Paired Statistics Results for Equipment Availability Before and After STTPM Implementation.

Sample	N	Mean	StDev	SE Mean
EV_BEFORE_STTPM	44	0.7502	0.1936	0.0292
EV_AFTER_STTPM	44	0.8411	0.1726	0.0260

Table 6-4: t-test Results In Equipment Availability Before and After STTPM Implementation.

Mean	StDev	SE Mean	95% Upper Bound for μ_difference
-0.0909	0.2874	0.0433	-0.0181

μ_difference: mean of (EV_BEFORE_STTPM - EV_AFTER_STTPM)

Null hypothesis	H_0: μ_difference = 0
Alternative hypothesis	H_1: μ_difference < 0
T-Value	**P-Value**
-2.10	0.021

6.2.3 Cycle Time

In Table 6-5 and Table 6-6, the results showed cycle time was less after STTPM implementation (mean= 2.9195, StDev =0.89082) than before (mean = 3.4425, StDev = 1.80039). The critical value for t distribution, with $\alpha = 0.05$, and 43 degrees of freedom is t = 1.681, (T-statistic = 2.11). The null hypothesis of no significant difference in the cycle time before and after the implementation of STTPM can be rejected, and there is a significant difference in the cycle time before and after the implementation of STTPM.

Table 6-5: Paired Statistics Results for Cycle Time Before and After STTPM Implementation.

Sample	N	Mean	StDev	SE Mean
CT_BEFORE_STTPM	44	3.443	1.800	0.271
CT_AFTER_STTPM	44	2.920	0.891	0.134

Table 6-6: t-Test Results Cycle Time Before and After STTPM Implementation.

Mean	StDev	SE Mean	95% Lower Bound for µ_difference
0.523	1.642	0.248	0.107

µ_difference: mean of (CT_BEFORE_STTPM - CT_AFTER_STTPM)

Null hypothesis H_0: µ_difference = 0
Alternative hypothesis H_1: µ_difference > 0

T-Value	**P-Value**
2.11	0.020

6.2.4 OEE

The paired t-test should come from a distribution that is close to Normal. OEE testing for normality to meet four main assumptions (see Appendix F). In Table 6-7 and Table 6-8, the results showed that OEE increased after STTPM implementation (mean= 0.5510, StDev = 0.31572) than before (mean = 0.7390, StDev = 0.27630). The critical value for *t* distribution, with $\alpha = 0.05$, and 41 degrees of freedom is t = -1.683. The computed T-statistic = -2.76. The null hypothesis of no significant difference in the OEE before and after the implementation of STTPM can be rejected. Consequently, there is a significant difference in the OEE before and after the implementation of STTPM.

Table 6-7: Paired Statistics Results for Cycle Time Before and After STTPM Implementation.

Sample	N	Mean	StDev	SE Mean
OEE_BEFORE_STTPM	42	0.5499	0.3162	0.0488
OEE_AFTER_STTPM	42	0.7391	0.2760	0.0426

Table 6-8: t-test Results Cycle Time Before and After STTPM Implementation.

Mean	StDev	SE Mean	95% Upper Bound for µ_difference
-0.1892	0.4438	0.0685	-0.0739

µ_difference: mean of (OEE_BEFORE_STTPM -OEE_AFTER_STTPM)

Null hypothesis	H_0: µ_difference = 0
Alternative hypothesis	H_1: µ_difference < 0
T-Value	**P-Value**
-2.76	0.004

6.3 OEE Calculation and Contribution

To illustrate the OEE calculation and contribution in this study, examples are presented for OEE calculation, OEE correlation to financial results, and design of experiment and OEE simulation.

Overall Equipment Effectiveness (OEE) is used as the key performance measure of success for TPM implementation. As mentioned earlier, OEE is one of the performance assessment measures commonly used in manufacturing industries. Therefore, OEE will be calculated to assess the short-term TPM impact on the performance of equipment. The table below contains shift data, to be used for a complete OEE calculation, starting with the calculation of the OEE Factors of EV, PR, and QR. Note that the same units of measurement (in this case minutes and pieces) are consistently used throughout the calculations.

Item	**Data**
Shift length	8 hours (480 minutes).
Short break	2 at 15min. =30 min.
Meal break	1 at 30 min.= 30 min.
Downtime	60 min.
ideal cycle time	1.5 pieces per minute
Total pieces	200 pieces
Reject pieces	2 pieces

OEE is the product of the equipment availability rate, performance rate and quality rate (Nakajima, 1989). OEE can be calculated using the following Equations:

$$OEE\% \quad = EV\,\% \times PR\,\% \times QR\,\%.$$

$$EV \qquad = \frac{Operating\ Time}{Planned\ Production\ Time}$$

$$Operating\ time = Planned\ production\ time\ \text{-}\ Downtime$$

$$Planned\ production\ time = Shift\ length - Breaks$$

$$PR \qquad = \frac{(\ Ideal\ Cycle\ Time * Total\ Pieces\ )}{Operating\ \ Time}$$

$$QR \qquad = \frac{Good\ Pieces}{Total\ Pieces}$$

Planned production time= Scheduled Time- Break time

= 480 - 60 = 420 minutes

Operating time = planned production time- Breakdown

= 420 - 60 = 360 minutes

$$EV = \frac{Operating\ Time}{Planned\ Production\ Time} = \frac{360}{420} = 0.8571\ (85.7\%)$$

$$PR = \frac{(\ Ideal\ Cycle\ Time * Total\ Pieces\ )}{Operating\ \ Time} = \frac{1.5 * 200}{360} = 0.833\ (83.3\%)$$

$$QR = \frac{Good\ Pieces}{Total\ Pieces} = \frac{198}{200} = 0.99\ (99\%)$$

$$OEE\% \quad = 85.7\% \times 83.3\ \% \times 99\ \% = 70.6\%$$

The company’s production lines data was collected from a real production environment. Equipment availability rate, performance rate, and quality rate.

6.3.1 Financial Benefits

STTPM is about improving plant availability and it needs to quantify the unavailability costs. According to Oskar, (2017), correlating the OEE measurable with financial measures can be difficult, although such comparisons prove extremely valuable. He stated that an improvement of one percentage point in OEE can be expressed in additional profits or reduced costs. The financial staff could be charged with the task of investigating and establishing the links of OEE to profits for each process unit or line. The value of linking the OEE to financial information can be explained by our case study from production lines 1, 2 as summarized below. Manufacturing processing needed to measure the financial opportunities for improvement in their process.

Example of OEE correlation to financial results: we assume that the annual revenues were in the range of \$20 million with OEE = 55% and it improved to 74%.

Therefore,

$$\text{Production lines sales revenues at } 74\%, \text{OEE} = \frac{(\$20 \text{ million x } 74\%)}{55\%} = \$26.9 \text{ million}$$

Therefore, the total annual revenues have increased from \$20 million to \$26.9 million after OEE has been increased. From Table 6-9 below, it was seen that STTPM methodology is a very effective strategy for improving Manufacturing Performance. The average monthly overall equipment effectiveness OEE was 55% but after STTPM initiatives OEE increased to 74%, also there was an enhancement of EV; and PR increased to 86%.

Table 6-9: Benefits from STTPM.

	Before	**After**	**Unit**	**Improvement**
EV	0.75	0.86	%	12%
PR	0.77	0.86	%	10%
QR	0.9995	0.9998	%	0.03%
OEE	0.55	0.74	%	24%

The purpose of this calculation is to show how profit losses can be significantly reduced through increases in OEE. Also, this cost analysis can help persuade senior level management of the need to reconsider their maintenance strategy and to manage the STTPM approach as a crucial method of improving plant productivity.

6.3.2 Design of Experiments

The DOE was used to determine the relationship between factors that affect the output of the process. This information is needed to assess and predict the contribution of the process inputs to the achievement of the desired output. The DOE is a multipurpose tool that can help in many situations, such as planning an experiment to gather data to decide between two or more alternatives or selecting the few that matter most from among many possible factors. In general, the DOE is used to study the performance of processes and systems. Therefore, it is a test or a series of tests in which purposeful changes are made to the input variables or factors of a system so that we may observe and identify the reasons for changes in the output response (Montgomery, 2017).

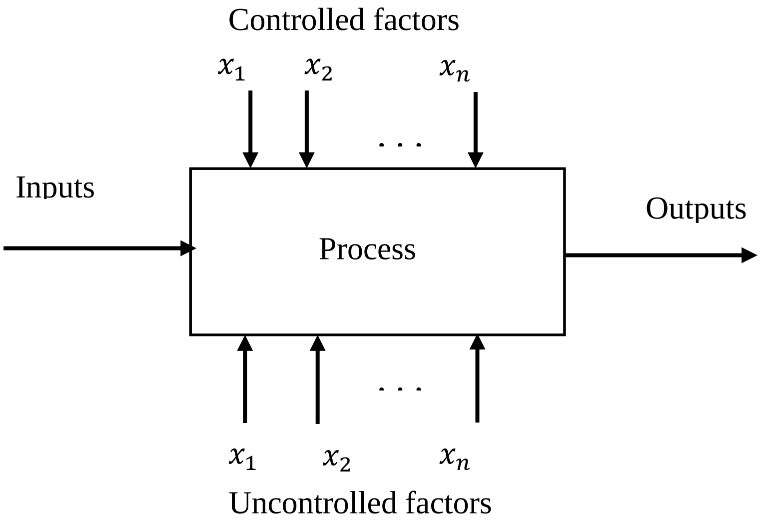


Figure 6-4. General Model of a Process or System (Montgomery 2017).

The process or system can be represented by the model shown in Figure 6-4. Overall equipment effectiveness (OEE) improvement is one of the main benefits of TPM implementation and was discussed in Chapter 2. In this section, the DOE will be used to study OEE to choose the main factors that influence response. Suppose that we need to improve the OEE result for a production line. The three inputs (factors) are equipment availability, performance rate, and quality rate. As the input variable, equipment availability includes setup, adjustment, and breakdown. Performance rate contains reduced speed, ideal cycle time, minor stoppages, and idling. The quality rate includes production defects and rework and start-up yield loss. The output of the experiment is the OEE of the system under consideration. Unscheduled breakdowns and ideal cycle time are considered as uncontrolled factors in this system.

Table 6-10: OEE Calculations.

Production Line	Equipment Availability %	Performance Rate %	Quality Rate %	OEE %
PL1	87.45	90	99.89	78.62
PL2	92.85	83.23	97.36	75.24
PL3	88.65	85.55	98.33	74.57
PL4	**85.66**	**77.93**	**97.86**	**65.33**

The results of the three-factor calculations of OEE are presented in Table 6-10. Production Line 4 was found to be underperforming with the following: EV 85.66 %, PR 77.93 %, and QR 97.86%. These values yield an OEE of 65.33 %. To improve the OEE of PL 4, three factors, equipment availability (X_1), performance rate (X_2), and quality rate (X_3), were studied. We wanted to determine the relative importance of each of these factors on OEE (Y). OEE was observed to vary smoothly when progressive changes are made to the inputs. This led us to believe that the ultimate response surface for Y will be smooth. A full factorial design was created by using MiniTab19 statistical software. An experiment was designed to study the three factors at two levels.

Table 6-11: Factor Level Settings.

OEE Factors		Levels	
		Low performance (%)	High performance (%) (world-class values)
Equipment Availability	X_1	85.66	90
Performance Rate	X_2	77.93	95
Quality Rate	X_3	97.86	99.9

Reference values of PL 4 low performance and world-class OEE factors (Peter & McCarthy, 2000) are shown in Table 6-11. An experimental setup design was modeled by entering the data into MiniTab19 software. As a result, Table 6-12 shows the differing settings that were generated to analyze PL 4. From the results, OEE is the response variable.

Table 6-12: Experimental Setup for OEE (Un-coded variables).

Run	**EV%**	**PR%**	**QR%**	**OEE%**
1	90.00	95.00	99.90	85.41
2	90.00	77.93	99.90	70.07
3	85.66	77.93	99.90	66.69
4	85.66	95.00	99.90	81.30
5	85.66	95.00	97.86	79.64
6	85.66	77.93	97.86	65.33
7	90.00	95.00	97.86	83.67
8	90.00	77.93	97.86	68.64

Table 6-13 shows the different effects and coefficients of this design of the experiment. We can see that PR has the largest effect on OEE, with a value of 14.825. This means PR is a significant factor that increases the OEE value.

Table 6-13: Estimated Effects and Coefficients for OEE.

Term	**Effect**	**Coefficient**
Constant		75.09
EV	3.711	1.855
PR	**14.825**	7.412
QR	1.5492	0.7746
EV×PR	0.3663	0.1831
EV×QR	0.03828	0.01914
PR×QR	0.15292	0.07646
EV×PR×QR	0.003778	0.001889

Regression analysis gives the classic equation of OEE with equipment availability, performance rate, and quality rate as predictors and OEE as a response. The regression Equation (6.1) (OEE versus EV, PR, and QR) is the following (see Table 6-14):

$$OEE = -150.2 + 0.8550\ EV + 0.8685\ PR + 0.7594\ QR \qquad (6.1)$$

Therefore, we can see that three factors have a positive effect on the yield because their coefficients are positive. Table 6-14 shows that EV, PR, and QR affect the OEE because the T statistics have a positive value. The regression analysis report shows (R^2) to be 99.93%, which indicates a good fit with the data. We can see that the effects of EV, PR, and QR are significant because their P-value is lower than the confidence level, $\alpha = 0.05$. Therefore, one can conclude that the PR factor is the most significant in the experiment.

Table 6-14: Coefficients of Regression Analysis.

Term	**Coef**	**SE Coef**	**T-Value**	**P-Value**
Constant	-150.2	10.5	-14.27	0.000
EV	0.8550	0.0459	18.61	0.000
PR	0.8685	0.0117	74.35	0.000
QR	0.7594	0.0977	7.77	0.001
S = 0.281974				
R^2 = 99.93%				
R^2 (adj) = 99.88%				

Figures 6-5 and 6-6 present a contour plot and surface plot of the experimental values, respectively. Also, the OEE value increases with the increase in equipment availability and performance rate. The variation of OEE concerning EV and PR can be observed in the surface plot. Moreover, the surface plot shows a direction of potential improvement for a process. A contour plot shows how the PR and EV variables impact the OEE response variable. The dark green regions indicate high OEE values and the dark blue regions indicate lower OEE values. An analysis of variance revealed that PR could be a vital factor in increasing the OEE for production line 4. This DOE indicates that OEE will be significantly improved if the focus is on performance rate improvement. Hence, improving PR will require considerable attention to eliminate idling and minor stoppages. To achieve an OEE of 85.41%, optimized values are EV 90%, PR 95%, and QR 99.9%.

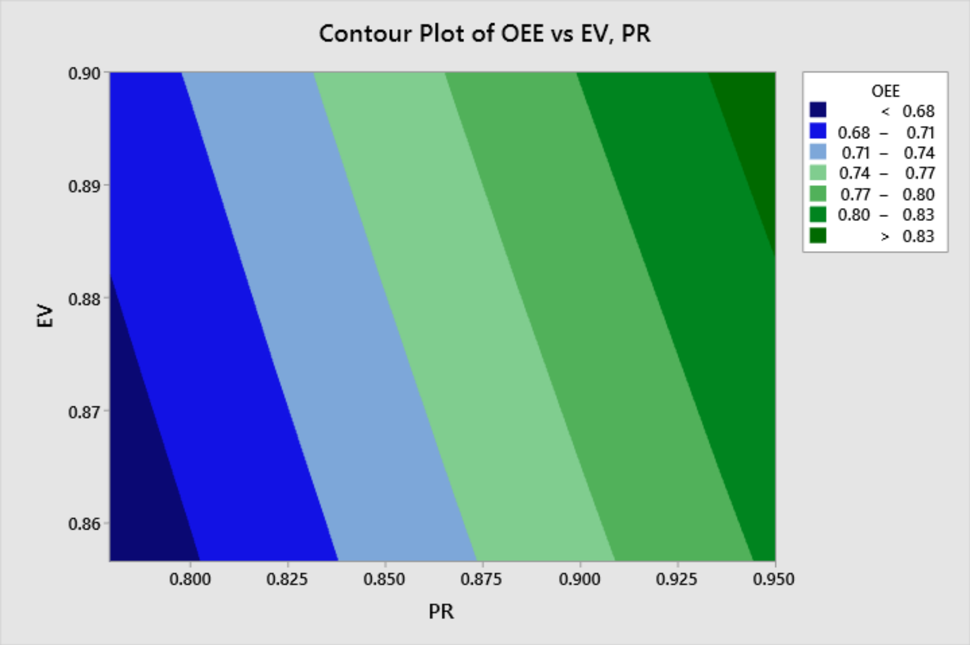


Figure 6-5. Contour Plot of OEE vs EV, PR.

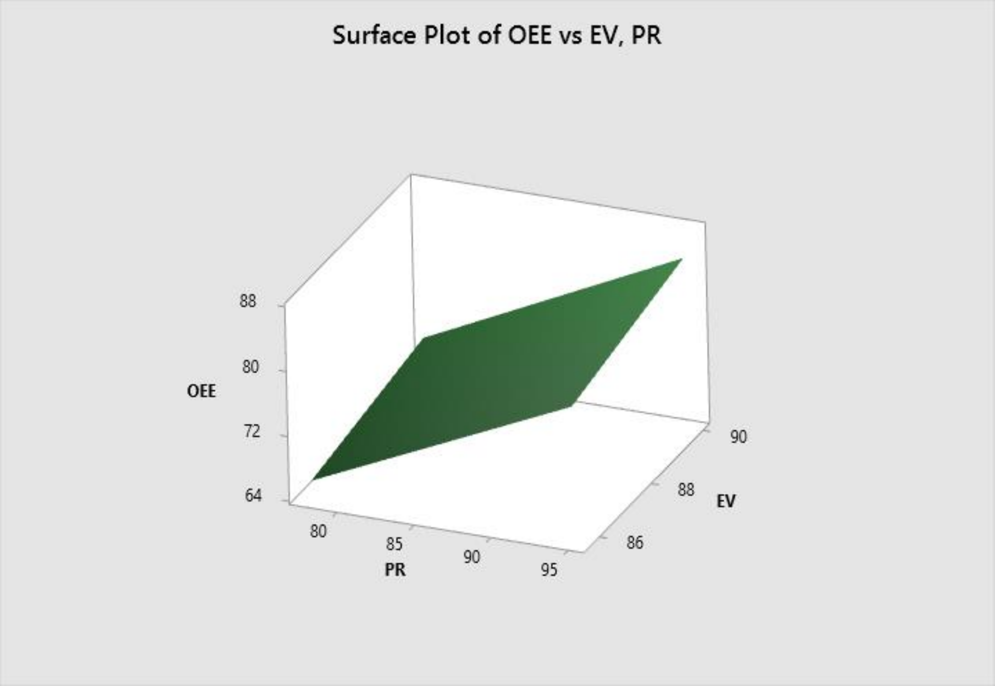


Figure 6-6. Surface Plot of OEE vs EV, PR.

6.3.3 OEE Simulation

Another way to predict the OEE is using a Monte Carlo simulation. The simulation approach helps in determining the predicted OEE value over the number of production shifts. Therefore, to predict the OEE after implementing STTPM at a future time, one can use the Monte Carlo experiments. Equipment Availability, Performance Rate, and Quality Rate data for production shifts are measured for the goodness of fit. The test results were as follows EV [Weibull (0, 8.62, 0.927)], PR [Weibull (0, 5.2, 0.896)], and QR [an empirical distribution, mean=0.999186, and standard deviation =0.00309574]. Therefore, random variates were generated for EV, PR, and QR based on their distribution for an average of 1000 production shifts. The benchmark OEE value based on the average of improvement after implementing STTPM is 0.74.

Table 6-15: Simulated OEE Values

Shift	EV	PR	QR	OEE
1	0.880	0.824	1.000	0.725
2	0.877	0.871	0.998	0.762
3	0.879	0.875	0.999	0.769
4	0.872	0.879	0.999	0.766
5	0.880	0.873	0.999	0.767
6	0.878	0.821	1.000	0.720
7	0.873	0.877	0.998	0.764
8	0.878	0.879	0.999	0.771
9	0.877	0.872	0.999	0.764
10	0.877	0.873	0.999	0.765
11	0.881	0.827	1.000	0.728
12	0.871	0.875	0.998	0.761
13	0.877	0.877	0.999	0.769
14	0.878	0.879	0.999	0.771
15	0.871	0.878	0.999	0.764
16	0.881	0.820	1.000	0.723
17	0.870	0.882	0.998	0.766
18	0.880	0.876	0.999	0.770
19	0.878	0.879	0.999	0.771
20	0.872	0.879	0.999	0.766

21	0.881	0.835	1.000	0.736
22	0.879	0.875	0.998	0.767
23	0.878	0.876	0.999	0.769
24	0.873	0.878	0.999	0.767
25	0.876	0.877	0.999	0.768
26	0.877	0.825	1.000	0.724
27	0.877	0.877	0.998	0.768
28	0.877	0.878	0.999	0.769
29	0.872	0.873	0.999	0.761
30	0.869	0.876	0.999	0.761
31	0.876	0.821	1.000	0.719
32	0.871	0.873	0.998	0.760
33	0.876	0.867	0.999	0.759
34	0.875	0.873	0.999	0.764
35	0.872	0.879	0.999	0.766
36	0.874	0.818	1.000	0.715
37	0.881	0.875	0.998	0.769
38	0.882	0.878	0.999	0.775
39	0.871	0.878	0.999	0.764
40	0.882	0.873	0.999	0.769
41	0.879	0.821	1.000	0.722
42	0.876	0.869	0.998	0.760
43	0.872	0.870	0.999	0.758
44	0.879	0.877	0.999	0.770
45	0.879	0.873	0.999	0.768
46	0.879	0.825	1.000	0.724
47	0.878	0.885	0.998	0.776
48	0.871	0.873	0.999	0.761
49	0.874	0.878	0.999	0.767
50	0.885	0.881	0.999	0.780

As the benchmark OEE value is 0.74, the simulation results are assessed by considering the ratio of observations above 0.74 to the total number of observations. Table 6-15 presents the total number of observations of the predicted OEE value for the production line. This prediction helps TPM teams to monitor the changeability of OEE. The predicted OEE values for the production line are shown in Figure 6-7. Accordingly, the number of observations above 0.74 is 40, and the total number of observations is 50.

$$\text{Simulation Results} = \frac{\text{The number of observations above} 0.74}{\text{Total number of observations}} = \frac{40}{50} = 0.8$$

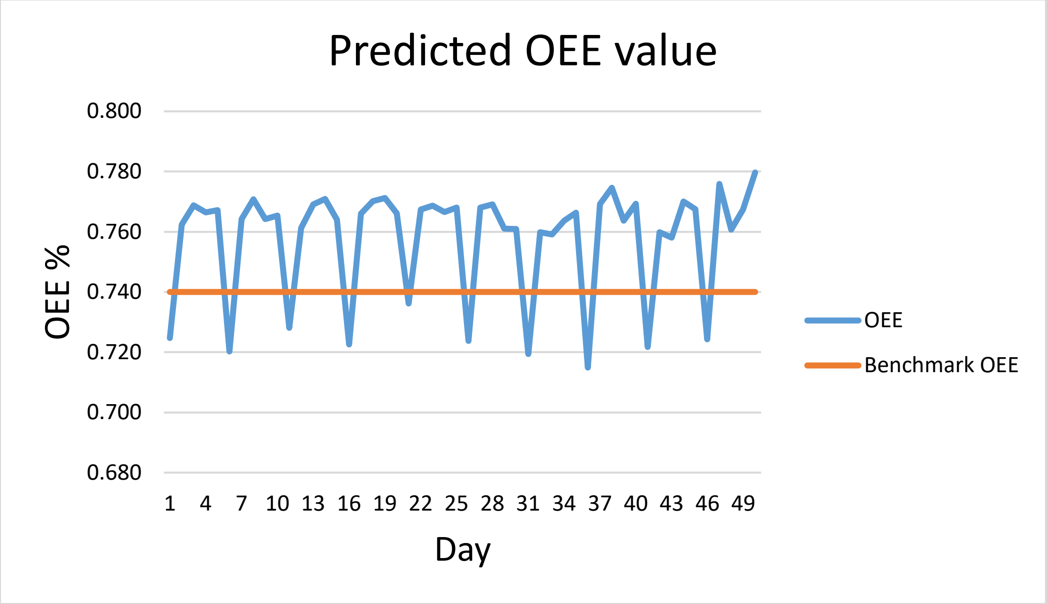


Figure 6-7. Predicted OEE Value

This chapter presented and discussed the results from the hypothesis testing, design of experiments, and OEE simulation. The hypothesis testing showed the positive effect of STTPM implementation on manufacturing performance. The DOE considered three input factors to study OEE and determine the most influential factors. Lastly, the simulation study helped predicting OEE values for the production line.

Chapter 6 below outlines the main findings of this thesis and presents the conclusions, and recommendations of future research.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

Based on the literature survey, research problems, and objectives the theoretical STTPM framework was proposed to maintain productivity performance in SME companies. This study developed an STTPM approach in the context of Canadian industry application through significant improvement in manufacturing performance (MP). The STTPM approach introduced in this study supports SME's in four ways. The framework is concise, simple and flexible for companies to implement. The framework does not require significant financial support, and any initial costs can be offset by the potential long-term profit increase and cost reduction. Manufacturing improvement can be achieved shortly after implementation. Finally, the framework does not require the expertise of an external TPM team and is better implemented utilizing the knowledge and experience of already present internal staff, another cost-saving measure. The STTPM approach helps SMEs improve the production rate, equipment availability and therefore reduce the cycle time.

The main objective of this study is to determine whether the Short-Term TPM (STTPM), based on two TPM pillars (AM & PM) and 5S technique can minimize losses in the production process and have a positive impact on MP. This study concluded that there was a significant difference in the MP variables before and after the implementation of STTPM in the production line. The case study was intended to illustrate that the STTPM approach can be successfully applied to the other manufacturing industries. The STTPM approach can produce desirable results. The STTPM approach in this study should be used whenever applicable to impact on manufacturing equipment performance. The result shows that (P_rR, EV, and CT) had a significant difference before and after the implementation of STTPM in the production line. Figure 7-1 shows the rate of improvement for production line 1, 2 after STTPM implementation. Similarly, The Overall Equipment Effectiveness was a significant difference before and after the implementation of STTPM in the production line.

Table 7-1 illustrated the summary of paired t-test results for (P_rR, EV, CT). The findings showed that the Production Rate, Equipment Availability, and Cycle time improved significantly in PL1, 2. The findings suggest that the STTPM approach has a positive effect on production rate, equipment availability and cycle time. Besides, the results suggest that implementing STTPM principles may result in decreased costs by improving productivity, cycle time and OEE, which, in turn, increases profits. This study produced statistical evidence to support the theory that the STTPM minimizes losses in the production process and have a positive impact on MP. Furthermore, the STTPM approach is the first step to facilitate a more extensive TPM implementation and can help to improve manufacturing performance.

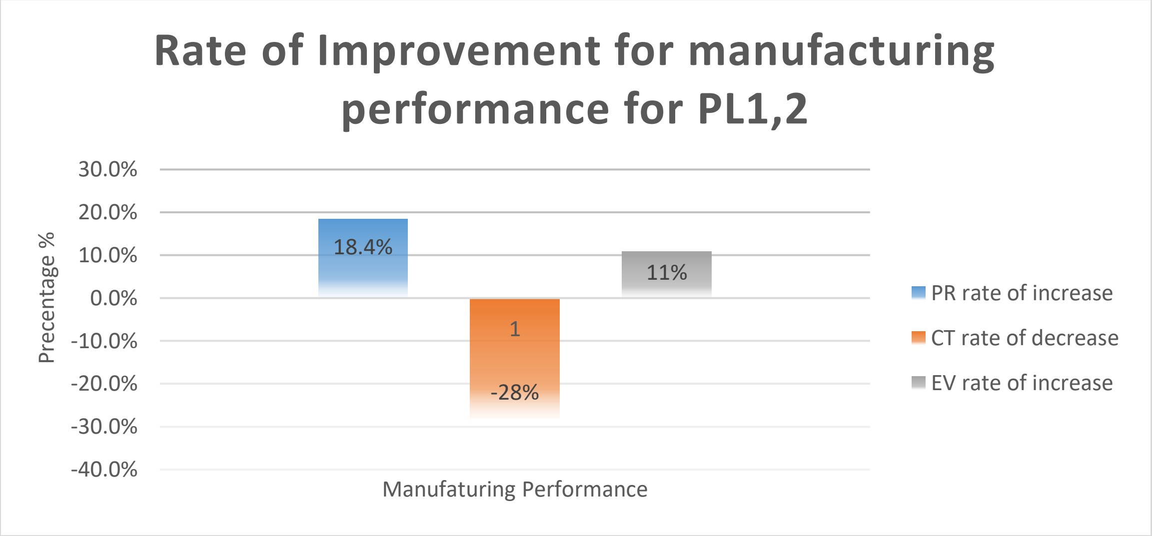


Figure 0-1. Rate of Improvement for Manufacturing Performance for PL1, 2.

Table 0-1: Summary of t-test Results for PL1, 2.

Variable	P-Value	Conclusion
Production Rate	.002	Significant
Equipment Availability	.021	Significant
Cycle time	.020	Significant
OEE	.004	Significant

We have developed a simple cost analysis procedure that companies could use to assess the consequences of the STTPM implementation in production line and to highlight the financial impact. The OLE calculation is very effective to find the production line problems and what improvements should be made to increase the effectiveness of the production line. We used the PCA to convert multivariate quality characteristics measured in one machine into a univariate form.

6.4 Research Limitations

The STTPM approach has its limitations, including the difficulty of quantifying the cost of each process due to a lack of information within the company. Even though the study offers useful insights, the limitation is that:

1. The process depends heavily on human experience and knowledge. It also depends on the work team’s understanding of the implementation method.
2. The decision-making is:
    - Based on human intuition, not on an optimization decision support system
    - Not standardized (no data bank for such improvement processes exists yet). So, if the approach takes place in two identical facilities, there is no

guarantee that it will be either planned or implemented similarly, and no guarantee that the results will be identical.

3. There is a potential loss for the companies who implement STTPM if they do not have a continuous improvement strategy and do not assess the contribution of the remaining TPM pillars on their manufacturing performance measures.
4. The illustrative example presented in this research may not be sufficient, although it provides insights into the application of the methodology. It is appropriate to conduct more exploratory research on TPM implementation in SMEs.

6.5 Recommendations

To further enhance this approach, it is wise to investigate ways of collecting data on a real-time basis from the production equipment. Real-time data from production equipment will facilitate identifying the equipment losses. Through this process, the equipment losses can be addressed timely without much loss to operations. Addressing these losses will improve manufacturing performance.

In addition, building an Artificial Intelligence (AI) environment considering data storage and communication capacities can be envisaged. As such, the Total Productive Maintenance (TPM) implementation can be facilitated by monitoring manufacturing performance in real-time. Consequently, production actions can be taken timely to avoid overproduction and poor quality and to perform maintenance activities.

6.6 Future work

- To reduce the manual work and human intervention, by using computer systems to both handle the clerical work and recall pre-stored practices (based on standardized historical experience).
- To use optimization model to select the least costly trade-off of implementing eight pillars of TPM or focus on some of them.
- To globalize the standard, possibly by involving the certification body (JIPM)

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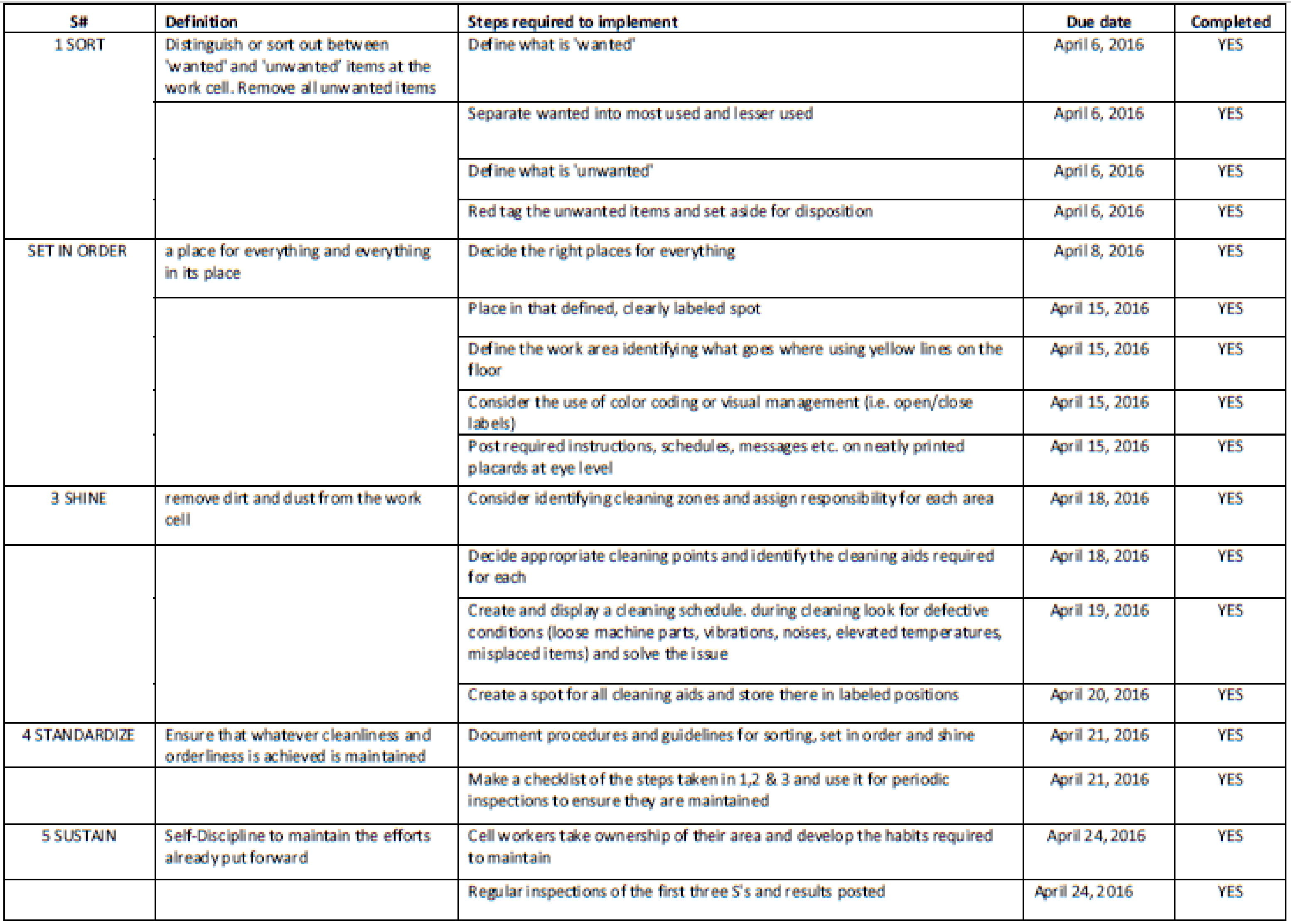
APPENDICES.

Appendix A. Guidance for 5S Implementation



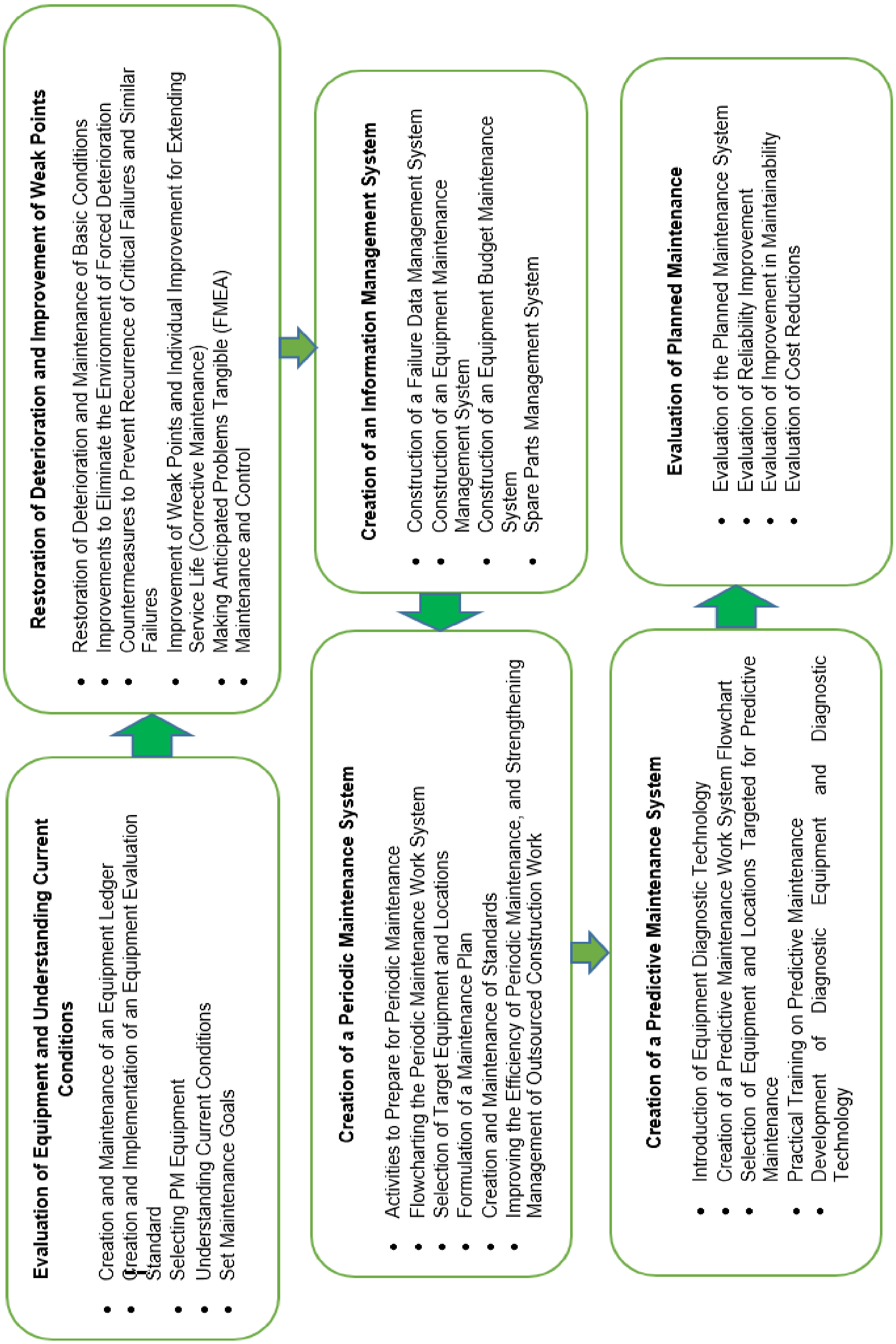
S#	Definition	Steps required to implement	Due date	Completed
1 SORT	Distinguish or sort out between 'wanted' and 'unwanted' items at the work cell. Remove all unwanted items	Define what is 'wanted'	April 6, 2016	YES
		Separate wanted into most used and lesser used	April 6, 2016	YES
		Define what is 'unwanted'	April 6, 2016	YES
		Red tag the unwanted items and set aside for disposition	April 6, 2016	YES
SET IN ORDER	a place for everything and everything in its place	Decide the right places for everything	April 8, 2016	YES
		Place in that defined, clearly labeled spot	April 15, 2016	YES
		Define the work area identifying what goes where using yellow lines on the floor	April 15, 2016	YES
		Consider the use of color coding or visual management (i.e. open/close labels)	April 15, 2016	YES
		Post required instructions, schedules, messages etc. on neatly printed placards at eye level	April 15, 2016	YES
3 SHINE	remove dirt and dust from the work cell	Consider identifying cleaning zones and assign responsibility for each area	April 18, 2016	YES
		Decide appropriate cleaning points and identify the cleaning aids required for each	April 18, 2016	YES
		Create and display a cleaning schedule. during cleaning look for defective conditions (loose machine parts, vibrations, noises, elevated temperatures, misplaced items) and solve the issue	April 19, 2016	YES
		Create a spot for all cleaning aids and store there in labeled positions	April 20, 2016	YES
4 STANDARDIZE	Ensure that whatever cleanliness and orderliness is achieved is maintained	Document procedures and guidelines for sorting, set in order and shine	April 21, 2016	YES
		Make a checklist of the steps taken in 1,2 & 3 and use it for periodic inspections to ensure they are maintained	April 21, 2016	YES
5 SUSTAIN	Self-Discipline to maintain the efforts already put forward	Cell workers take ownership of their area and develop the habits required to maintain	April 24, 2016	YES
		Regular inspections of the first three S's and results posted	April 24, 2016	YES

Appendix B. 5S Assessment Form

Level	Sort	Simplify	Shine	Standardize	Sustain
Baseline 0	Unsafe items in work area.	Placement of items causes unsafe conditions.	Spills, waste, trash, etc. produce unsafe conditions.	No work methods or procedures documented.	No routine review/correction of unsafe conditions.
Beginner 1	Needed and un-needed items found in work area.	Needed and un-needed items are placed randomly throughout the workplace.	Work area and machines are not cleaned on a regular basis.	Methods of work not completely documented.	Occasional, unscheduled 5S activity.
Basic 2	Needed /un-needed items separated, un-needed tagged.	Needed items stored in an organized manner.	Area and equipment cleaned daily.	Methods of work documented but not consistently used.	5S activities conducted on regular basis.
Visual 3	Red tag area created, all un-needed items removed.	Needed items have dedicated positions which are clearly indicated.	Standard work layout posted and maintained.	Methods of work posted and consistently used by some cell team members.	5S assessment conducted occasionally and results posted.
Systematic 4	List of needed items developed, maintained, posted.	Needed items can be retrieved within (cell target) seconds and (cell target) number of steps.	Daily inspections of plant and area occurs.	Methods of work consistently used by all cell team members.	5S assessment conducted on a regular basis and recurring problems are identified.
Preventive 5	Un-needed items are not allowed in area.	Method for adding/deleting indicators for needed items	Root cause sources of dirt, grease & spillage have been eliminated.	Methods of work are regularly reviewed and improved.	Root causes of problems revealed by 5S assessment are identified and eliminated.
Score					

Total:		**By:**		**Date:**	

Appendix C. Implementation of Planned Maintenance Phase (JIPM 2017)



Evaluation of Equipment and Understanding Current Conditions

- Creation and Maintenance of an Equipment Ledger
- Creation and Implementation of an Equipment Evaluation Standard
- Selecting PM Equipment
- Understanding Current Conditions
- Set Maintenance Goals

Restoration of Deterioration and Improvement of Weak Points

- Restoration of Deterioration and Maintenance of Basic Conditions
- Improvements to Eliminate the Environment of Forced Deterioration
- Countermeasures to Prevent Recurrence of Critical Failures and Similar Failures
- Improvement of Weak Points and Individual Improvement for Extending Service Life (Corrective Maintenance)
- Making Anticipated Problems Tangible (FMEA)
- Maintenance and Control

Creation of an Information Management System

- Construction of a Failure Data Management System
- Construction of an Equipment Maintenance Management System
- Construction of an Equipment Budget Maintenance System
- Spare Parts Management System

Creation of a Periodic Maintenance System

- Activities to Prepare for Periodic Maintenance
- Flowcharting the Periodic Maintenance Work System
- Selection of Target Equipment and Locations
- Formulation of a Maintenance Plan
- Creation and Maintenance of Standards
- Improving the Efficiency of Periodic Maintenance, and Strengthening Management of Outsourced Construction Work

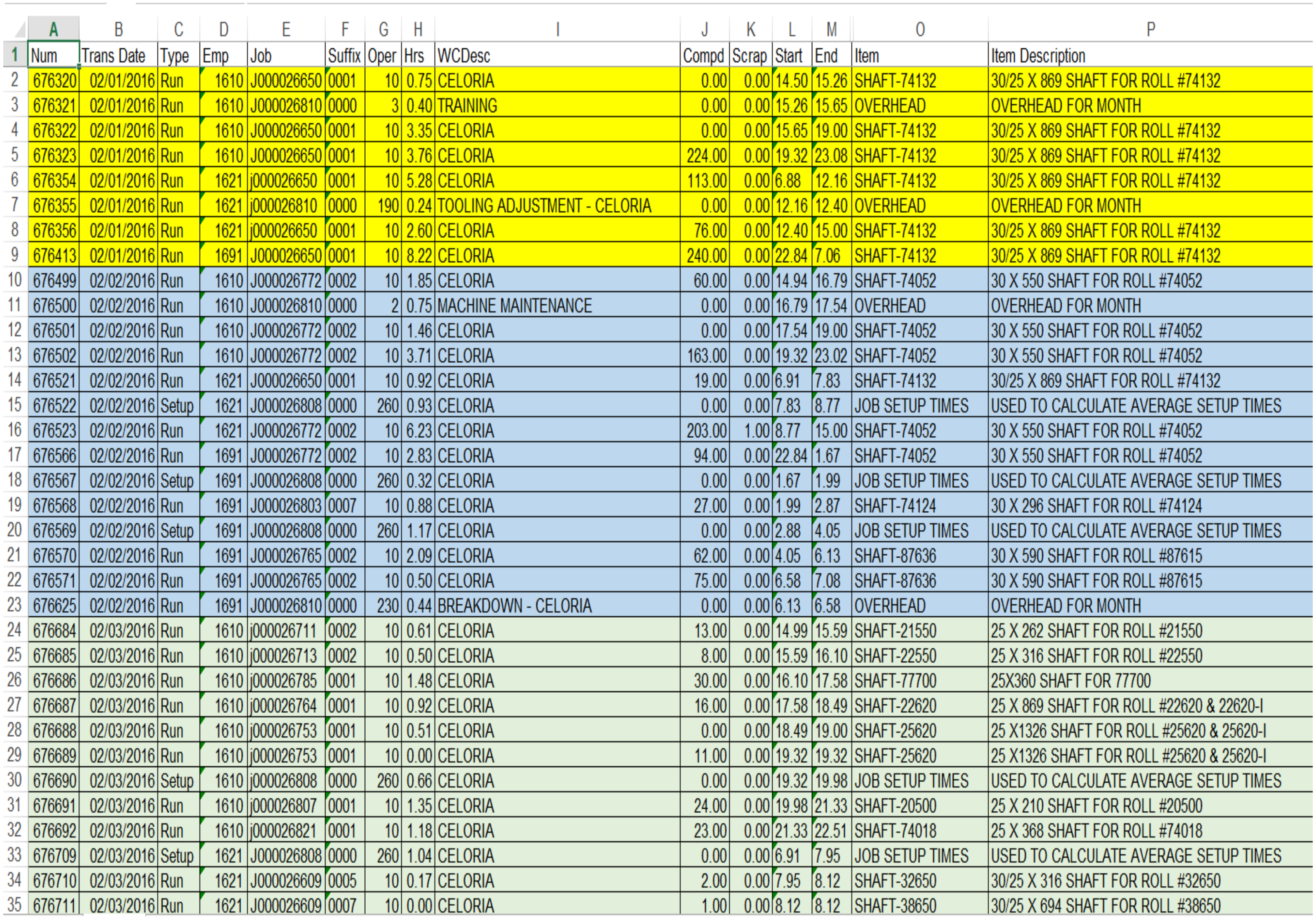
Creation of a Predictive Maintenance System

- Introduction of Equipment Diagnostic Technology
- Creation of a Predictive Maintenance Work System Flowchart
- Selection of Equipment and Locations Targeted for Predictive Maintenance
- Practical Training on Predictive Maintenance
- Development of Diagnostic Equipment and Diagnostic Technology

Evaluation of Planned Maintenance

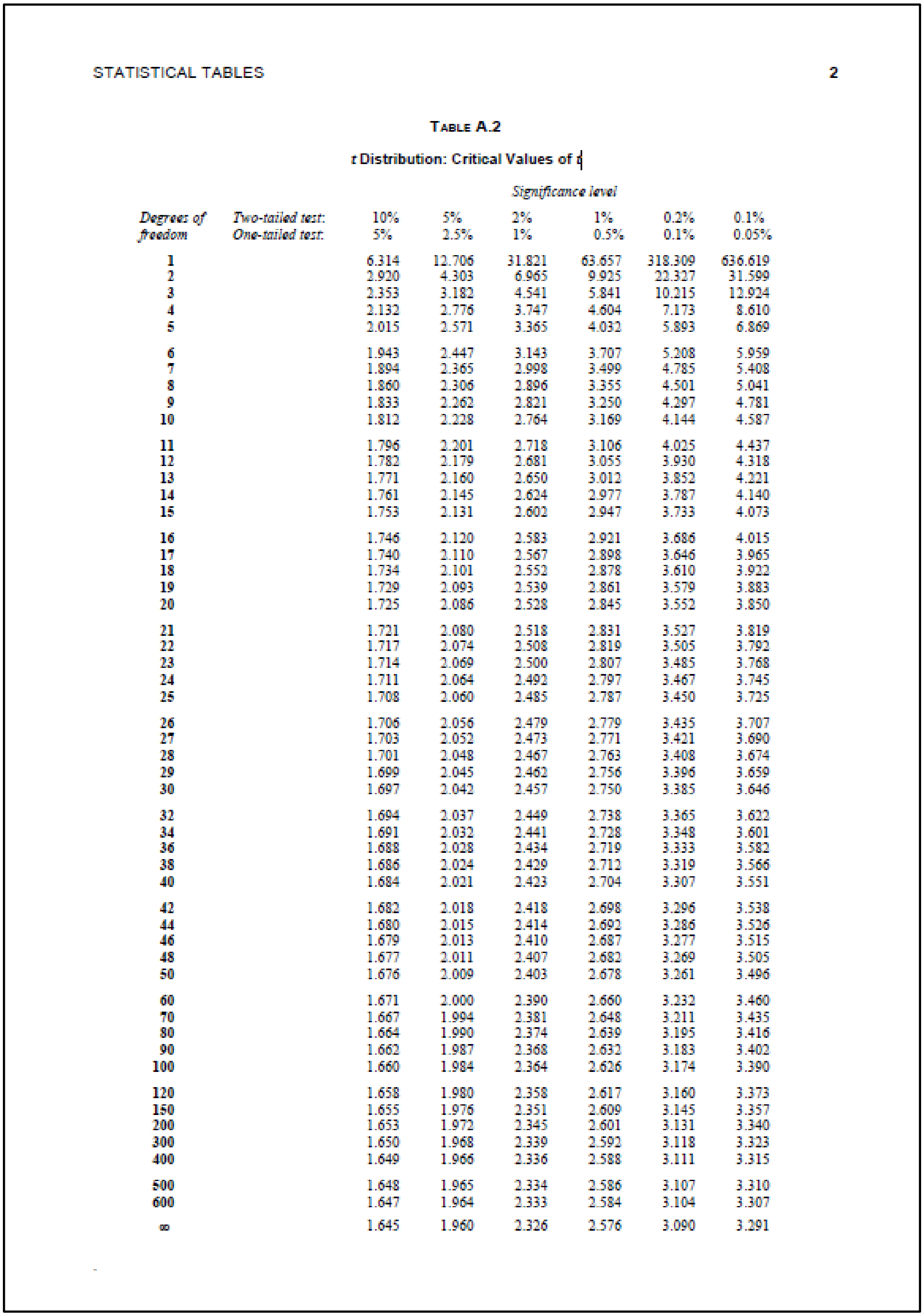
- Evaluation of the Planned Maintenance System
- Evaluation of Reliability Improvement
- Evaluation of Improvement in Maintainability
- Evaluation of Cost Reductions

Appendix D. Manufacturing Data Obtained from Operation Records in Excel Sheet



	A	B	C	D	E	F	G	H	I	J	K	L	M	O	P
1	Num	Trans Date	Type	Emp	Job	Suffix	Oper	Hrs	WCDesc	Compd	Scrap	Start	End	Item	Item Description
2	676320	02/01/2016	Run	1610	J000026650	0001	10	0.75	CELORIA	0.00	0.00	14.50	15.26	SHAFT-74132	30/25 X 869 SHAFT FOR ROLL #74132
3	676321	02/01/2016	Run	1610	J000026810	0000	3	0.40	TRAINING	0.00	0.00	15.26	15.65	OVERHEAD	OVERHEAD FOR MONTH
4	676322	02/01/2016	Run	1610	J000026650	0001	10	3.35	CELORIA	0.00	0.00	15.65	19.00	SHAFT-74132	30/25 X 869 SHAFT FOR ROLL #74132
5	676323	02/01/2016	Run	1610	J000026650	0001	10	3.76	CELORIA	224.00	0.00	19.32	23.08	SHAFT-74132	30/25 X 869 SHAFT FOR ROLL #74132
6	676354	02/01/2016	Run	1621	j000026650	0001	10	5.28	CELORIA	113.00	0.00	6.88	12.16	SHAFT-74132	30/25 X 869 SHAFT FOR ROLL #74132
7	676355	02/01/2016	Run	1621	j000026810	0000	190	0.24	TOOLING ADJUSTMENT - CELORIA	0.00	0.00	12.16	12.40	OVERHEAD	OVERHEAD FOR MONTH
8	676356	02/01/2016	Run	1621	j000026650	0001	10	2.60	CELORIA	76.00	0.00	12.40	15.00	SHAFT-74132	30/25 X 869 SHAFT FOR ROLL #74132
9	676413	02/01/2016	Run	1691	J000026650	0001	10	8.22	CELORIA	240.00	0.00	22.84	7.06	SHAFT-74132	30/25 X 869 SHAFT FOR ROLL #74132
10	676499	02/02/2016	Run	1610	J000026772	0002	10	1.85	CELORIA	60.00	0.00	14.94	16.79	SHAFT-74052	30 X 550 SHAFT FOR ROLL #74052
11	676500	02/02/2016	Run	1610	J000026810	0000	2	0.75	MACHINE MAINTENANCE	0.00	0.00	16.79	17.54	OVERHEAD	OVERHEAD FOR MONTH
12	676501	02/02/2016	Run	1610	J000026772	0002	10	1.46	CELORIA	0.00	0.00	17.54	19.00	SHAFT-74052	30 X 550 SHAFT FOR ROLL #74052
13	676502	02/02/2016	Run	1610	J000026772	0002	10	3.71	CELORIA	163.00	0.00	19.32	23.02	SHAFT-74052	30 X 550 SHAFT FOR ROLL #74052
14	676521	02/02/2016	Run	1621	J000026650	0001	10	0.92	CELORIA	19.00	0.00	6.91	7.83	SHAFT-74132	30/25 X 869 SHAFT FOR ROLL #74132
15	676522	02/02/2016	Setup	1621	J000026808	0000	260	0.93	CELORIA	0.00	0.00	7.83	8.77	JOB SETUP TIMES	USED TO CALCULATE AVERAGE SETUP TIMES
16	676523	02/02/2016	Run	1621	J000026772	0002	10	6.23	CELORIA	203.00	1.00	8.77	15.00	SHAFT-74052	30 X 550 SHAFT FOR ROLL #74052
17	676566	02/02/2016	Run	1691	J000026772	0002	10	2.83	CELORIA	94.00	0.00	22.84	1.67	SHAFT-74052	30 X 550 SHAFT FOR ROLL #74052
18	676567	02/02/2016	Setup	1691	J000026808	0000	260	0.32	CELORIA	0.00	0.00	1.67	1.99	JOB SETUP TIMES	USED TO CALCULATE AVERAGE SETUP TIMES
19	676568	02/02/2016	Run	1691	J000026803	0007	10	0.88	CELORIA	27.00	0.00	1.99	2.87	SHAFT-74124	30 X 296 SHAFT FOR ROLL #74124
20	676569	02/02/2016	Setup	1691	J000026808	0000	260	1.17	CELORIA	0.00	0.00	2.88	4.05	JOB SETUP TIMES	USED TO CALCULATE AVERAGE SETUP TIMES
21	676570	02/02/2016	Run	1691	J000026765	0002	10	2.09	CELORIA	62.00	0.00	4.05	6.13	SHAFT-87636	30 X 590 SHAFT FOR ROLL #87615
22	676571	02/02/2016	Run	1691	J000026765	0002	10	0.50	CELORIA	75.00	0.00	6.58	7.08	SHAFT-87636	30 X 590 SHAFT FOR ROLL #87615
23	676625	02/02/2016	Run	1691	J000026810	0000	230	0.44	BREAKDOWN - CELORIA	0.00	0.00	6.13	6.58	OVERHEAD	OVERHEAD FOR MONTH
24	676684	02/03/2016	Run	1610	j000026711	0002	10	0.61	CELORIA	13.00	0.00	14.99	15.59	SHAFT-21550	25 X 262 SHAFT FOR ROLL #21550
25	676685	02/03/2016	Run	1610	j000026713	0002	10	0.50	CELORIA	8.00	0.00	15.59	16.10	SHAFT-22550	25 X 316 SHAFT FOR ROLL #22550
26	676686	02/03/2016	Run	1610	j000026785	0001	10	1.48	CELORIA	30.00	0.00	16.10	17.58	SHAFT-77700	25X360 SHAFT FOR 77700
27	676687	02/03/2016	Run	1610	j000026764	0001	10	0.92	CELORIA	16.00	0.00	17.58	18.49	SHAFT-22620	25 X 869 SHAFT FOR ROLL #22620 & 22620-I
28	676688	02/03/2016	Run	1610	j000026753	0001	10	0.51	CELORIA	0.00	0.00	18.49	19.00	SHAFT-25620	25 X1326 SHAFT FOR ROLL #25620 & 25620-I
29	676689	02/03/2016	Run	1610	j000026753	0001	10	0.00	CELORIA	11.00	0.00	19.32	19.32	SHAFT-25620	25 X1326 SHAFT FOR ROLL #25620 & 25620-I
30	676690	02/03/2016	Setup	1610	j000026808	0000	260	0.66	CELORIA	0.00	0.00	19.32	19.98	JOB SETUP TIMES	USED TO CALCULATE AVERAGE SETUP TIMES
31	676691	02/03/2016	Run	1610	j000026807	0001	10	1.35	CELORIA	24.00	0.00	19.98	21.33	SHAFT-20500	25 X 210 SHAFT FOR ROLL #20500
32	676692	02/03/2016	Run	1610	j000026821	0001	10	1.18	CELORIA	23.00	0.00	21.33	22.51	SHAFT-74018	25 X 368 SHAFT FOR ROLL #74018
33	676709	02/03/2016	Setup	1621	J000026808	0000	260	1.04	CELORIA	0.00	0.00	6.91	7.95	JOB SETUP TIMES	USED TO CALCULATE AVERAGE SETUP TIMES
34	676710	02/03/2016	Run	1621	J000026609	0005	10	0.17	CELORIA	2.00	0.00	7.95	8.12	SHAFT-32650	30/25 X 316 SHAFT FOR ROLL #32650
35	676711	02/03/2016	Run	1621	J000026609	0007	10	0.00	CELORIA	1.00	0.00	8.12	8.12	SHAFT-38650	30/25 X 694 SHAFT FOR ROLL #38650

Appendix E. Table Critical Values of *t.*



STATISTICAL TABLES 2

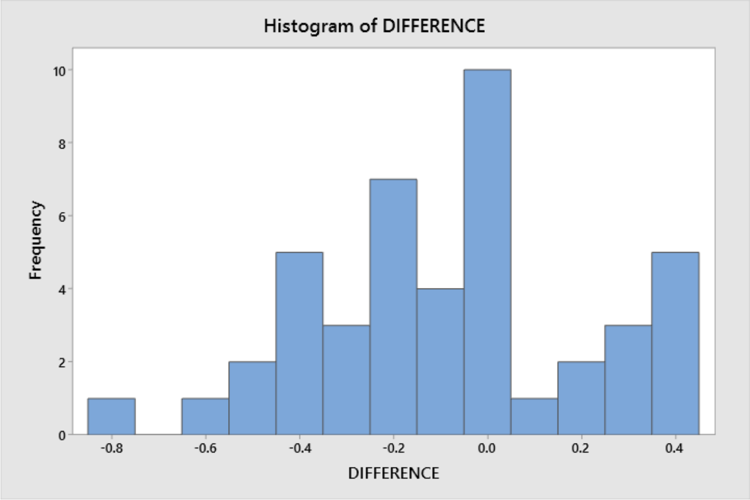
TABLE A.2

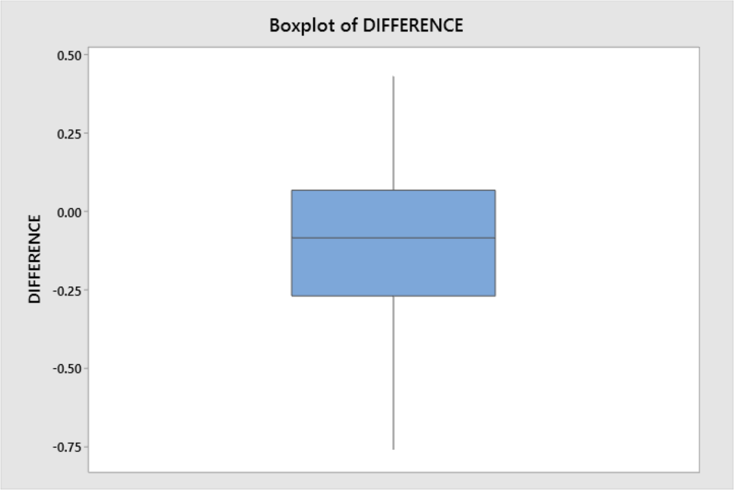
t Distribution: Critical Values of *t*

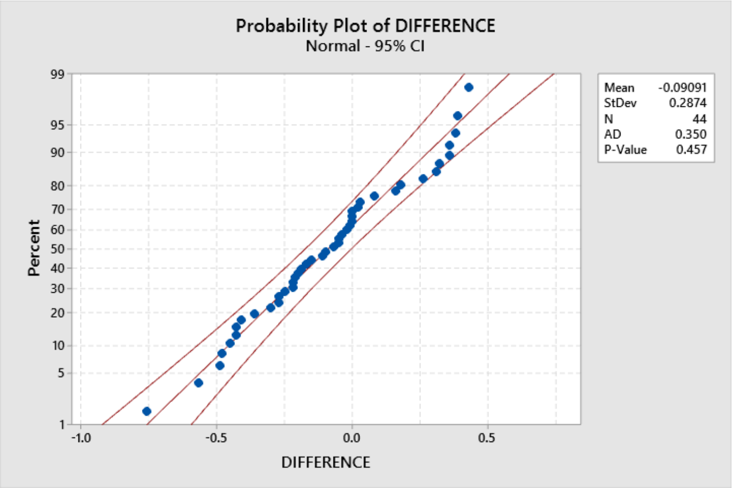
		Significance level					
Degrees of freedom	*Two-tailed test:*	10%	5%	2%	1%	0.2%	0.1%
	One-tailed test:	5%	2.5%	1%	0.5%	0.1%	0.05%
1		6.314	12.706	31.821	63.657	318.309	636.619
2		2.920	4.303	6.965	9.925	22.327	31.599
3		2.353	3.182	4.541	5.841	10.215	12.924
4		2.132	2.776	3.747	4.604	7.173	8.610
5		2.015	2.571	3.365	4.032	5.893	6.869
6		1.943	2.447	3.143	3.707	5.208	5.959
7		1.894	2.365	2.998	3.499	4.785	5.408
8		1.860	2.306	2.896	3.355	4.501	5.041
9		1.833	2.262	2.821	3.250	4.297	4.781
10		1.812	2.228	2.764	3.169	4.144	4.587
11		1.796	2.201	2.718	3.106	4.025	4.437
12		1.782	2.179	2.681	3.055	3.930	4.318
13		1.771	2.160	2.650	3.012	3.852	4.221
14		1.761	2.145	2.624	2.977	3.787	4.140
15		1.753	2.131	2.602	2.947	3.733	4.073
16		1.746	2.120	2.583	2.921	3.686	4.015
17		1.740	2.110	2.567	2.898	3.646	3.965
18		1.734	2.101	2.552	2.878	3.610	3.922
19		1.729	2.093	2.539	2.861	3.579	3.883
20		1.725	2.086	2.528	2.845	3.552	3.850
21		1.721	2.080	2.518	2.831	3.527	3.819
22		1.717	2.074	2.508	2.819	3.505	3.792
23		1.714	2.069	2.500	2.807	3.485	3.768
24		1.711	2.064	2.492	2.797	3.467	3.745
25		1.708	2.060	2.485	2.787	3.450	3.725
26		1.706	2.056	2.479	2.779	3.435	3.707
27		1.703	2.052	2.473	2.771	3.421	3.690
28		1.701	2.048	2.467	2.763	3.408	3.674
29		1.699	2.045	2.462	2.756	3.396	3.659
30		1.697	2.042	2.457	2.750	3.385	3.646
32		1.694	2.037	2.449	2.738	3.365	3.622
34		1.691	2.032	2.441	2.728	3.348	3.601
36		1.688	2.028	2.434	2.719	3.333	3.582
38		1.686	2.024	2.429	2.712	3.319	3.566
40		1.684	2.021	2.423	2.704	3.307	3.551
42		1.682	2.018	2.418	2.698	3.296	3.538
44		1.680	2.015	2.414	2.692	3.286	3.526
46		1.679	2.013	2.410	2.687	3.277	3.515
48		1.677	2.011	2.407	2.682	3.269	3.505
50		1.676	2.009	2.403	2.678	3.261	3.496
60		1.671	2.000	2.390	2.660	3.232	3.460
70		1.667	1.994	2.381	2.648	3.211	3.435
80		1.664	1.990	2.374	2.639	3.195	3.416
90		1.662	1.987	2.368	2.632	3.183	3.402
100		1.660	1.984	2.364	2.626	3.174	3.390
120		1.658	1.980	2.358	2.617	3.160	3.373
150		1.655	1.976	2.351	2.609	3.145	3.357
200		1.653	1.972	2.345	2.601	3.131	3.340
300		1.650	1.968	2.339	2.592	3.118	3.323
400		1.649	1.966	2.336	2.588	3.111	3.315
500		1.648	1.965	2.334	2.586	3.107	3.310
600		1.647	1.964	2.333	2.584	3.104	3.307
∞		1.645	1.960	2.326	2.576	3.090	3.291

Appendix F. Testing to Meet Four Main Assumptions (EV, CT & OEE)

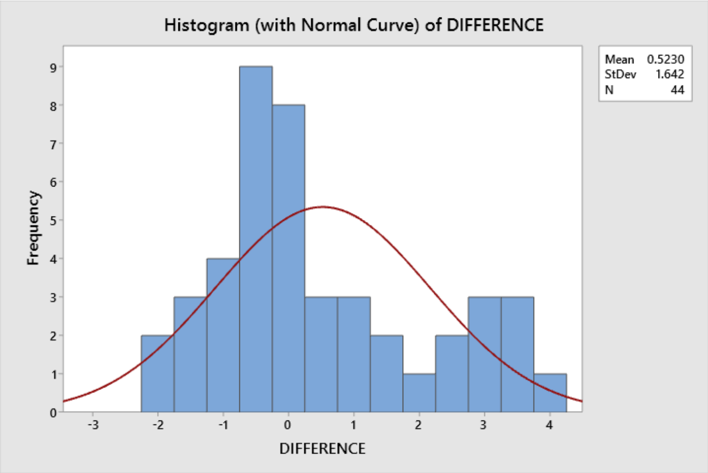
Equipment Availability

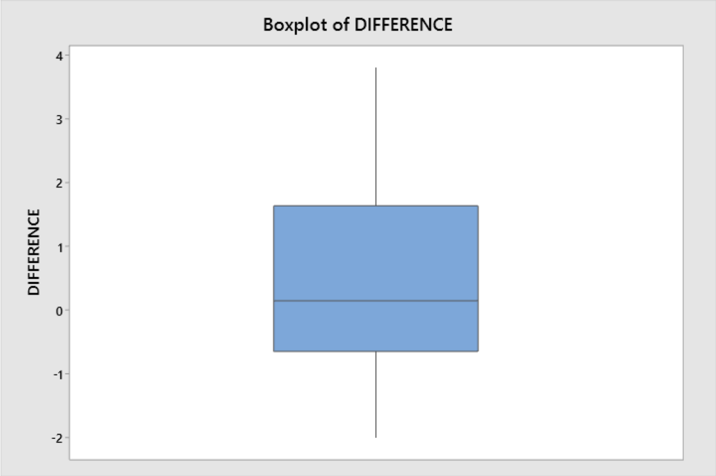


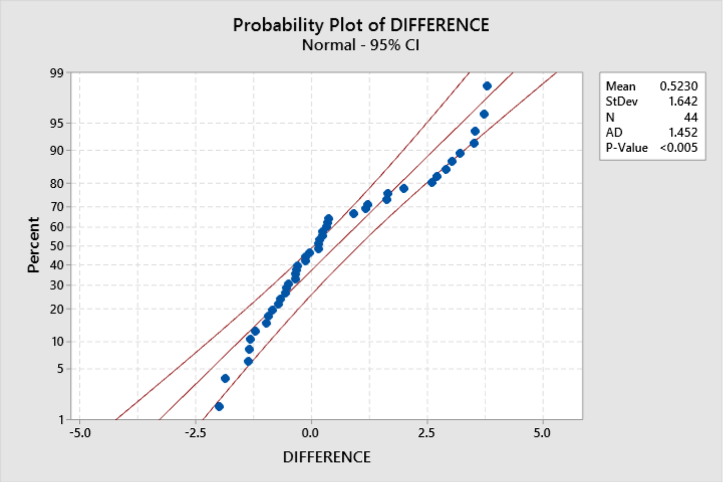




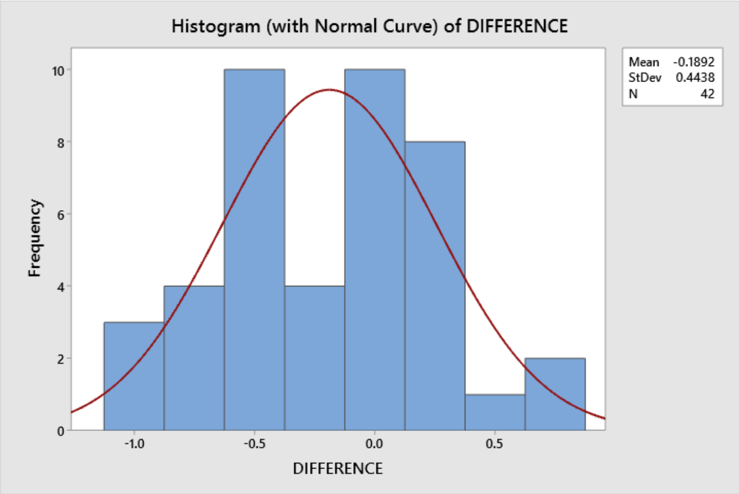
Cycle Time


Histogram (with Normal Curve) of DIFFERENCE
Mean 0.5230
StDev 1.642
N 44
Frequency
9
8
7
6
5
4
3
2
1
0
-3
-2
-1
0
1
2
3
4
DIFFERENCE

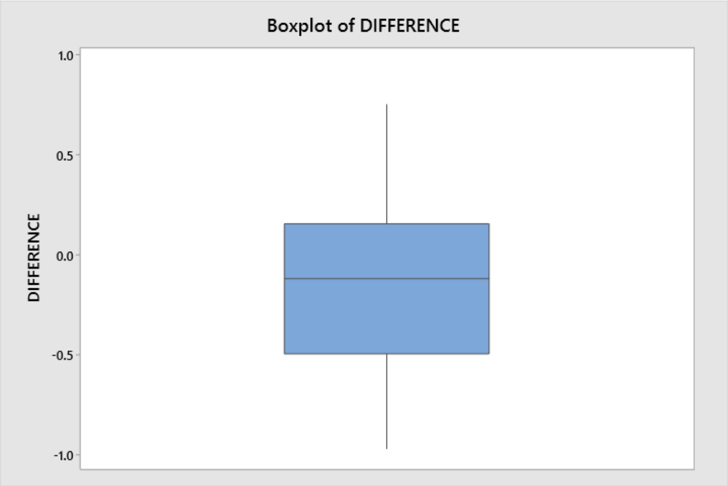

Boxplot of DIFFERENCE
DIFFERENCE
4
3
2
1
0
-1
-2


Probability Plot of DIFFERENCE
Normal - 95% CI
Mean 0.5230
StDev 1.642
N 44
AD 1.452
P-Value <0.005
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-5.0
-2.5
0.0
2.5
5.0
DIFFERENCE

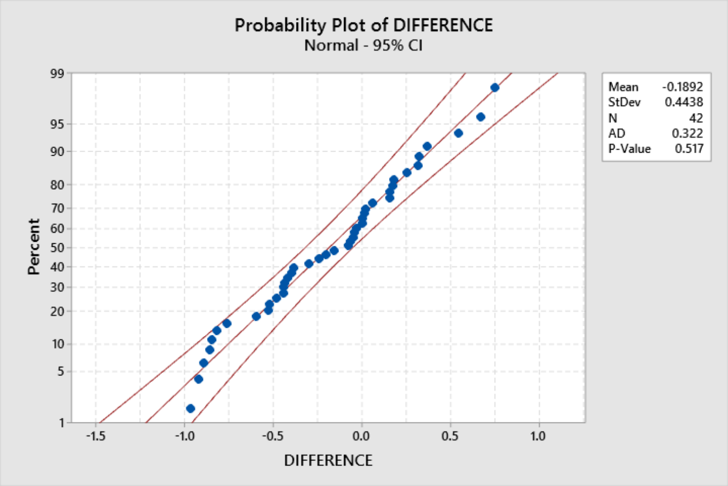
OEE



Histogram (with Normal Curve) of DIFFERENCE
Frequency
0
2
4
6
8
10
-1.0
-0.5
0.0
0.5
DIFFERENCE
Mean -0.1892
StDev 0.4438
N 42



Boxplot of DIFFERENCE
DIFFERENCE
1.0
0.5
0.0
-0.5
-1.0



Probability Plot of DIFFERENCE
Normal - 95% CI
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-1.5
-1.0
-0.5
0.0
0.5
1.0
DIFFERENCE
Mean -0.1892
StDev 0.4438
N 42
AD 0.322
P-Value 0.517

Appendix G. A Data Collection Sheet

Data	**Units**
Date	Day/month/ year
Machine Status	Run-Setup- Maintenance
Employee Number	
Job order	J0000000000
Machines name	M1
Completed quantities	0000unit
Number of defects	0000unit
Time start	Clock time
Time end	Clock time
How much time	0000 Hrs.
Machine cycle time	0000 Hrs.
Actual cycle time	0000 Hrs.
Ratio between machine time, actual cycle time	%
Employee Name	-------
Item name	-------
item description	-------
Reason for breakdown	-------

Appendix H. Production Data for OEE Simulation

Table of OEE calculation

Shift	Quality Rate	Availability Rate	Performance Rate	OEE
1	1.000	0.971	0.970	0.94
2	0.999	0.836	0.804	0.67
3	1.000	0.654	0.471	0.31
4	1.000	0.890	0.876	0.78
5	1.000	0.603	0.341	0.21
6	1.000	0.958	0.956	0.92
7	0.998	1.000	1.000	1.00
8	1.000	1.000	1.000	1.00
9	1.000	0.938	0.934	0.88
10	1.000	0.905	0.895	0.81
11	1.000	0.806	0.759	0.61
12	1.000	0.861	0.839	0.72
13	1.000	0.862	0.839	0.72
14	1.000	1.000	1.000	1.00
15	1.000	0.950	0.948	0.90
16	1.000	0.812	0.769	0.62
17	0.995	0.666	0.498	0.33
18	1.000	0.922	0.915	0.84
19	1.000	0.607	0.354	0.21
20	1.000	1.000	1.000	1.00
21	1.000	1.000	1.000	1.00
22	1.000	0.914	0.906	0.83
23	1.000	1.000	1.000	1.00
24	0.998	1.000	1.000	1.00
25	1.000	1.000	1.000	1.00
26	1.000	0.671	0.510	0.34
27	1.000	0.797	0.745	0.59
28	1.000	1.000	1.000	1.00
29	1.000	0.993	0.993	0.99
30	1.000	0.639	0.435	0.28
31	1.000	1.000	1.000	1.00
32	1.000	1.000	1.000	1.00
33	1.000	0.811	0.767	0.62
34	1.000	1.000	1.000	1.00
35	1.000	1.000	1.000	1.00
36	1.000	0.972	0.971	0.94
37	1.000	0.729	0.628	0.46
38	1.000	0.688	0.547	0.38
39	1.000	0.768	0.698	0.54

40	0.994	0.593	0.313	0.18
41	0.981	0.741	0.651	0.47
42	1.000	1.000	1.000	1.00
43	1.000	0.944	0.941	0.89
44	1.000	0.839	0.808	0.68

Appendix I. Permission to Reuse Copyrighted Materials

Lean Manufacturing Project

Abdullatif Benhassan <benhass@uwindsor.ca> Tue, Oct 23, 2018, 1:10 PM

to Chris, Walid

Dear Chris

As part of my Ph.D. research I have been studying Lean Manufacturing with Rulmeca Canada Limited and University of Windsor engage Project 2016.

I am completing a doctoral dissertation at the University of Windsor entitled "Assessment of Total Productive Maintenance (TPM) Implementation in Industrial Environment”.

I would like your permission to reuse the data collected during the project and reprint your company name in my dissertation. If you are agreed please reply to this e-mail.

Thank you

BenHassan

Abdullatif Ben Hassan
PhD. Candidate- Research Assistant
Systems Optimization Lab
University of Windsor
1192 CEI Building, Windsor, Ontario, Canada N9B 3P4
Email: benhass@uwindsor.ca
Tel: 519 253 3000 (EX. 5779)

Chris Duchene cDuchene@rulmeca.com via rulmeca.onmicrosoft.com Fri, Oct 26, 2018, 3:34 PM

to me, Walid

Ben Hassan,

I give permission to use the Rulmeca Canada name and the data collected during the study in your dissertation.

Regards,

Chris Duchene, P.Eng.
Engineering Manager

RULMECA CANADA LIMITED

Appendix J. Line Quality Rate Calculation.

The principal components loading matrix for Machine M2:

	PC1	PC2	PC3	PC4
Characteristic 1	0.009	-0.942	-0.241	-0.235
Characteristic 2	-1.000	-0.007	-0.014	0.003
Characteristic 3	-0.012	-0.238	0.970	-0.041
Characteristic 4	0.005	-0.238	-0.017	0.971

Quality characteristic	LSL	USL	Target
d	19.86	20.11	20.00
Lc	504.77	511.06	508.115
ch	13.90	14.11	14
g	8.93	9.07	9

The(LSL_{PC_i},USL_{PC_i}, T_{PC_i}) are calculated:

$$LSL_{PC_1} = U_1\, LSL$$

$$LSL_{PC1} = |0.009 \quad -1.000 \quad -0.012 \quad 0.005| \times \begin{pmatrix} 19.86 \\ 504.77 \\ 13.90 \\ 8.93 \end{pmatrix}$$

$$LSL_{PC1} = |0.17874 - 504.77 - 0.1668 + 0.04465| = 504.71341$$

$$USL_{PC_1} = U_1\, USL$$

$$USL_{PC1} = |0.009 \quad -1.000 \quad -0.012 \quad 0.005| \times \begin{pmatrix} 20.11 \\ 511.06 \\ 14.11 \\ 9.07 \end{pmatrix}$$

$$USL_{PC1} = |0.18199 - 511.06 - 0.16932 + 0.04535| = 511.00198$$

$$T_{PC_1} = U_1\, T$$

$$T_{PC_i} = |0.009 \quad -1.000 \quad -0.012 \quad 0.005| \times \begin{pmatrix} 20.00 \\ 508.115 \\ 14 \\ 9 \end{pmatrix}$$

$$T_{PC_i} = |0.18 - 508.115 - 0.168 + 0.045| = 507.058$$

$LSL_{PC_2} = U_2\, LSL$

$$LSL_{PC_2} = |-0.942 \quad -0.007 \quad -0.238 \quad -0.238| \times \begin{pmatrix} 19.86 \\ 504.77 \\ 13.90 \\ 8.93 \end{pmatrix}$$

$LSL_{PC_2} = |-18.70812 - 3.53339 - 3.3082 - 2.12534| = 24.66157 = 27.67556$

$USL_{PC_2} = U_2\, USL$

$$USL_{PC_2} = |-0.942 \quad -0.007 \quad -0.238 \quad -0.238| \times \begin{pmatrix} 20.11 \\ 511.06 \\ 14.11 \\ 9.07 \end{pmatrix}$$

$USL_{PC_2} = |-18.94362 - 3.57742 - 3.35818 - 2.1566| = 28.03582$

$T_{PC_2} = U_2\, T$

$$T_{PC_2} = |-0.942 \quad -0.007 \quad -0.238 \quad -0.238| \times \begin{pmatrix} 20.00 \\ 508.115 \\ 14 \\ 9 \end{pmatrix}$$

$T_{PC_2} = |-18.84 - 3.556805 - 3.332 - 2.142| = 27.870805$

$LSL_{PC_3} = U_3\, LSL$

$$LSL_{PC_3} = |-0.241 \quad -0.014 \quad 0.970 \quad -0.017| \times \begin{pmatrix} 19.86 \\ 504.77 \\ 13.90 \\ 8.93 \end{pmatrix}$$

$LSL_{PC_3} = |-4.78626 - 7.06678 + 13.483 - 0.15181| = 1.47815$

$USL_{PC_3} = U_3\, USL$

$$= |-0.241 \quad -0.014 \quad 0.970 \quad -0.017| \times \begin{pmatrix} 20.11 \\ 511.06 \\ 14.11 \\ 9.07 \end{pmatrix}$$

$$USL_{PC_3} = |-4.84651 - 7.15484 + 13.6867 - 0.15419| = 1.53116$$

$$T_{PC_3} = U_3\, T$$

$$T_{PC_3} = |-0.241 \quad -0.014 \quad 0.970 \quad -0.017| \times \begin{pmatrix} 20.00 \\ 508.115 \\ 14 \\ 9 \end{pmatrix}$$

$$T_{PC_3} = |-4.82 - 7.11361 + 13.58 - 0.153| = 1.49339$$

$$LSL_{PC_4} = U_4\, LSL$$

$$LSL_{PC_4} = |-0.235 \quad 0.003 \quad -0.041 \quad 0.971| \times \begin{pmatrix} 19.86 \\ 504.77 \\ 13.90 \\ 8.93 \end{pmatrix}$$

$$LSL_{PC_4} = |-4.6671 + 1.51431 - 0.5699 + 8.67103| = 4.94834$$

$$USL_{PC_4} = U_4\, USL$$

$$USL_{PC_4} = |-0.235 \quad 0.003 \quad -0.041 \quad 0.971| \times \begin{pmatrix} 20.11 \\ 511.06 \\ 14.11 \\ 9.07 \end{pmatrix}$$

$$USL_{PC_4} = |-4.72585 + 1.53318 - 0.57851 + 8.80697| = 5.03579$$

$$T_{PC_4} = U_4\, T$$

$$T_{PC_4} = |-0.235 \quad 0.003 \quad -0.041 \quad 0.971| \times \begin{pmatrix} 20.00 \\ 508.115 \\ 14 \\ 9 \end{pmatrix}$$

$$T_{PC_4} = |-4.7 + 1.524345 - 0.574 + 8.739| = 4.989345$$

Proportion of Conformance Calculation for Machine M2:

	PC1	PC2	PC3	PC4
LSL_{PC_i}	504.7134	27.67556	1.47815	4.94834
USL_{PC_i}	511.0019	28.03582	1.53116	5.03579
T_{PC_i}	507.058	27.870805	1.49339	4.989345
Proportion of Conformance	0.75656	0.938003	0.379756	0.923161

	λ_1	λ_2	λ_3	λ_4
Eigenvalue	6.3713	0.0090	0.0024	0.0006

$$P_{PC1} = pr(Z_{1PC1} \le Z \le Z_{2PC1})$$

$$Z_{2PC1} = \left(\frac{USL_{PC_1} - T_{PC_1}}{\sqrt{\lambda_1}}\right)$$

$$Z_{1PC1} = \left(\frac{LSL_{PC_1} - T_{PC_1}}{\sqrt{\lambda_1}}\right)$$

$$Z_{2PC1} = \frac{511.0019 - 507.058}{\sqrt{6.3713}} = \frac{3.9439}{\sqrt{6.3713}} = 1.56$$

$$Z_{1PC1} = \frac{504.7134 - 507.058}{\sqrt{6.3713}} = \frac{-2.3446}{\sqrt{6.3713}} = -0.9$$

$$P_{PC1} = pr(-0.9 \le Z \le 1.56) = 0.75656$$

$$P_{PC2} = pr(Z_{1PC2} \le Z \le Z_{2PC2})$$

$$Z_{2PC2} = \left(\frac{USL_{PC_2} - T_{PC_2}}{\sqrt{\lambda_2}}\right)$$

$$Z_{1PC2} = \left(\frac{LSL_{PC_2} - T_{PC_2}}{\sqrt{\lambda_2}}\right)$$

$$Z_{2PC2} = \frac{28.03582 - 27.870805}{\sqrt{0.0090}} = \frac{0.165015}{\sqrt{0.0090}} = 1.73$$

$$Z_{1PC2} = \frac{27.67556 - 27.870805}{\sqrt{0.0090}} = \frac{-0.195245}{\sqrt{0.0090}} = -2.05$$

$$P_{PC2} = pr(-2.05 \leq Z \leq 1.73) = 0.938003$$

$$P_{PC3} = pr(Z_{1PC3} \leq Z \leq Z_{2PC3})$$

$$Z_{2PC3} = \left(\frac{USL_{PC_3} - T_{PC_3}}{\sqrt{\lambda_3}}\right)$$

$$Z_{1PC3} = \left(\frac{LSL_{PC_3} - T_{PC_3}}{\sqrt{\lambda_3}}\right)$$

$$Z_{2PC3} = \frac{1.53116 - 1.49339}{\sqrt{0.0024}} = \frac{0.03777}{\sqrt{0.0024}} = 0.7$$

$$Z_{1PC3} = \frac{1.49339 - 1.47815}{\sqrt{0.0024}} = \frac{-0.01524}{\sqrt{0.0024}} = -0.31$$

$$P_{PC3} = pr(-0.31 \leq Z \leq 0.7) = 0.379756$$

$$P_{PC4} = pr(Z_{1PC4} \leq Z \leq Z_{2PC4})$$

$$Z_{2PC4} = \left(\frac{USL_{PC_4} - T_{PC_4}}{\sqrt{\lambda_4}}\right)$$

$$Z_{1PC4} = \left(\frac{LSL_{PC_4} - T_{PC_4}}{\sqrt{\lambda_4}}\right)$$

$$Z_{2PC4} = \frac{5.03579 - 4.989345}{\sqrt{0.0006}} = \frac{0.046445}{\sqrt{0.0006}} = 1.89$$

$$Z_{1PC4} = \frac{4.94834 - 4.989345}{\sqrt{0.0006}} = \frac{-0.041005}{\sqrt{0.0006}} = -1.67$$

$$P_{PC4} = pr(-1.67 \leq Z \leq 1.89) = 0.923161$$

The principal components loading matrix for Machine M3:

	PC1	PC2
Characteristic 1	0.175	0.984
Characteristic 2	0.984	-0.175

Quality characteristic	Target	USL	LSL
Width-1	1.4258	1.429	1.419
Depth-1	2.0788	2.09	2.066

The(LSL_{PC_i} USL_{PC_i} T_{PC_i}) are calculated:

$LSL_{PC_1} = U_1\, LSL$

$$LSL_{PC_1} = |0.175 \quad 0.984| \times \begin{pmatrix} 1.419 \\ 2.066 \end{pmatrix}$$

$$LSL_{PC_1} = |0.248325 + 2.032944| = 2.281269$$

$USL_{PC_1} = U_1\, USL$

$$USL_{PC_1} = |0.175 \quad 0.984| \times \begin{pmatrix} 1.429 \\ 2.09 \end{pmatrix}$$

$$USL_{PC_1} = |0.250075 + 2.05656| = 2.306635$$

$T_{PC_1} = U_1\, T$

$$T_{PC_1} = |0.175 \quad 0.984| \times \begin{pmatrix} 1.4258 \\ 2.0788 \end{pmatrix}$$

$$T_{PC_1} = |0.249515 + 2.0455392| = 2.2950542$$

$LSL_{PC_2} = U_2 \, LSL$

$$LSL_{PC_2} = |0.984 \quad -0.175| \times \begin{pmatrix} 1.419 \\ 2.066 \end{pmatrix}$$

$$LSL_{PC_2} = |1.396296 - 0.36155| = 1.034746$$

$USL_{PC_2} = U_2 \, USL$

$$USL_{PC_2} = |0.984 \quad -0.175| \times \begin{pmatrix} 1.429 \\ 2.09 \end{pmatrix}$$

$$USL_{PC_2} = |1.406136 - 0.36575| = 1.040386$$

$T_{PC_2} = U_2 \, T$

$$T_{PC_2} = |0.984 \quad -0.175| \times \begin{pmatrix} 1.4258 \\ 2.0788 \end{pmatrix}$$

$$T_{PC_2} = |1.4029872 - 0.36379| = 1.0391972$$

Proportion of Conformance Calculation for Machine M3:

	PC1	PC2
LSL_{PC_i}	2.281269	1.034746
USL_{PC_i}	2.306635	1.040386
T_{PC_i}	2.2950542	1.0391972
Proportion of Conformance	**0.839694**	**0.566899**

	λ_1	λ_2
Eigenvalue	0.000079662	0.000009805

Proportion of Conformance=the probability that Z-score is between

$\frac{LSL_{PC_i} - T_{PC_i}}{\sqrt{\lambda_i}}$ and $\frac{USL_{PC_i} - T_{PC_i}}{\sqrt{\lambda_i}}$:

$$P_{PC1} = pr(Z_{1PC1} \leq Z \leq Z_{2PC1})$$

$$Z_{2PC1} = \left(\frac{USL_{PC_1} - T_{PC_1}}{\sqrt{\lambda_1}}\right)$$

$$Z_{1PC1} = \left(\frac{LSL_{PC_1} - T_{PC_1}}{\sqrt{\lambda_1}}\right)$$

$$Z_{2PC1} = \frac{2.306635 - 2.2950542}{\sqrt{0.000079662}} = \frac{0.0115808}{\sqrt{0.000079662}} = 1.29$$

$$Z_{1PC1} = \frac{2.281269 - 2.2950542}{\sqrt{0.000079662}} = \frac{-0.0137852}{\sqrt{0.000079662}} = -1.54$$

$$P_{PC1} = pr(-1.54 \leq Z \leq 1.29) = \mathbf{0.839694}$$

==

$$P_{PC2} = pr(Z_{1PC2} \leq Z \leq Z_{2PC2})$$

$$Z_{2PC2} = \left(\frac{USL_{PC_2} - T_{PC_2}}{\sqrt{\lambda_2}}\right)$$

$$Z_{1PC2} = \left(\frac{LSL_{PC_2} - T_{PC_2}}{\sqrt{\lambda_2}}\right)$$

$$Z_{2PC2} = \frac{1.040386 - 1.0391972}{\sqrt{0.000009805}} = \frac{0.00011888}{\sqrt{0.000009805}} = 0.379$$

$$Z_{1PC2} = \frac{1.034746 - 1.0391972}{\sqrt{0.000009805}} = \frac{-0.00044512}{\sqrt{0.000009805}} = -1.4$$

$$P_{PC2} = pr(-1.4 \leq Z \leq 0.379) = \mathbf{0.566899}$$

VITA AUCTORIS

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