A PRACTICAL METHOD FOR ASSESSING MAINTENANCE FACTORS USING A
VALUE STREAM MAINTENANCE MAP

A Thesis by

Arunprakash Thiruvengadam

B.E. Mechanical Engineering, Bharathiar University, India, 2004

Submitted to the Department of Industrial Engineering
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

December 2009

A PRACTICAL METHOD FOR ASSESSING MAINTENANCE FACTORS USING A
VALUE STREAM MAINTENANCE MAP

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Industrial Engineering.

_____
Lawrence E. Whitman, Committee Chair

_____
Janet Twomey, Committee Member

_____
Ramazan Asmatulu, Committee Member

DEDICATION

To my family and friends

ABSTRACT

In today's highly competitive business environment every company is heading to increase its overall production and profit by decreasing its consumed manufacturing cost. Reduction in manufacturing cost can be effectively achieved by means of reducing the non-value added costs and activities involved in the production process. Breakdown maintenance effectiveness plays a vital role in machines availability for production. Assessing breakdown maintenance activities helps an organization to organize and effectively streamline the maintenance actions carried out in order to reduce the consumption of input resources.

In this research work, a method is proposed for assessing the breakdown maintenance factors using a value stream maintenance map (VSMM) enabling the assessment of measurable maintenance factors. To attain the proposed method, initially, various breakdown maintenance factors are identified and grouped. Then a breakdown maintenance performance measures hierarchy and a framework are developed in this thesis. Next a method which incorporates the calculation of key breakdown maintenance metrics and a VSMM along with the key breakdown maintenance metrics and their respective trends is detailed. Finally the proposed method is implemented in a hypothetical and three industrial case studies. This helps to record and assess the breakdown maintenance effectiveness of a production line and thus leading to continuous improvement opportunities.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

In order to attain world class performance, companies are striving to improve their equipment availability, overall productivity, safety and product quality. Many manufacturers are turning to lean manufacturing as a tactic to augment profits and cut unnecessary expenses. Companies are reducing the non-value added activities in all forms for each and every process in the entire organization. Breakdown maintenance activities play a critical role in an organization's production as it directly influences the availability of machines, the phase at which products are produced, the manufacturing cost of products and also product quality.

1.2 Overview to lean manufacturing

Lean manufacturing is the philosophy of systematically reducing waste by all members of the organization from all areas and in all forms (Smith and Hawkins, 2004). According to Russell and Taylor (1999) waste is any activity other than the minimum amount (in-terms of manpower, materials, assets, time & space) that essentially does not add value to the final product.

Lean assists organizations to quickly respond to the highly volatile customer needs by adding value to products at a lower cost. Lean manufacturing is commonly associated with benefits such as reduction of work in progress (WIP), reduction in production time, cycle time

reduction, improved product quality, improved flexibility, improved labor utilization, improved customer satisfaction and improved on-time deliveries (Alavi, 2003).

1.3 Significance of maintenance

Maintenance can be defined as the mix of different key efforts like technical and administrative actions in-order to retain a physical asset, or to restore it to a condition in which it can perform its intended function (British Standards Institution, 1993). Maintenance has emerged as one of the critical issues that have to be focused in an organization to keep its equipment in an available state (Duffuaa et al., 1999). Due to the increased focus on automation, managers are forced to concentrate more on bottleneck equipment maintainability.

Maintenance is considered to be an important factor influencing product quality as inconsistencies in production equipment operations lead to excessive variability in the product, thus producing a defective output. 15% to 40% of total production costs can be attributed to the maintenance department (Sheu and Krajewski, 1994). Maintenance activities should be optimized in order to maximize the output of a maintenance system. Effective maintenance helps in sustaining long term profitability for a company (Duffuaa et al., 1999).

1.4 Integrating lean manufacturing and maintenance

The key objective of integrating lean manufacturing tools and techniques with breakdown maintenance activities is to enhance equipment uptime as well as capacity by bringing down unnecessary maintenance cost and time involved. For increasing the overall performance of the equipment, various maintenance strategies have been adopted by maintenance people with

incredible efforts, however less effort has been taken to make maintenance activities more efficient (Kannan et al., 2007).

Improved maintenance performance can be achieved by taking all actions that are necessary for eliminating the non-value added activities from the maintenance task. Non-value added activities in terms of material and information can be easily categorized and analyzed visually with the aid of value stream mapping (VSM), a primary lean manufacturing tool (Tapping et al., 2002).

1.5 Need for maintenance factors assessment

The main objective of maintenance is to achieve high plant performance at low cost spent for maintenance activities. Maintenance activities play a key role in achieving an acceptable level of overall performance in an organization. In order to improve the maintenance productivity, maintenance people should assess the current state of operations that are carried out at the manufacturing facilities.

According to Parida (2007) performance measurement is used extensively to assess the efficiency and effectiveness of actions taken in a quantifiable manner. All the significant factors that affect the maintenance effectiveness are integrated in performance measurement in order to measure the effectiveness of the maintenance action. Maintenance performance indicators (MPIs) are used to measure the effectiveness of maintenance performance.

To effectively streamline the breakdown activities, maintenance factors and maintenance performance indicators should be in terms of SMART (Specific, Measurable, Appropriate, Result - oriented and Time - bound) system (Hatton and Riches (2008).

1.6 SWOT analysis

Strength, weakness, opportunities and threats for assessing maintenance factors with the aid of value stream maintenance mapping (VSMM) – a lean manufacturing tool and maintenance performance indicators are explained in this section. Table1.1 shows the SWOT analysis for assessing maintenance factors using value stream maintenance mapping (VSMM).

1.6.1 Strengths

Maintenance activities consume much non-value added time which drastically reduces the output of a manufacturing firm. In order to effectively streamline the breakdown maintenance activities, maintenance value stream mapping is employed. This helps in increasing the availability of equipment. Maintenance metrics or maintenance performance indicators (MPI's) are employed to measure the value created by the breakdown maintenance activities. Assessing the maintenance factors with the help of performance measurement technique assists to measure the effectiveness of the maintenance process and to take appropriate actions (Wireman, 1998).

1.6.2 Weaknesses

There are two main weaknesses in assessing maintenance factors. To identify and incorporate the maintenance factors effectively, companies require greater support and involvement from top management. Most organizations fail to adopt a particular method or framework that is specifically intended for them for assessing the identified maintenance factors (Parida and Chattopadhyay, 2006).

❖ Strengths
- Streamlines the maintenance activities using MVSM (Kannan et al., 2007)
- Enhances availability of the equipment (Kannan et al., 2007)
- Measures the value created by the maintenance activities (Parida and Kumar, 2006)
- Assesses the maintenance effectiveness performed (Wireman, 1998)

❖ Opportunities
- Forms the integral part of the production process (Parida and Kumar, 2006)
- Identifies untapped source in several organizations (Schnoebelen et al., 1999)
- Improves capacity of the manufacturing facility (Kannan et al., 2007)
- Improves throughput of the production line

❖ Threats
- Requires data accuracy and report appropriateness which are recurrent problems while addressing maintenance performance (Pintelon and Puyvelde, 1997)
- Requires effective communication and distribution of results (Parida and Kumar, 2006)

❖ Weaknesses
- Requires better management integration within the company (Davies and Greenough, 2004)
- Needs a standard framework for maintenance performance measurement designed for all industries (Parida and Chattopadhyay, 2006)

Figure 1.1 SWOT analysis for assessing maintenance factors using VSMM

1.6.3 Opportunities

From analyzing existing systems there is an ample opportunity to measure and streamline maintenance activities. In today's business scenario maintenance activities align to form a vital part in production process. Presently in many organizations maintenance remains an untapped source for improvement which could increase the overall production capacity and improve the throughput of a production line (Schnoebelen et al., 1999).

1.6.4 Threats

Existing systems face problems when maintenance data are communicated and transmitted inside the company. Data accuracy and report appropriateness are repetitive problems that occur in many companies while addressing the maintenance performance (Pintelon

and Puyvelde, 1997). Effective communication and distribution of results within all levels of the organization are required to reduce the communication gap between operators and managers when the results are circulated.

1.7   Thesis road map

In this section, the existing and desired conditions of the maintenance assessment factors that influence the obstacles are identified, the general strategy followed, factors that are influencing the objectives to attain the goal are described in detail. Figure 1.2 illustrates the thesis road map.

1.7.1   Existing condition

In many organizations, maintenance factors are often ignored as they are not considered as an integral part for continuous improvement.

1.7.2   Desired condition

Maintenance factors are considered as an integral part for improvement in this thesis. By developing a method for assessing a value stream maintenance map (VSMM) enabling the assessment of clearly measurable maintenance factors maintenance activities can be further streamlined and key maintenance factors can be effectively assessed.

1.7.3   Obstacles

Various obstacles that might hinder from reaching the desired condition are addressed in the following sub-divisions:
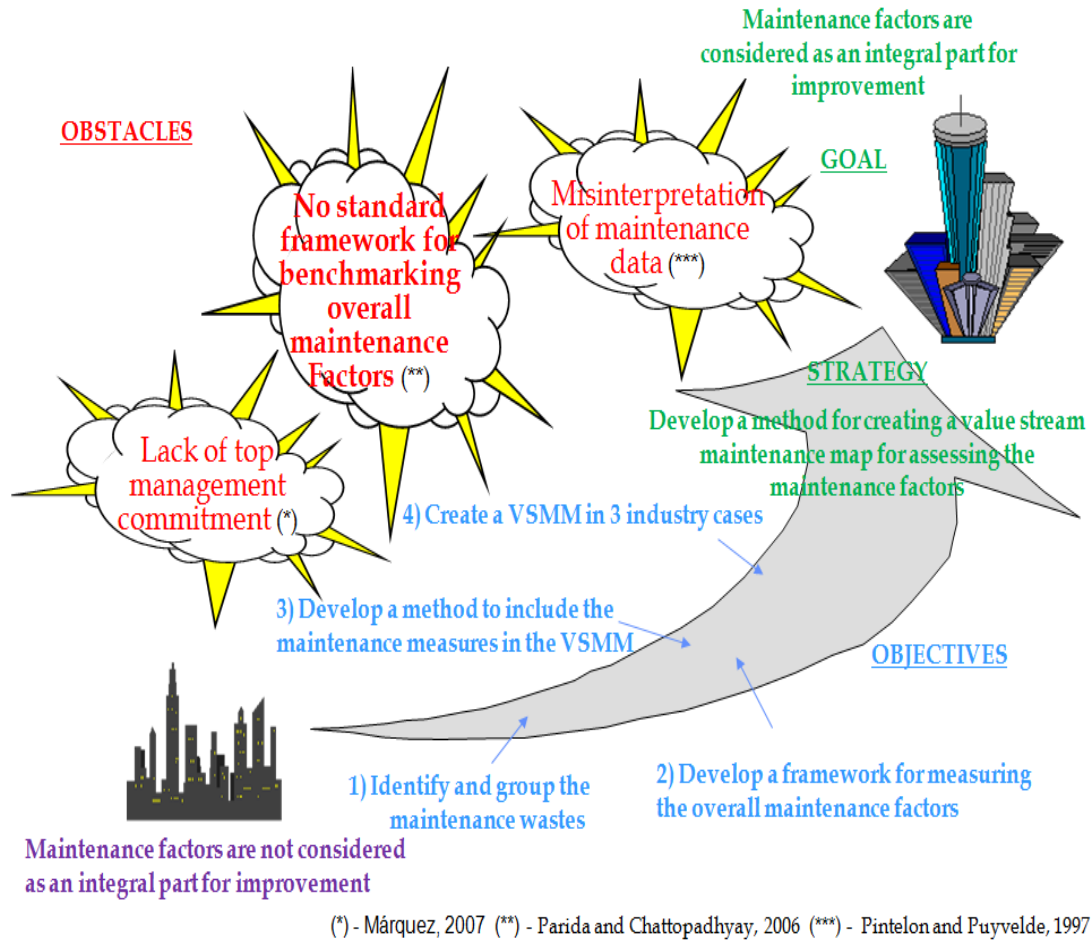
Figure 1.2 Thesis road map

- **Misinterpretation of maintenance data**

Most existing systems fail to train the personnel who are involved in the data collection. For an effective performance assessment, accuracy of maintenance data is required. Based upon the collected data maintenance managers can determine how effectively the resources allotted were utilized (Pintelon and Puyvelde, 1997). It also helps to perform improvement activities in areas that are not effectively utilized.

- **No standard framework for benchmarking overall maintenance factors**

The existing systems do not provide a standard framework for assessing maintenance factors and differentiate them in a clear method. In many organizations maintenance factors are not incorporated in the value stream map (VSM) similar to the other production factors (cycle time, changeover time, set-up time, etc.). This leads to the firm's inability to track the losses that occur due to maintenance activities.

- **Lack of top management commitment**

The impact of top management commitment plays a vital role on maintenance benchmarking. Top management does not actively support the entire process by allotting the required funds, provide training to operators and managers. In general, most organizations consider maintenance as a non-value added activity.

1.7.4 Strategy

The desired condition can be reached by following the proposed strategy. The strategy adopted for this thesis is to develop a clear method for creating a value stream maintenance map intended for assessing maintenance factors.

1.7.5 Objectives

To reach the desired condition successfully, the following objectives must be addressed clearly:

- **Identify and group the maintenance wastes**

During the breakdown maintenance process different types of wastes are identified and categorized. The different types of breakdown maintenance wastes identified are grouped and

8

documented clearly in chapter 2. By grouping (process related losses, cost related losses, material related losses, maintenance task related losses, information related losses, and employee related losses), an organization can recognize the impact of various maintenance factors that directly affect the overall production.

- **Develop a framework for measuring the overall maintenance factors**

An exclusive framework is developed which effectively measures the maintenance factors. In this framework a set of key performance indicators (KPI's) are utilized to assess the maintenance productivity. Chapter 3 will contain a table which incorporates a complete list of metrics related to breakdown maintenance. The maintenance KPI's employed are in terms of SMART (Specific, Measurable, Appropriate, Result - oriented and Time - bound) system (Hatton and Riches (2008). The breakdown maintenance framework is described in detail in chapter 3.This unique framework is integrated with the value stream map (VSM), a lean manufacturing tool in order to attain continuous improvement.

- **Develop a method to include the maintenance measures in the VSMM**

A value stream map is developed exclusively for incorporating measured maintenance values in chapter 3. The value stream maintenance mapping (VSMM) includes the maintenance factors (equipment effectiveness (E), mean time to repair (MTTR) mean time between maintenance (MTBM), etc.) as well as the production factors (cycle time, set up time, change over time, etc.). After developing a VSMM, a practical method is developed in chapter 3 to incorporate and document the assessed values of various maintenance factors.

- **Create a VSMM for 3 industry cases**

In chapter 3 the VSMM developed can be practically investigated in one hypothetical and three industrial cases for assessing the intensity of the breakdown maintenance activities.

1.8 Summary

The present scenario of breakdown maintenance activities, the performance measurement systems and also incorporating maintenance factors for assessing maintenance factors using value stream maintenance map (VSMM) were explained in the SWOT analysis. Furthermore, in the thesis road map, the existing and desired conditions of the maintenance assessment, the obstacles that could be faced, the strategy utilized and the objectives that influence in attaining the desired conditions were discussed.

1.9 Thesis report organization

The second chapter will include a literature review related to this thesis in which the basic concepts of value stream mapping, lean maintenance and the importance of assessing maintenance in an organization are discussed. Moreover it will present the importance of maintenance metrics, various organizational breakdown maintenance wastes, performance measurement (PM) systems, PM frameworks and their limitations. The third chapter will present a breakdown maintenance performance measures hierarchy and a framework which illustrates a method for calculating breakdown maintenance factors. This chapter will also include a set of breakdown maintenance metrics to help maintenance managers for assessing the breakdown maintenance effectiveness. It also explains a method to create a VSMM by incorporating maintenance factors within a VSM by incorporating a 1 hypothetical case study. The fourth chapter will contain VSMM for assessing the breakdown maintenance actions. The VSMM developed is practically investigated in 3 industrial cases for assessing the intensity of the breakdown maintenance activities. The fifth chapter will contain the obtained results from the case studies performed and recommends the possible future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the basic concepts about value stream mapping, lean maintenance and the importance of assessing maintenance in an organization are reviewed. This chapter also reviews in detail, the importance of maintenance metrics, the need for key performance indicators, maintenance and quality. Moreover various organizational breakdown maintenance wastes, performance measurement (PM) systems, PM frameworks and their limitations are discussed.

2.2 Value stream mapping

Value stream mapping (VSM), a visual tool that helps to represent graphically or in a narrative form the flows of information and material associated right from manufacturing to delivery of a product (Haik and Aomar, 2006). It helps to visualize the non-value added (NVA) activities such as enormous waste of time, effort and movement that occurs in production process by providing a linkage between the information flow and the material flow in the value stream.

A VSM provides a common language to communicate about the manufacturing process as it forms a basis for an implementation plan. Value stream mapping primarily helps management, engineers, suppliers and customers to recognize different forms of waste and its sources. It is developed to address the following issues namely: (i) an individual must understand the interdependence of one function/department (ii) to obtain the whole aspect regarding a

situation where traditional industrial engineering recording tools do not provide as much insight (Seth et al., 2008).

According to Hines and Rich (1996), a value stream map helps to assess the flows of information and material in order to eliminate waste in the form of inventory, overproduction, excessive lead time, overcapacity, excessive cycle time, wrong processing methods, NVA activities and thereby improve quality, cost and delivery.

One key metric of value stream mapping is value added time percentage which measures value added (VA) activities with non-value added (NVA) activities (Monden, 1993). VSM's also have a few limitations namely: (i) it is a technological tool, as it fails to address non-technical/human problems and (ii) it does not help to map multiple products that do not have identical production routings in a value stream (Anonymous, 2004).

2.3   Lean maintenance

Lean maintenance is defined as a maintenance philosophy that generates a desirable maintenance outcome consuming a minimum amount of inputs possible (Levitt, 2008). By applying lean manufacturing principles in maintenance environment an organization can reduce unscheduled downtime by optimizing maintenance support activities and maintenance overhead. To effectively achieve lean maintenance improvements, key lean tools such as value stream mapping (VSM) - for assessing the current situation, 5 (S) - for workplace organization, visual management tools and techniques, and other lean manufacturing tools are employed (Smith and Hawkins, 2004).

2.4 Importance of assessing maintenance

In today's highly competitive manufacturing environment the significance of the maintenance task has increased as most organizations strive to satisfy their customers by decreasing their profit margins and increasing overall productivity, availability of the equipment, safety and product quality (Al-Najjar and Alsyouf, 2003). A significant amount of overall operating costs accounts for maintenance costs. Hence it is necessary to track maintenance performance. Assessing maintenance plays a vital role in order to reduce the non value added time for maintenance tasks and effectively utilize its input resources (Dekker, 1996).

To clearly illustrate the importance of assessing maintenance, fifteen types of wastes that occur in a production environment with all its corresponding maintenance wastes are shown in table 2.1.

2.5 Metrics

Metrics are often the means to measure the current performance and effectiveness of either a process or a result. Metrics must be straight, clearly defined and brief (Smith and Mobley, 2008). Metrics serve as a basis for identifying viable opportunities for improvement, monitor effective resource utilization, and assess the significance of the improvements attained. Metrics are measured by individuals or departments that deal closer to the lower levels of the organization at high frequencies (hourly, daily, weekly, etc.). Metrics also link the upper level and the lower level of a corporation in order to identify the origin of deviation (Smith and Mobley, 2008). The following five metrics will be considered in this thesis by incorporating them in a VSM for assessing the breakdown maintenance factors.

13

Table 2.1 Lean production wastes and corresponding wastes within maintenance (Davies and Greenough, 2004)

(Ohno, 1985)	Waste of Overproduction	Excessive WIP
		Excessive PM and Predictive maintenance coverage (Davies & Greenough, 2004)
	Waste of Waiting	Non moving materials
		Less Work-order turnover (Campbell & Jardine, 2001)
	Waste of Transporting	Movement is waste
		High Breakdown frequency rate (Davies & Greenough, 2004)
	Waste of Processing	Too much variation
		Less PM and PdM Compliance execution (Davies & Greenough, 2004)
	Waste of Inventory	Excessive stock
		Low Inventory turnover rate (Davies & Greenough, 2004)
	Waste of Motions	Double handling
		High frequency of maintenance tasks (Davies & Greenough, 2004)
	Waste of Defects	Scrap, Rework
		Increase in rework percentage (SMRP, 2006)
(Bicheno, 2000)	Waste of Human Potential	Poor worker creativity
		Lack of training (SMRP, 2006)
	Inappropriate Systems	Poor record keeping
		Poor information flow (Kelly, 2006)
	Energy and Water	Energy management
		High maintenance intensity (Davies & Greenough, 2004)
	Wasted Materials	Material Conservation
		More unplanned maintenance works (Bagadia, 2008)
	Service and Office wastes	Data Legacy
		High mean time to organize (Kannan et al., 2007)
	Customer time	Customer inconvenience
		Poor Schedule compliance (SMRP, 2006)
	Defecting customers	Poor quality goods
		Lack of continuous improvement hours (SMRP, 2006)
	Physical Setting waste	Poor space configuration
		Poor physical ambience (Higgins, 1995)

14

2.5.1 Overall Equipment Effectiveness (OEE)

Overall Equipment Effectiveness (OEE) is a quantitive metric used primarily to identify and measure the productivity of an individual equipment. It improves equipment performance by identifying and measuring the losses of potential sources namely availability, performance rate, and quality rate. OEE can be used to measure and compare the overall performance of an organization, compare the production line performance, and spot the machines that require immediate maintenance (Nakajima, 1989). OEE eliminates the six big losses with the aid of an integrated workforce by means of bottom-up approach thereby increasing the efficiency of the Overall Equipment Effectiveness (Nakajima, 1988).

According to SEMI (2001), six main states of manufacturing equipment are depicted in figure 2.1. OEE comprises: AE - availability efficiency, OE - operational efficiency, RE- rate efficiency and QE - quality efficiency.

Figure 2.1 OEE equipment states (SEMI, 2001)

OEE = [AE *(OE * RE) *QE]

Where:

$$AE = \frac{\text{Equipment uptime}}{\text{Total time}}$$

$$OE = \frac{\text{Production time}}{\text{Equipment uptime}}$$

$$RE = \frac{\text{Theoretical production time for actual units}}{\text{Production time}}$$

$$QE = \frac{\text{Theoretical production time for effective units}}{\text{Theoretical production time for actual units}}$$

2.5.2   Equipment Effectiveness (E)

Equipment Effectiveness (E) is a performance measure that primarily monitors the effectiveness of individual equipment, independent of the operating surroundings. As a basis for measurement, equipment effectiveness utilizes the available effective time when compared with overall equipment effectiveness which utilizes the total time. Equipment Effectiveness (E) is a real equipment metric that monitors the equipment status by itself (Ron and Rooda, 2006).

Overall equipment effectiveness incorporates time losses due to equipment independent states such as lack of input raw materials, lack of buffer space, improper scheduling arrangements and operator unavailability. Equipment Effectiveness considers time losses that mainly occur of its own such as unplanned downtime, job setups and job reworks. OEE measures the effectiveness of the equipment and its surroundings whereas E measures the effectiveness of particular equipment independent of its surroundings in a production/manufacturing line. Unlike Overall Equipment Effectiveness (OEE), Equipment Effectiveness (E) does not rely on utilization as it is measured by the effective time and the production time. In a production line

16

two identical machines may have the same OEE whereas E may vary from one equipment to the other (Ron and Rooda, 2006). A comparison of OEE and E is shown in table 2.2

Table 2.2 OEE and E comparison (Ron and Rooda, 2006)

OEE	E
OEE includes equipment independent conditions	E includes equipment dependent conditions
OEE measures the effectiveness of the equipment and its surroundings	E measures the effectiveness of stand - alone equipment
Time base for OEE is total time	Time base for E is effective time
OEE depends upon utilization	E does not depend upon utilization
Two identical machines may have same OEE	Two identical machines may not have same E
OEE = AE * (OE * RE) * QE	E = A * R * Y

According to (Ron and Rooda, 2006), the three main sub metrics of equipment effectiveness (E) are yield (Y), rate factor (R) and availability (A). Figure 2.2 shows the different equipment states.

$$A = T_o / T_e$$

$$R = N / N_{max}$$

$$Y = N_Q / N$$

$$E = A * R * Y$$

Where,

N_Q = Number of qualified items
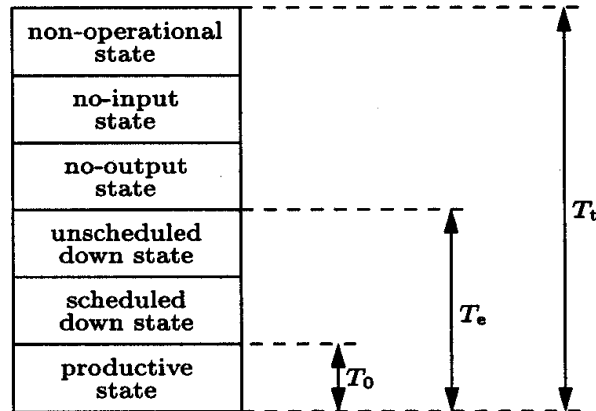
Figure 2.2 Equipment states (Ron and Rooda, 2006)

N = Total number of produced items

N_{max} = Maximum number of items that can be produced

T_o = Productive time

T_e = Effective time

2.5.3   Mean Time To Repair (MTTR)

Mean Time To Repair (MTTR) is defined as the time taken to repair failures that occur in an equipment that can be repaired. This downtime is mainly caused due to machine failures. The duration for repairing a piece of equipment depends upon the service performance of the maintenance department and maintainability (Fleischer et al., 2006).

MTTR = (Total time to restore / Number of failures) * 100……………………..….. (SMRP, 2006)

Total time to restore = E_1+ E_2+ E_3+ E_4+ E_5+ E_6....................................... (Fleischer et al., 2006)
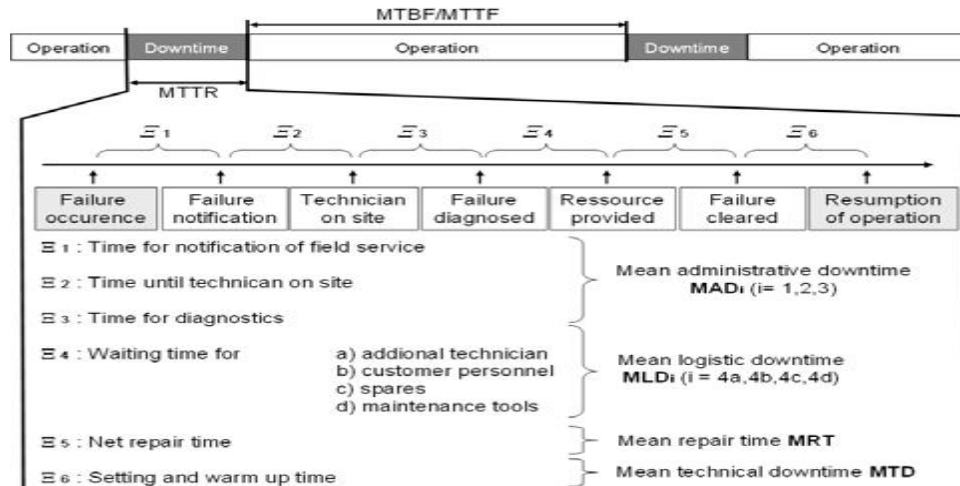
Figure 2.3 Characteristic downtime units (Fleischer et al., 2006)

Figure 2.3 and figure 2.4 shows that the maintenance crew efficiency and the design factors of the equipment have an adequate impact on mean time to repair (MTTR). By reducing the time spent on service readiness (mean administrative downtime (MAD), mean logistic downtime (MLD), mean technical downtime (MTD)) and maintainability (mean repair time (MRT)) availability of the equipment can be increased considerably.

Figure 2.4 Influences on time-related key figures of availability (Fleischer et al., 2006)

2.5.4 Mean Downtime (MDT)

Mean downtime is defined as the average downtime consumed to reinstate a piece of equipment so that it reaches its full productive capacity (SMRP, 2009). This metric includes the total time taken from failure to normal working of the equipment. MDT helps to cut short the number of maintenance crews and increase its efficiency thereby reducing the time to repair and other activities.

$$Mean\ downtime\ (MDT) = \frac{Total\ downtime\ (hours)}{Number\ of\ downtime\ events}$$ …………….………… (SMRP, 2009)

2.5.5 Mean Maintenance Lead Time (MMLT)

Mean Maintenance Lead Time (MMLT) is defined as the mean time taken to recognize the need for maintenance to the actual performance of maintenance carried out (repair) on a particular piece of equipment. It considers the time consumed initially for coordinating the maintenance tasks (MTTO), the time consumed for repairing the equipment (MTTR) and the time consumed for yielding quality product initially after maintenance process (Kannan et al., 2007).

MMLT = MTTO + MTTR + MTTY…………………………………..… (Kannan et al., 2007)

Where,

MTTO = Mean time to organize

MTTR = Mean time to repair

MTTY = Mean time to yield

Within MMLT, MTTR is the only maintenance operation that adds value because this is the effective time where the maintenance activities are performed. MTTO and MTTY are non-value added times since these are spent on maintenance activities.

Maintenance efficiency is the ratio of mean time to repair (MTTR) to mean maintenance lead time (MMLT).

$$\% \text{ Maintenance efficiency} = \frac{MTTR}{MMLT} \times 100$$

……………….… (Kannan et al., 2007)

2.6   Need for key performance indicators

Performance measurement is an essential organization principle. It classifies the existing performance gaps and the desired level of performance to be attained and recommends the possible ways to reduce the performance gaps (Parida and Chattopadhyay, 2007).

An appropriate key performance indicator plays a vital role in accurately pointing out the root cause of failures thereby improving the performance of machines. Maintenance key performance indicators are used to measure the impact of maintenance on the overall manufacturing performance (Smith and Hawkins, 2004).

Maintenance key performance indicators can be classified as leading and lagging indicators. Leading indicators monitor and measure the maintenance performance before any complexity occurs. Lagging indicators are result oriented metrics that intend actions for the deviations after completion of the activities (Smith and Hawkins, 2004).

2.7   Maintenance and quality

Maintenance is one of the significant sources that influence quality deficit, as equipment that are not properly maintained produce defective products (Raouf, 1994). Quality maintenance plays an important role in reducing the non value added time spent for maintenance activities and thereby increasing overall productivity. Production influences productivity and maintenance influences the capability for production (Daya and Duffuaa, 1995).

2.8   Organizational breakdown maintenance wastes

Breakdown maintenance has a huge impact throughout the organization. It directly influences the product cost structure (Levitt, 1997). This is due to the setback in measuring and evaluating the maintenance productivity as it is more complex within the production environment.

By properly identifying the different losses that occur within the breakdown maintenance process like equipment related losses, cost related losses, parts related losses, losses due to maintenance task itself, information related losses and customer satisfaction related losses as shown in table 2.2, management will be able to identify the factors that cause these losses in order to improve the overall breakdown maintenance efficiency.

2.8.1   Equipment/process related losses

This section explains losses that are related to individual equipment. Total downtime (scheduled and unscheduled) losses must be reduced to increase the availability. Equipment availability loss is the amount of time that particular equipment would not respond to operational demands under its normal operating condition. This leads to low utilization rate and usability of

an equipment. Frequent emergency stops and setups are non-value added activities that reduce the availability of an equipment for production.

2.8.2 Cost/finance related losses

Reducing maintenance cost related losses such as overhead, materials, equipment, sub-contractors and manpower helps in reducing the maintenance cost per unit of production.

- Stores inventory turnover measures inventory effectiveness.

- Maintenance hours measures manpower effectiveness.

- Preventive maintenance (PM) effectiveness measures work scheduling.

- Breakdown severity measures quality effectiveness.

- Sub-contracted maintenance measures sub-contracted manpower utilized.

2.8.3 Parts/material related losses

Maintenance material related losses are one of the principal maintenance support functions that lead to low maintenance effectiveness. Low stores inventory turns influences stock-outs and a high number of overdue tasks and capacity losses that increases the equipment downtime. Rework accounts for excess spares consumption indirectly increasing manpower cost and inventory value. The purchase to issue ratio depicts the amount of inventory accumulated or depleted and helps the stores personnel to effectively utilize the materials and issue work orders. Low work order turnover augments in increasing equipment downtime.

Table 2.3 Breakdown maintenance wastes

Breakdown Maintenance Wastes					
Equipment/Process Related losses	**Cost/Finance Related losses**	**Parts/Material Related losses**	**Maintenance Task Related losses**	**Information/Learning and Growth Related losses**	**Customer/Employee Satisfaction Related losses**
Equipment availability loss (Davies & Greenough, 2004)	Low inventory turnover rate (Davies & Greenough, 2004)	High stock-outs (Campbell & Jardine, 2001)	Low wrench time (SMRP, 2006)	Rework loss (SMRP, 2006)	Losses due to lack of customer retention (Kumar & Parida, 2008)
Scheduled downtime loss (SMRP, 2006)	High cost of maintenance hours (Manpower) (Duffuaa et al., 1999)	Low stores inventory turns (Levitt, 1997)	High emergency man hours (Duffuaa et al., 1999)	Improper training (SMRP, 2006)	Losses due to poor physical setting (Higgins, 1995)
Unscheduled downtime loss (SMRP, 2006)	High PM effectiveness cost (Davies & Greenough, 2004)	High number of overdue tasks (Kutucuoglu et al., 2001)	High breakdown repair hours (Cholasuke et al., 2004)	Lack of co-ordination between maintenance and production departments (Kelly, 2006)	Lack of continuous improvement hours (SMRP, 2006)
Frequent emergency stops (Kumar & Parida, 2008)	High breakdown severity loss (Davies & Greenough, 2004)	High work-orders Planned & Scheduled (Duffuaa et al., 1999	Less manpower efficiency (Campbell & Jardine, 2001)	Delays - waiting for information to be transmitted (Peters, 2006)	High repeat jobs index (Campbell & Jardine, 2001)
Low utilization rate (SMRP, 2006)	High scheduled service cost (Davies & Greenough, 2004)	Low work-order turnover (Campbell & Jardine, 2001)	More number of PM and predictive inspection (Peters, 2006)	High injury rate (Smith & Hawkins, 2004)	Higher customer complaint level (Smith & Hawkins, 2004)
Low equipment usability (Badiger & Gandhinathan, 2008)	High maintenance costs/unit of production (Duffuaa et al., 1999)	High rework % (Kelly, 2006)	High manpower utilization (Campbell & Jardine, 2001)	Low response time to urgent requests (Smith & Hawkins, 2004)	
Setup time loss (Badiger & Gandhinathan, 2008	High cost of subcontracted maintenance (Duffuaa et al., 1999)	High purchase to issue ratio (Levitt, 1997)	PM and predictive maintenance coverage (Davies & Greenough, 2004)	Low maintenance improvement justification (Priel, 1962)	
			Low degree of scheduling (Davies & Greenough, 2004)	High Training hours/employee (Smith & Hawkins, 2004)	
			Low maintenance intensity (Davies & Greenough, 2004)		
			High breakdown frequency (Davies & Greenough, 2004)		
			Overtime (SMRP, 2006)		
			Losses due to maintenance backlog (SMRP, 2006)		

2.8.4 Maintenance task related losses

This section primarily tracks a set of losses that impact the efficiency of a maintenance work carried out. High breakdown frequencies account for more manpower utilization and spares consumed. Manpower related losses like wrench time, less manpower efficiency, high emergency man hours and overtime increases equipment downtime, ready backlog and overall cost of maintenance respectively. Poor work order systems imitate the poor performance of preventive maintenance schedules (Wireman, 2005).

2.8.5 Information/learning and growth related losses

Training plays a vital role in reducing the time consumed for breakdown maintenance and tracking maintenance improvement. Coordination between the maintenance and the production departments is necessary to effectively carry out maintenance activities in less time. Providing proper training to the operators about the equipment and its operating condition reduces equipment downtime, number of rework, injury rates and increases the overall productivity.

2.8.6 Customer/employee satisfaction related losses

Employee and customer satisfaction is an important factor that has a direct impact on an organization. Lack of continuous improvement hours and physical ambiance leads to high repeat jobs, higher number of complaints and lack of customer retention which reduces the overall image of the manufacturing facility.

2.9 Performance measurement systems

Performance measurement is widely used in industries as it assesses the progress of an organization by setting goals in a quantifiable way. It provides the necessary information to decision makers for important decision making, with effective allocation of resources and monitor the current status of performance. Performance measures are categorized as follows: financial, non financial, internal, external, diagnostic, strategic, outcome and performance drivers (Tsang et al., 1999).

A performance measurement system is directly related to business strategies and do not vary much from one organization to another. According to Atkinson et al., (1997) performance measurement addresses three significant purposes, namely, coordinate, monitor and diagnostic. A performance measurement system must align with corporate (top level) objectives of an organization to effectively take part in continuous improvement.

2.9.1 PM frameworks – An overview [Adapted from Parida and Chattopadhyay, (2007)]

Until the 1950's PM addressed only the financial measures. Table 2.3 adapted from Parida and Chattopadhyay, (2007) clearly depicts different frameworks and performance measures/indicators developed by various authors and researchers namely:

- Sink and Turtle – this is the first framework to address non-financial measures like customer satisfaction, employee safety.

- Du Point pyramid – this framework concentrated only on the financial measures.

• PM matrix – this framework deals with both cost and non-cost measures that affect the result internal (production) or external (customer relationship).

• Results and determinants matrix – this framework relates the results (cost and effectiveness) with quality, flexibility and resources consumed.

• PM questionnaire – this framework is complicated and does not account for human related measures.

• Brown's framework – this framework considers only the input/output measures, processes and its outcome measures.

• SMART pyramid – this framework assists in connecting the top level management measures with the operational level measures internally and externally.

• Balanced scorecard (BSC) – this framework is adopted by many organizations as it spots and incorporates both cost and non-cost measures like financial, customer, internal business and innovation/learning.

• Consistent PM system – this framework primarily deals with measures that lead to continuous improvement.

• Framework for small business PM – this framework concentrates on both financial and non financial measures but fails to concentrate on the growth/learning related measures.

• Cambridge PM process – this framework fails to address employee satisfaction and growth/learning related measures.

• <u>Integrated dynamic PM system</u> – this framework lacks concentration in equipment related losses and internal and external measures within all levels in an organization.

• <u>Integrated PM framework</u> – this framework does not include human related measures.

• <u>Integrated PM system</u> – this framework monitors internal as well as external measures but fails to focus on employee satisfaction measures.

• <u>Dynamic PM systems</u> – this framework includes external and internal measures and do not accounts for worker/customer satisfaction measures.

• <u>Integrated measurement model</u> – this framework does not address external effectiveness.

• <u>Comparative business scorecard</u> – this framework measures external effectiveness and lacks focus on all internal effectiveness measures.

• <u>Skandia navigator</u> - this framework deals with financial, customer, process, human and continuous improvement measures.

• <u>Balanced IT scorecard</u> - this framework additionally measures the infrastructure related metrics other than balanced scorecard.

• <u>BSC of advanced information services Inc</u> – this framework primarily measures process related indicators.

• <u>Intangible asset monitor</u> - this framework monitors the internal/external structure and individual competence.

• <u>QUEST</u> - this framework gives details about quality, economic, social and technical metrics.

Table 2.4 Performance measurement (PM) frameworks (Parida and Chattopadhyay, 2007)

Model/framework	Measures/indicators/criteria	Reference
Sink and Tuttle	Efficiency, Effectiveness, Quality, Productivity, Quality of work life and innovation, Profitability/budget ability, Excellence, survival and growth	Sink and Tuttle (1989)
Du Pont Pyramid	Financial ratios, ROI	Chandler (1977); Skousen *et al.* (2001)
PM matrix	Cost factors, Non-cost factors, External factors, Internal factors	Keegan *et al.* (1989)
Results and determinants matrix	Financial performance, Competitiveness, Quality, Flexibility, Resource utilization, Innovation	Fitzgerald *et al.* (1991)
PM questionnaire	Strategies, actions and measures are assessed, Extent to which they are supportive, Data analysis as per management position or function, Range of response and level of disagreement	Dixon *et al.* (1990)
Brown's framework	Input measures, Process measures, Output measures, Outcome measures	Brown (1996)
SMART pyramid (Performance pyramid)	Quality, Delivery, Process time, Cost, Customer satisfaction, Flexibility, Productivity, Marketing measures, Financial measures	Developed by Wang Laboratories. Lynch and Cross (1991)
Balanced Scorecard (BSC)	Financial, Customer, Internal processes, Learning and growth	Kaplan and Norton (1992)
Consistent PM system	Derived from strategy, continuous improvement, fast and accurate feedback, explicit purpose, relevance	Flapper *et al.* (1996)
Framework for small business PM	Flexibility, Timeliness, Quality, Finance, Customer satisfaction, Human factors	Laitinen (1996)
Cambridge PM process	Quality, Flexibility, Timeliness, Finance, Customer satisfaction, Human factors	Neely *et al.* (1997)
Integrated dynamic PM system	Timeliness, Finance, Customer satisfaction, Human factors, Quality, Flexibility	Ghalayini *et al.* (1997)
Integrated PM framework	Quality, Flexibility, Timeliness, Finance, Customer satisfaction	Medori and Steeple (2000)
Integrated PM system	Finance, Customer satisfaction, Human factors, Quality, Flexibility, Timeliness	Bititci (1994)
Dynamic PM systems	External and internal monitoring system, Review system, Internal deployment system, IT platform needs	Bititci *et al.* (2000)
Integrated measurement model	Customer satisfaction, Human factors, Quality, Flexibility, Timeliness, Finance	Oliver and Palmer (1998)
Comparative Business Scorecard	Stakeholder value, Delight the stakeholder, Organizational learning, Process excellence	Kanji (1998)
Skandia Navigator	Financial focus, Customer focus, Human focus, Process focus, Renewal and development focus	Edvinsson and Malone (1997); Sveiby (1997)
Balanced IT Scorecard (BITS)	Financial perspective, Customer satisfaction, Internal processes, Infrastructure and innovation, People perspective	ESI (1998) as mentioned in Abran and Buglione (2003)
BSC of Advanced Information. Services Inc (AISBSC)	Financial perspective, Customer perspective Processes, People, Infrastructure and innovation	Abran and Buglione (2003)
Intangible Asset-monitor (IAM)	*Internal structure:* Growth, Renewal, Efficiency, Stability, Risk (Concept models, Computers, Administrative systems); *External structure:* Customer, Supplier, Brand names, Trademark and image; *Individual competence:* Skills, Education, Experience, Values, Social skill	Sveiby (1997)
QUEST	Quality, Economic, Social and Technical factors	Abran and Buglione (2003)
European Foundation for Quality Management (EFQM)	Leadership, Enablers: people management, policy and strategy, resources; Processes, Results: people and customer satisfaction, impact on society; and Business results	www.efqm.org/ as mentioned in Wongrassamee *et al.* (2003)

• <u>European foundation for quality management framework</u> – this framework addresses performance factors such as leadership, policy and strategy, people, process and resources. A performance measurement system must have the necessary details as it should be integrated and linked with organizational objective at all level.

2.9.2 Limitations of performance measurement systems

As the existing business environment is progressive and volatile most companies evaluate manufacturing on the basis of cost and efficiency. Many companies adopt a traditional performance measurement system that consists of poorly defined performance measures as they lack strategic values. The balanced scorecard fails to address the impact of human resources, supplier performance and fails to specify targets that determine the success level (Kennerly and Neely, 2003).

Some of the regular mistakes that companies make are summarized as follows: (1) Lack of proper relation and similarity with performance measurement metrics aligned to the organizational strategy (2) Fail to validate the links identified (3) Fail to set a right performance target (4) Lack of appropriate information that led to accurate decision making (5) Fail to measure the improvements correctly (6) Fail to concentrate on the present and future performance improvements (Parida and Kumar, 2006).

2.10 Summary

In this chapter the basic concepts of value stream mapping, the need for assessing maintenance factors using a value stream map, the significance of lean maintenance in an organizational point of view and the importance of assessing maintenance in an organization were discussed. The various types of lean production wastes and their corresponding wastes

within maintenance were also discussed in detail. The influence of maintenance metrics and key performance indicators in assessing the maintenance factors were demonstrated.

Various organizational breakdown maintenance wastes that help companies to bring down the time taken for repairing the equipments were identified and briefly described in this chapter. Additionally performance measurement frameworks and the limitations that companies generally face while implementing performance measurement systems were discussed.

An overview of different frameworks that were discussed in this chapter fails to show how indicators are calculated and a common list of breakdown maintenance indicators that can to be measured by most of the organizations irrespective to the product they manufacture. Performance measurement frameworks fail to clearly define the breakdown maintenance metrics that are to be measured by an organization. In addition, frameworks fail to address the metrics trend and their specific target level that lead to continuous improvement.

Maintenance value stream map (MVSM) developed by Sawhney et al., (2009) includes framework of new symbols for mapping the breakdown maintenance process. MVSM only evaluates the impact of the bottleneck machine within the production process. MVSM is constructed exclusively for evaluating breakdown maintenance by changing the normal VSM terminologies to calculate MMLT, MTTR, MTTO, and MTTY of the bottleneck machine.

Combining value stream mapping (VSM) with maintenance performance systems will help to clearly visualize the breakdown maintenance waste in an organization and reduce the non-value added time spent on breakdown maintenance. A method for assessing a value stream maintenance map (VSMM) enabling the assessment of clearly measurable maintenance factors will be discussed in detail in chapter 3.

CHAPTER 3

METHOD AND CASE STUDIES

3.1   Introduction

This chapter discusses lean maintenance and the importance of assessing maintenance in an organization. It also explains a breakdown maintenance performance measures hierarchy and framework which illustrates the method for calculating breakdown maintenance factors. It includes a set of forty key breakdown maintenance metrics to help maintenance managers assess the breakdown maintenance effectiveness by creating a VSMM from an existing VSM for incorporating key breakdown maintenance factors. In this chapter, calculations and incorporation of key breakdown maintenance factors and their trends are shown for a hypothetical case study and three industrial case studies performed in three different manufacturing companies. A VSMM is created for the hypothetical case study with two different key metrics along with MMLT to illustrate that any key maintenance metrics incorporated in the framework can be added in a VSMM.

3.2   Lean maintenance

Lean maintenance is defined as a maintenance philosophy that generates a desirable maintenance outcome consuming a minimum amount of inputs possible (Levitt, 2008). By applying lean manufacturing principles in a maintenance environment an organization can reduce unscheduled downtime by optimizing maintenance support activities and maintenance overhead. To effectively achieve lean maintenance improvements, key lean tools such as: value stream mapping (VSM) - for assessing the current situation, 5 (S) - for workplace organization,

32

visual management tools and techniques, and other lean manufacturing tools are employed (Smith and Hawkins, 2004).

3.3   Importance of assessing maintenance

In today's highly competitive manufacturing environment, the significance of the maintenance task has increased as most organizations strive to satisfy their customers by decreasing their profit margins and increasing overall productivity, availability of the equipment, safety and product quality (Al-Najjar and Alsyouf, 2003).

A significant amount of overall operating costs accounts for maintenance costs. Hence it is necessary to track maintenance performance. Assessing maintenance plays a vital role in order to reduce the non value added time for maintenance tasks and effectively utilize its input resources (Dekker, 1996).

3.4   Need for key performance indicators

Performance measurement is an essential organization principle. It classifies existing performance gaps and the desired level of performance to be attained and recommends the possible ways to reduce the performance gaps (Parida and Chattopadhyay, 2007). An appropriate key performance indicator plays a vital role in accurately pointing out the root cause of failures thereby improving the performance of machines.

Key maintenance performance indicators are used to measure the impact of maintenance on the overall manufacturing performance (Smith and Hawkins, 2004). Maintenance key performance indicators can be classified as leading and lagging indicators. Leading indicators monitor and measure the maintenance performance before any complexity occurs. Lagging

indicators are result oriented metrics that intend actions for the deviations after the completion of activities (Smith and Hawkins, 2004).

3.5 Organizational breakdown maintenance wastes

Breakdown maintenance has a huge impact throughout the organization. It directly influences the product cost structure (Levitt, 1997). This is due to the setback in measuring and evaluating the maintenance productivity as it is more complex within the production environment.

By properly identifying the different losses that occur within the breakdown maintenance process like equipment related losses, cost related losses, parts related losses, losses due to maintenance task itself, information related losses and customer satisfaction related losses as shown in figure 3.1, management will be able to identify the factors that cause these losses in order to improve the overall breakdown maintenance efficiency.

3.6 Metrics – An overview

Metrics are often the means to measure the current performance and effectiveness of either a process or a result. Metrics must be straight, clearly defined and brief (Smith and Mobley, 2008). Metrics serve as a basis for identifying viable opportunities for improvement, monitor effective resource utilization, and assess the significance of the improvements attained.

Metrics are measured by individuals or departments that deal closer to the lower levels of an organization at high frequencies (hourly, daily, weekly, etc.). Metrics also link the upper level and the lower level of a corporation in order to identify the origin of deviation (Smith and Mobley, 2008). The next section describes five metrics which will be considered for one

hypothetical and three industrial case studies using a VSM for assessing the breakdown maintenance factors.

3.7 Need for maintenance performance measurement

In recent times, manufacturers strive to minimize their production costs and improve customer satisfaction to remain competitive. Many organizations consider maintenance as a key issue towards reducing their production costs by increasing the overall breakdown maintenance effectiveness as well as by decreasing maintenance costs involved in breakdown maintenance.

Tsang et al., (1999) states that maintenance managers are precisely presented exactly with quantitative information by performing maintenance measurement. Necessary actions may be taken by managers to effectively improve maintenance operations in order to meet maintenance goals.

3.8 Maintenance performance measurement (MPM) (Adapted from Parida and Kumar, 2006)

An MPM system is a set of metrics adopted to measure the maintenance impact on a process in order to quantify the efficiency and effectiveness of a maintenance action or operation performed. Managers need to effectively assess the effectiveness or value created by maintenance operations. Measuring maintenance effectiveness helps managers by giving a clear view for allocating resources (manpower and materials) to perform breakdown maintenance activities thereby reducing production losses and breakdown maintenance process wastes.

MPM helps to visualize bottleneck operations of the maintenance actions performed. It helps in reducing the non-value added activities and times spent to perform maintenance. An

Figure 3.1 Breakdown maintenance wastes

MPM system consists of a set of metrics or maintenance key performance indicators (MKPI's) which measures the breakdown maintenance significance in terms of maintenance perspective and production perspective. MKPI's can help maintenance managers in achieving continuous improvement to effectively track and improve maintenance performance.

3.9   Measuring breakdown maintenance factors

Measuring maintenance effectiveness with well–proportioned measures or MKPI's will assist an organization in monitoring its maintenance performance with its business objectives as well as with another organization of its type. Maintenance effectiveness is directly related to production output. A maintenance manager needs to be familiar with breakdown maintenance measures, the effects and losses eliminated in order to place full attention on the key areas that are critical on the shop floor. The breakdown maintenance performance measures hierarchy shown in figure 3.2 was modified from Kutucuoglu et al., (2001).

The framework incorporates about 40 MKPI's related to equipment, cost, material, maintenance task, information and customer satisfaction which are further broken down into three levels namely financial, quality and process flow and productivity. MKPI's illustrated in the hierarchy are in terms of SMART (Specific, Measurable, Appropriate, Result - oriented and Time - bound) system (Hatton and Riches, 2008). Breakdown maintenance measures categorized in this hierarchy help managers to precisely assess and document cost benefits, maintenance resources to be allotted and maintenance operation enhancement prospects in order to improve the overall breakdown maintenance performance of an organization.

Figure 3.2 Breakdown maintenance performance measures hierarchy

This unique framework can be effectively utilized by the maintenance managers in many organizations regardless of its type. Few important maintenance factors such as E, MMLT and maintenance efficiency should be taken from the hierarchy and incorporated in the normal VSM. Incorporation of maintenance factors in a VSM would help maintenance managers in understanding the purpose of specific measures in the hierarchy and in assessing the overall breakdown maintenance performance and effectiveness.

3.9.1 Breakdown maintenance performance measurement framework

A framework provides details and the assumed relationships either graphically or in a descriptive type between the key factors and the variables to be reviewed (Miles and Huberman, 1994). The breakdown maintenance performance measurement framework helps to evaluate the overall effectiveness of maintenance operations performed within an organization and to provide maintenance department personnel a clear view for assessing each and every breakdown maintenance performance measure. A standard set of maintenance metrics that consists of performance measures for breakdown maintenance operations are clearly illustrated in the framework. The framework consists of forty metrics classified into three levels. These metrics are acquired from the breakdown maintenance hierarchy shown in figure 3.2. For each metric, their respective units of measure, trend, goal for each metric and formulae are shown in table 3.1 below.

This framework identifies the current breakdown maintenance performance gaps as it represents the current performance and the desired level of performance to be achieved. The framework also provides a sign of improvement for closing the performance gap by indicating an individual performance measures trend. Moreover the developed framework facilitates managers

39

to focus on the scattered breakdown measures that are vital for the continual success and effectiveness of the organization.

Table 3.1 Breakdown maintenance performance measures framework

Performance Metrics	Unit of Measure	Trend	Goal / Target	Formula
Financial Metrics				
Stores inventory turnover	Turns	⬆	> 2 – 3 (Mitchell, 2007)	$\dfrac{Cost\ of\ issues}{Inventory\ value}$ (Campbell & Jardine, 2001)
Overtime %	Percentage	⬇	< 5% (Mitchell, 2007)	$\dfrac{Total\ overtime\ worked}{Total\ hours\ worked} \times 100$ (Davies and Greenough, 2004)
Training cost	Dollars	⬇	$2 – 3K/year/worker (Smith & Hawkins, 2004)	$\dfrac{Total\ training\ cost}{Number\ of\ maintenance\ employees}$ (SMRP, 2006)
Quality Metrics				
Overall equipment effectiveness (OEE)	Percentage	⬆	> 85% (Wireman, 2005)	$[AE * (QE * RE) * QE] \times 100$ (Ron and Rooda 2006)
Equipment Effectiveness (E)	Percentage	⬆	Industry specific	$A * R * Y \times 100$ (Ron and Rooda 2006)
Mean time to repair (MTTR)	Hours	⬇	Industry specific	$\dfrac{Total\ time\ to\ restore}{Number\ of\ failures} \times 100$ (SMRP, 2006)
Equipment Availability	Percentage	⬆	> 97% (Mitchell, 2007)	$\dfrac{Equipment\ runtime}{Equipment\ runtime + breakdown\ time}$ (Davies and Greenough, 2004)
PM effectiveness cost	Dollars	⬇	Industry specific	$\dfrac{Total\ PM\ cost\ (including\ production\ losses)}{Total\ breakdown\ cost}$ (Davies and Greenough, 2004)
Scheduled service cost	Dollars	⬇	Industry specific	$\dfrac{Total\ cost\ of\ scheduled\ service}{Total\ production\ cost\ for\ same\ period}$ (Davies and Greenough, 2004)

Table 3.1 (Continued)

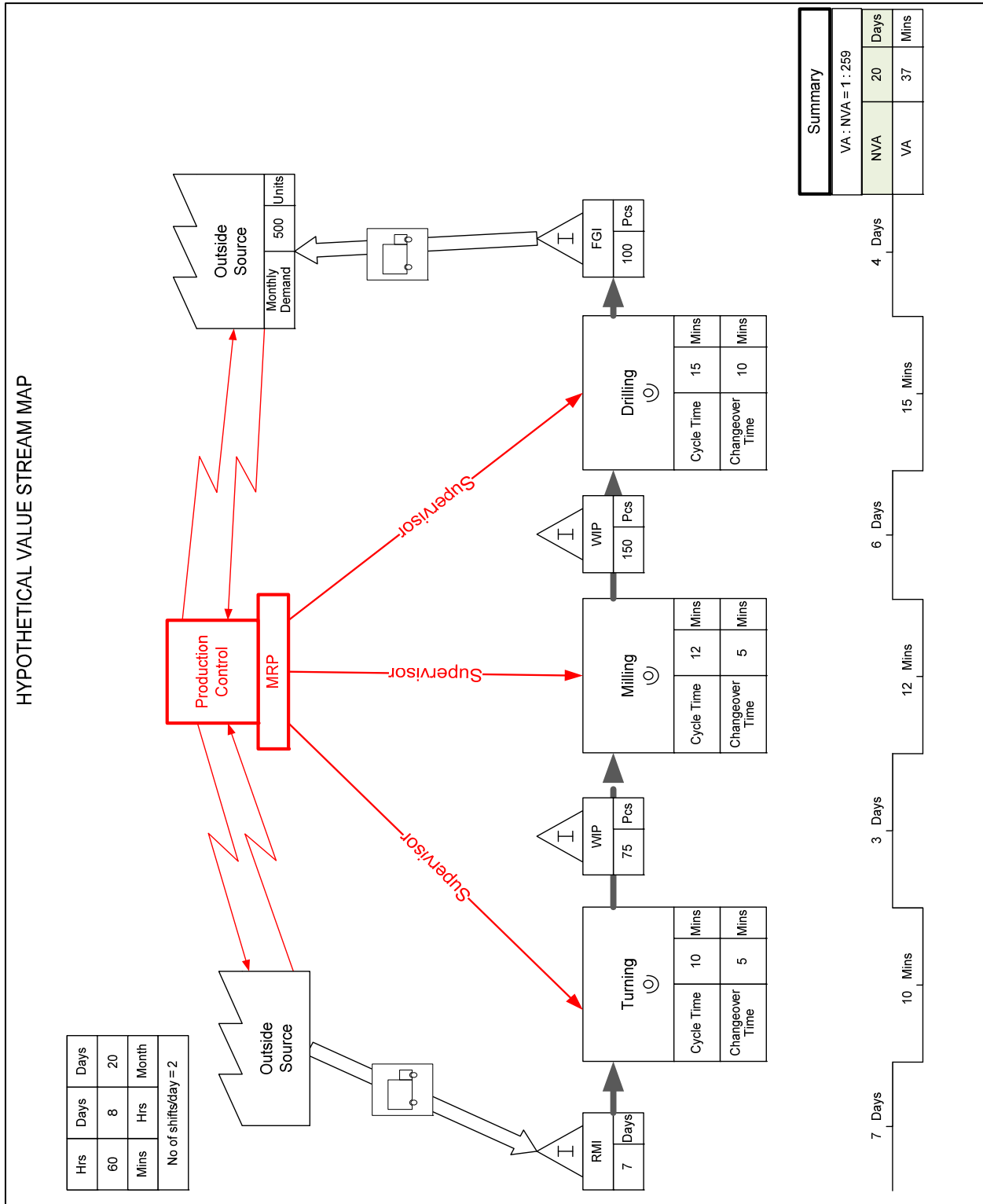| Maintenance breakdown severity	Dollars	⬇	Industry specific	$$\frac{\textit{Total cost of breakdown repairs}}{\textit{Total number of breakdowns}}$$ (Davies and Greenough, 2004)
Maintenance cost/ unit of production	Dollars	⬇	Industry specific	$$\frac{\textit{Total maintenance cost}}{\textit{Total units produced}}$$ (Duffuaa et al., 1999)
Rework percentage	Percentage	⬇	<3% (Smith & Mobley, 2008)	$$\frac{\textit{Corrective work identified as rework in actual hours}}{\textit{Total work in actual hours}} \times 100$$ (SMRP, 2006)
Percentage maintenance efficiency	Percentage	⬆	Industry specific	$$\frac{MTTR}{MMET} \times 100$$ (Kannan et al., 2007)
Maintenance intensity	Index	⬆	Industry specific	$$\frac{\textit{Total maintenance hours applied}}{\textit{Total production hours in same period}}$$ (Davies and Greenough, 2004)
PM &Predictive maintenance coverage	Percentage	⬇	60% (Mitchell, 2007)	$$\frac{\textit{Total man hours of predictive and PM}}{\textit{Total man hours worked}}$$ (Davies and Greenough, 2004)
Maintenance improvement justification	Percentage	⬆	> 7%/year (Smith & Hawkins, 2004)	$$\frac{\textit{Total cost of maintenance} + \textit{downtime losses for last period}}{\textit{Total cost of maintenance} + \textit{downtime losses for current period}}$$ (Priel, 1962)
Responsive time to urgent requests	Minutes	⬆	96% < 15min (Smith & Hawkins, 2004)	
Repeat job index	Index	⬇	Industry specific	$$\frac{\textit{Number of repeat jobs this year}}{\textit{Number of repeat jobs this year}} \times 100$$ (Campbell & Jardine, 2001)
Customer complaint level	Percentage	⬇	< 2%min (Smith & Hawkins, 2004)	
Employee complaints	Percentage	⬇	Industry specific	
Process Flow & Productivity Metrics				
Mean downtime (MDT)	Hours	⬇	Industry specific	$$\frac{\textit{Total downtime (hrs)}}{\textit{No. of downtime events}}$$ (SMRP, 2009)

Table 3.1 (Continued)

Utilization rate	Percentage	↑	Industry specific	$\dfrac{Standard\ hours}{Total\ clock\ time} \times 100$ (Priel, 1962)
Scheduled downtime	Hours	↓	Industry specific	*Sum of asset downtime identified on the weekly schedule* (SMRP, 2006)
Unscheduled downtime	Hours	↓	< 2% (Levitt, 1997)	*Sum of asset downtime elements not identified on the weekly schedule* (SMRP, 2006)
Sub-contracted maintenance hours	Percentage	↓	20 - 35% (Smith & Hawkins, 2004)	$\dfrac{Cost\ of\ sub-contracting\ (man\ power)}{Direct\ cost\ of\ maintenance} \times 100$ (Duffuaa et al., 1999)
Overdue tasks	Percentage	↓	Should not exceed 3 – 5% (Smith & Mobley, 2008)	$\dfrac{Number\ of\ jobs\ overdue\ by\ one\ week}{Number\ of\ jobs\ completed\ in\ same\ week}$ (Davies and Greenough, 2004)
Work orders Planned/Scheduled	Percentage	↓	> 85% (Gulati, 2009)	$\dfrac{Work\ orders\ Planned/Scheduled}{Total\ work\ orders\ executed} \times 100$ (Duffuaa et al., 1999)
Work order turnover	Percentage	↑	> 95% (Smith & Mobley, 2008)	$\dfrac{Number\ of\ tasks\ completed\ last\ month}{Work\ requests\ last\ month} \times 100$ (Campbell & Jardine, 2001)
Stock-outs	Percentage	↓	3 – 5% (Wireman, 2005)	$\dfrac{Total\ number\ of\ items\ not\ filled\ on\ demand}{Total\ number\ of\ items\ requested} \times 100$ (Wireman, 2005)
Degree of scheduling	Percentage	↑	Target 80% of work hours applied to scheduled work (Smith & Mobley, 2008)	$\dfrac{Hours\ scheduled}{Total\ hours\ worked}$ (Davies and Greenough, 2004)
Emergency man hours	Percentage	↓	< 20% (Wireman, 2005)	$\dfrac{Man\ hours\ spent\ on\ emergency\ jobs}{Total\ direct\ maintenance\ hours\ worked} \times 100$ (Duffuaa et al., 1999)
Manpower efficiency	Percentage	↑	> 85% (Smith & Hawkins, 2004)	$\dfrac{Wrench\ time}{Planned/allowed\ time} \times 100$ (Campbell & Jardine, 2001)
Wrench time	Percentage	↓	60 – 70% (Peters, 2006)	$\dfrac{Productive\ work\ time}{Total\ work\ time\ scheduled} \times 100$ (SMRP, 2006)
Ready backlog	Weeks	↓	2 – 4 weeks (Smith & Hawkins, 2004)	$\dfrac{Total\ of\ estimated\ hours\ of\ ready\ work}{Hours/week\ of\ crew\ capacity}$ (SMRP, 2006)

Table 3.1 (Continued)

Schedule compliance	Percentage	↑	> 90% (Smith & Hawkins, 2004)	$\dfrac{Total\ scheduled\ jobs\ completed\ as\ per\ schedule}{Total\ jobs\ scheduled}$ (Peters, 2006)
Breakdown frequencies	Percentage	↓	Industry specific	$\dfrac{Number\ of\ maintenance\ breakdowns}{Total\ number\ of\ breakdowns} \times 100$ (Davies and Greenough, 2004)
Maintenance training hours/employee (Annual)	Percentage	↓	> 100 /year (Smith & Hawkins, 2004)	$\dfrac{Total\ Training\ Hours}{Number\ of\ maintenance\ employees} \times 100$ (SMRP, 2006)
Jobs not done right at the first time	Percentage	↓	< 5% min. (Smith & Hawkins, 2004)	$\dfrac{Jobs\ not\ done\ right\ at\ first\ time}{Total\ number\ of\ jobs\ attended} \times 100$
OSHA injuries	Percentage	↓	< 5% (Smith & Hawkins, 2004)	$\dfrac{Number\ of\ OSHA\ recordable\ injuries}{100000\ labour\ hours} \times 100$ (Wireman, 1998)
Continuous improvement hours	Percentage	↑	Industry specific	$\dfrac{Internal\ labour\ hours\ used\ for\ continuous\ improvement}{Total\ internal\ maintenance\ personnel\ labour\ hours} \times 100$ (SMRP, 2006)

3.9.1.1 Financial metrics (Adapted from Mejabi, 2003)

In a competitive environment every element of business is assessed by financial metrics. The primary purpose of financial metrics is to monitor and to ensure that the maintenance department is meeting the financial goals set as per the strategic plan. Financial metrics are essential to measure and justify the significant impact over maintenance operations performed and the worth of investments made in improving breakdown maintenance process in an organization. Three vital financial metrics (stores inventory turnover, overtime percentage and training cost) detailed in the breakdown maintenance performance measures framework help maintenance managers in assessing the effectiveness of breakdown maintenance operations.

HYPOTHETICAL VALUE STREAM MAP

Hrs	Days	Days
60	8	20
Mins	Hrs	Month

No of shifts/day = 2

Summary

VA : NVA = 1 : 259		
NVA	20	Days
VA	37	Mins

Figure 3.3 Sample current state value stream map (VSM)

44

3.9.1.2 Quality metrics (Adapted from Mejabi, 2003)

Quality metrics are employed to measure operating and quality performance of the maintenance actions performed. It includes equipment management metrics and asset utilization metrics. It measures the process and equipment effectiveness in a production environment associated with the maintenance department. Seventeen essential quality metrics (overall equipment effectiveness (OEE), maintenance breakdown severity, repeat job index, customer complaint level) enumerated in the breakdown maintenance performance measures framework help maintenance managers in assess the effectiveness breakdown maintenance operations.

3.9.1.3 Process flow & productivity metrics (Adapted from Mejabi, 2003)

Process flow and productivity measures are used to assess the effectiveness of how effectively resources (man power, material) are deployed in order to meet the maintenance operation objectives. Twenty essential Process flow and productivity metrics (mean downtime (MDT), wrench time, jobs not done right the first time, continuous improvement hours) are listed in the breakdown maintenance performance measures framework to help maintenance managers assess the effectiveness breakdown maintenance operations.

3.10 Value stream map

Before a current state VSM is drawn, it is necessary to understand the maintenance department requirements for assessing maintenance factors. Factors like cycle time, changeover time and setup time are collected from the production line by visiting the company. Figure 3.3 shows a sample current state VSM.

3.11 Maintenance factors incorporation in a VSM

In this section, the method for incorporating maintenance factors in a VSM will be explained in detail for a turning process as shown in figure 3.3. Incorporating significant maintenance factors like E, MMLT, maintenance efficiency and their trends in the VSM can effectively present maintenance status and reduce the breakdown maintenance non – value added activities and the time spent in a production line. Moreover it helps maintenance managers to assess the breakdown maintenance impact over the production process which in turn reduces the resource consumed (manpower, inventory cost, materials/parts) and serve as a basis for continuous improvement.

3.11.1 Effectiveness of the equipment

Assessing equipment effectiveness (E) plays a vital role in improving its availability which in turn improves overall productivity in a manufacturing process. E and its trend gives an outline of the amount of equipment's effectiveness utilized to its full capacity. Effectiveness of the equipment will be evaluated using the MKPI's indicated in the breakdown maintenance hierarchy. Equipment effectiveness incorporated in the sample VSM is specified in terms of percentage is shown in figure 3.4

Sample calculations and notations are as follows:

A   = Equipment availability

R   = Equipment Rate

Y   = Equipment Yield

N_Q = Number of qualified items

N = Total Number of produced items

N_{max} = Maximum Number of items that can be produced

T_o = Productive time

T_e = Effective time

<u>Note</u>: Break time includes lunch time

$E = A * R * Y$……………………………………………….……..(Ron and Rooda, 2006)

Total shifts   = 2   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 10mins

Changeover time   = 5mins

Total time consumed for 1 component   = 15mins

Breakdown time (unplanned)   = 20 hrs / month

                            = 1200mins / month

Effective time (T_e)   = (number of shifts / day * number of working days / month)

          = (16 * 20)   = 320 hrs / month

          = 19200mins / month

Actual time = [(number of shifts / day – break time) * number of working days / month] – breakdown time

= (14 * 20)   = (280hrs / month) – 1200mins / month

= 15600mins/month

(T_o) Productive time $= (T_e$ - Breakdown time$)$ $= 18000$mins / month

$$N = \frac{Actual\ time}{Total\ time\ consumed\ for\ 1\ component} = \frac{15600}{15} = 1040\ components$$

$$N_{max} = \frac{Effective\ time\ (Te)}{Total\ time\ consumed\ for\ 1\ component} = \frac{19200}{15} = 1280\ components$$

$A = T_o / T_e$ $= 18000/19200$ $= 0.93$

$R = N / N_{max}$ $= 1040/1280$ $= 0.81$

$Y = N_Q / N$ $= 1019/ 1040$ $= 0.97$

Equipment effectiveness (E) = 74.3 %

Turning ⌣		
Cycle Time	10	Mins
Changeover Time	5	Mins
E	74.3	% ↑
MMLT	20	Hrs ↓
Maintenance Efficiency	75	% ↑

Figure 3.4 Incorporating E and its trend in a process box

3.11.2 Total maintenance time

Estimating total maintenance time consumed using a VSM helps to visualize the amount of non–value time consumed for performing maintenance actions in a production line. It forms the basis for improving the mean time to repair which directly impacts the mean maintenance time. The total maintenance time spent and its trend can be calculated for every process individually can be calculated as shown in this sub-division and incorporated in the sample VSM as shown in figure 3.5

MMLT = MTTO + MTTR + MTTY…………………………...………(Kannan et al., 2007)

MTTO = Mean time to organize

MTTR = Mean time to repair

MTTY = Mean time to yield

(Assuming MTTO = 3hrs, MTTR = 15hrs, MTTY = 2hrs)

MMLT = 3+15+2 = 20hrs

Mean maintenance lead time (MMLT) = 20hrs

Figure 3.5 Incorporating MMLT and its trend in a process box

3.11.3   Efficiency of maintenance process

Assessment of maintenance efficiency provides a basis for improving the effectiveness of the breakdown maintenance operations/actions carried out thereby providing continuous improvement opportunities. Mean time to repair and mean maintenance lead time are breakdown maintenance factors that have a significant impact on the maintenance efficiency. A method for calculating maintenance efficiency is shown below. Figure 3.6 portrays the incorporation of maintenance efficiency and its trend.

% Maintenance efficiency   = (MTTR / MMLT) * 100…………………...(Kannan et al., 2007)

= 15/20

= 0.75

Maintenance efficiency = 75%

Figure 3.6 Incorporating maintenance efficiency and its trend in a process box

Figure 3.7 shows a sample current state VSMM after incorporating the three key breakdown maintenance indicators in the current state VSM shown in fig 3.2. All appropriate inputs required for calculating maintenance metrics will be first collected individually for every machine from the maintenance department personnel. After analyzing the maintenance management principle, every breakdown maintenance process/operation, maintenance information distribution patterns and current state VSMM will be drawn for a production line. In the VSMM important breakdown maintenance factors like E, MMLT and maintenance efficiency are added unlike other normal process inputs like cycle time, changeover time and setup time. Apart from incorporation of breakdown maintenance factors the VSMM portrays the trend of each factor which can be used as a basis for identifying the areas of improvement in maintenance operations/activities.
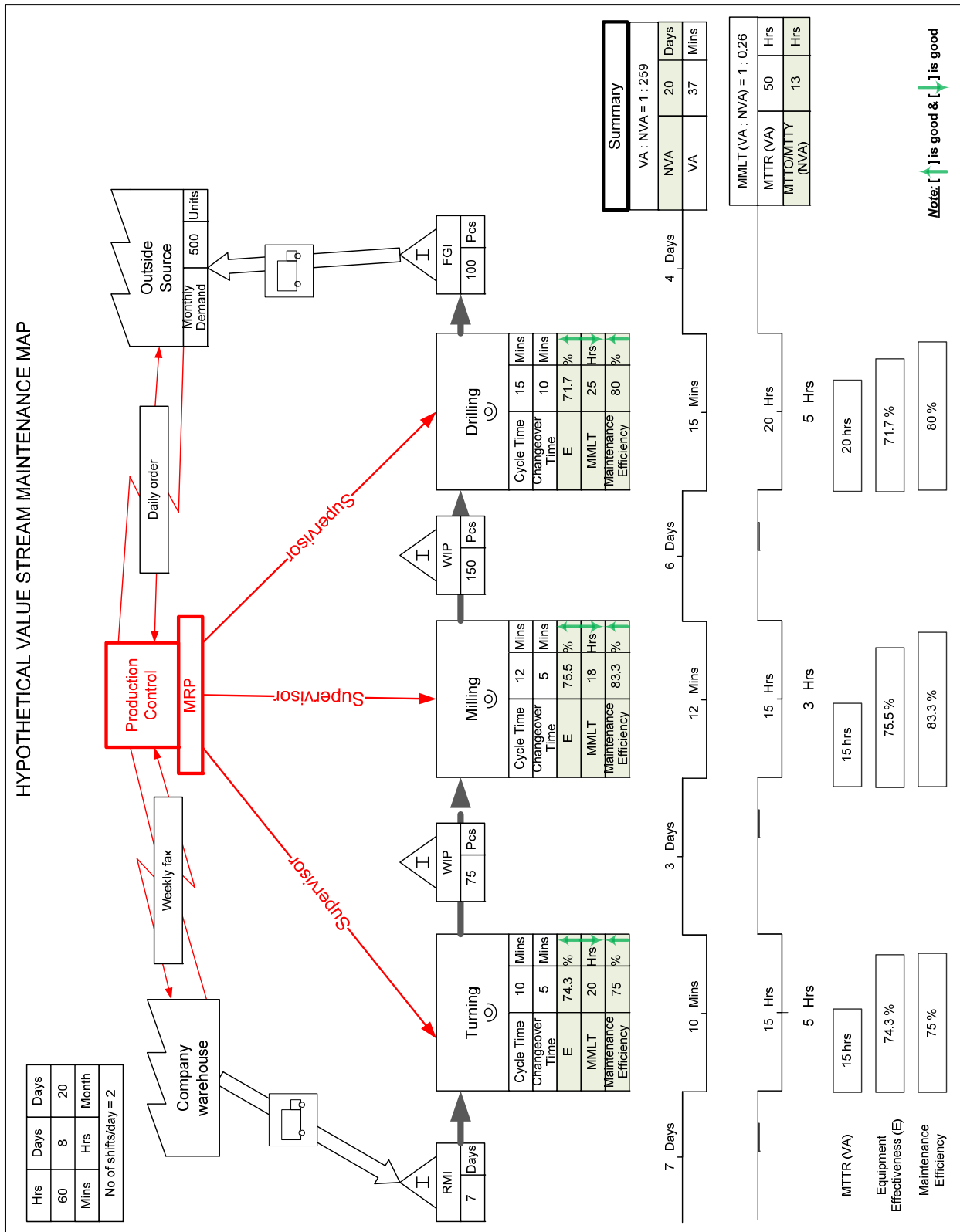
Figure 3.7 Sample current state value stream maintenance map (VSMM)

In the following section three case studies are presented for which maintenance factors are calculated and incorporated with their respective trends in a value stream maintenance map (VSMM). The VSMM can be used to assess the breakdown maintenance effectiveness of a manufacturing/production line and also helps in identifying breakdown maintenance improvement opportunities across the production line which in turn significantly benefits the organization.

3.12   Case study scenario

The case studies are performed in order to test the developed method in 3 industrial cases X, Y and Z. A current state value stream maintenance map (VSMM) is drawn for evaluating the effectiveness of the breakdown maintenance. After analyzing the integrated requirements of management, operation, distribution and maintenance work process, a VSMM is drawn for a manufacturing / assembly line by visiting the company. All inputs required for calculating the maintenance metrics from the maintenance department personnel are first collected individually for every machine. Then other inputs like cycle time, changeover time and setup time are collected additionally to incorporate in a VSMM. The measured maintenance factors are indicated in a VSMM for each process. A maintenance timeline is shown in the VSMM. The VSMM can be used as a basis for identifying the areas of maintenance improvement.

3.13 Company X overview

Company X was founded in late 80's. It produces various components and accessories for textile spinning machines, ring frames, draw frames, blow room and carding machines and provide work for about 150 employees. The company has two manufacturing units and one assembly unit located in the southern part of India. The company exports its components throughout the world.

3.13.1 Production line of a textile spindle blade

The workstations in the production line of a textile spindle blade are taken into account for this case study. The current state value stream map (VSM) is shown in figure 3.8. The company gets EN 8 steel blocks raw material shipped weekly once from its supplier. Each raw material block weighs about 1.2 pounds. The company operates 3 shifts per day and 26 days per month. The demand for the spindle blade production line is 10,000 pieces per day. The raw material is converted into a spindle blade through a series of processes and is shipped daily to assembly unit II. Workstations examined in this case study are explained in detail in the sub sections below. The defect rate is 5 percentage of the total number of produced items. A current state VSMM illustrates how the maintenance factors are incorporated as shown in figure 3.9.
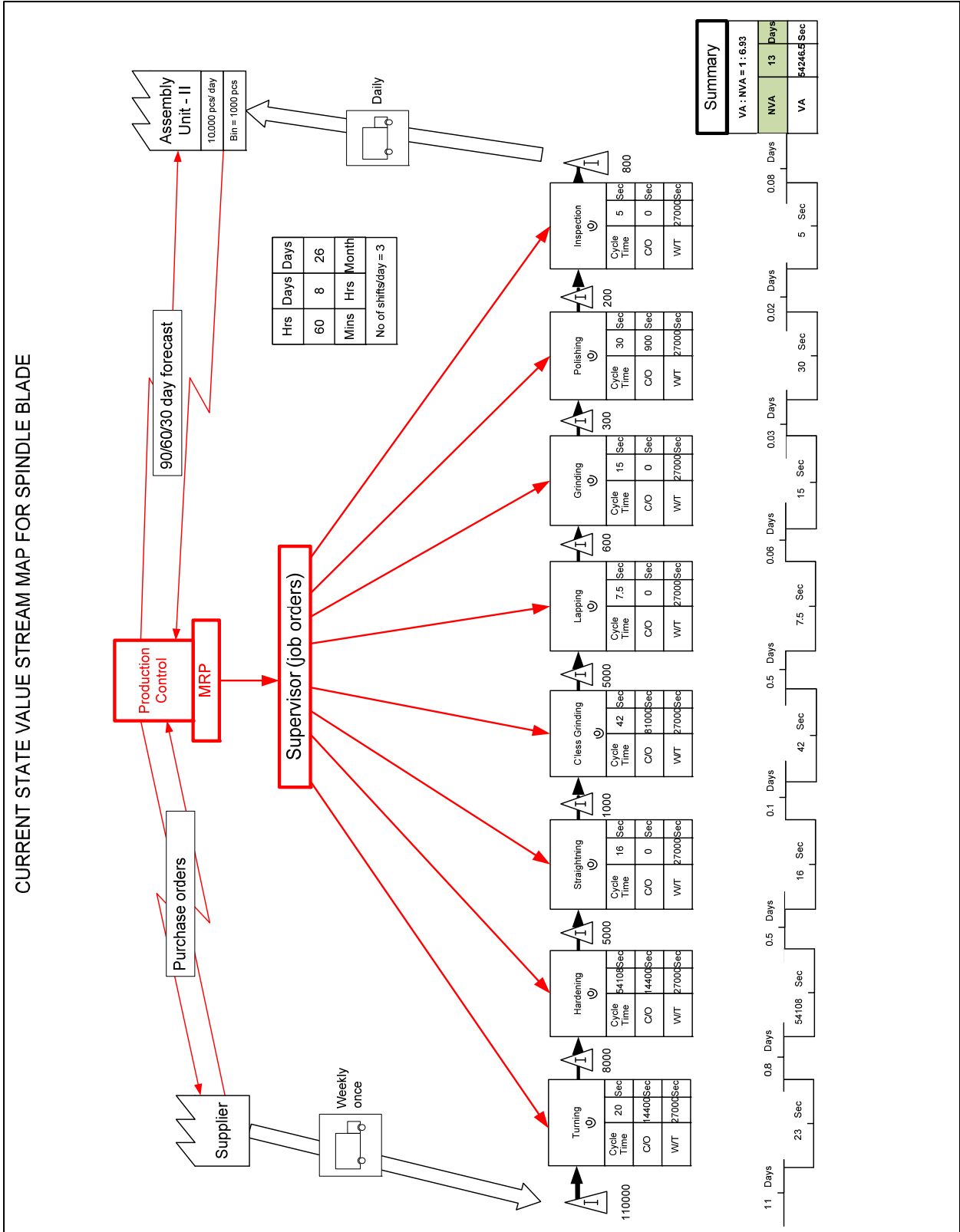
CURRENT STATE VALUE STREAM MAP FOR SPINDLE BLADE

Assembly Unit - II
10,000 pcs/ day
Bin = 1000 pcs

Daily

90/60/30 day forecast

Production Control

MRP

Purchase orders

Supplier

Weekly once

Supervisor (job orders)

	Hrs	Days	Days
	60	8	26
	Mins	Hrs	Month

No of shifts/day = 3

Turning
Cycle Time 20 Sec
C/O 14400 Sec
W/T 27000 Sec
8000

Hardening
Cycle Time 54108 Sec
C/O 14400 Sec
W/T 27000 Sec
5000

Straightning
Cycle Time 16 Sec
C/O 0 Sec
W/T 27000 Sec
1000

C'less Grinding
Cycle Time 42 Sec
C/O 81000 Sec
W/T 27000 Sec
5000

Lapping
Cycle Time 7.5 Sec
C/O 0 Sec
W/T 27000 Sec
600

Grinding
Cycle Time 15 Sec
C/O 0 Sec
W/T 27000 Sec
300

Polishing
Cycle Time 30 Sec
C/O 900 Sec
W/T 27000 Sec
200

Inspection
Cycle Time 5 Sec
C/O 0 Sec
W/T 27000 Sec
800

110000

11 Days
23 Sec

0.8 Days
54108 Sec

0.5 Days
16 Sec

0.1 Days
42 Sec

0.5 Days
7.5 Sec

0.06 Days
15 Sec

0.03 Days
30 Sec

0.02 Days
5 Sec

0.08 Days

Summary

VA : NVA = 1 : 6.93

NVA	Days	13
VA	Sec	54246.5

Figure 3.8 Current state value stream map (VSM) for spindle blade production line

55

3.13.2 Turning

Automat CNC turning machine is used for machining EN 8 steel block. The machine is pre-programmed to machine the component. Cycle time for turning process is 20 seconds. Changeover time for turning process is 14400 seconds. The work time of this machine is about 27000 seconds per shift and is operated for 3 shifts per day.

3.13.2.1 Effectiveness of the equipment

Equipment effectiveness is calculated for turning process as shown below:

Total shifts / day   = 3   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 20 sec   = 0.333 mins

Changeover time   = 14400 sec   = 240 mins

Total time consumed for 1 component   = 240.333 mins

Breakdown time (unplanned)   = 229.5 hrs/year   = 13770 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working days/month)] *12

$\qquad$ = [(24 * 26) * 60 *12] mins/year

$\qquad$ = 449280 mins/year

Actual time   = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

$\qquad$ breakdown time

$\qquad$ = {[(24 - 1.5)* 26 * 60]* 12} mins/year – 13770 mins/year

= 407430 mins/year

(T$_o$) Productive time = (T$_e$ - Breakdown time) = 435510 mins/year

A = T$_o$ / T$_e$ = 435510/449280   = 0.969

R = N / N$_{max}$ = 1695.27/1869.40   = 0.906

Y = N$_Q$ / N   = 1610.506/1695.27   = 0.950

N = 407430/240.33 = 1695.27 pieces;   N$_{max}$ = 449280/240.33 = 1869.40 pieces

E = A * R * Y……………………………………………….………….(Ron and Rooda, 2006)

Equipment effectiveness (E) = 83.47 %

Note: Break time includes lunch break and tea break

3.13.2.2   Total maintenance time

The total maintenance time spent for turning process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY………………………...……………(Kannan et al., 2007)

MMLT = 53.70 + 75.80 = 229.50 hrs/year

Mean maintenance lead time (MMLT) = 229.50 hrs/year

Note: (MTTO + MTTY = 53.70 hrs/year & MTTR = 175.80 hrs/year)

3.13.2.3   Efficiency of maintenance process

Maintenance efficiency of turning process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100……..……(Kannan et al., 2007)

                              = (175.80/229.50) * 100

Maintenance efficiency = 76.60 %

3.13.3   Straightening

After turning process, the spindle blade is hardened and then straightened using an automatic CNC straightening machine. In this machine minor bends are removed and it is flattened. The machine is pre-programmed to machine the component. Cycle time for straightening process is 16 seconds. The work time of this machine is about 27000 seconds per shift and is operated for 3 shifts per day.

3.13.3.1   Effectiveness of the equipment

Equipment effectiveness is calculated for straightening process as shown below:

Total shifts / day   = 3   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 16 sec   = 0.266 mins

Total time consumed for 1 component   = 0.266 mins

Breakdown time (unplanned)   = 80.20 hrs/year   = 4812 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working days/month)] * 12

                    = [(24 * 26) * 60 *12] mins/year

                    = 449280 mins/year

Actual time   = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

breakdown time

= {[(24 - 1.5)* 26 * 60]* 12} mins/year – 4812 mins/year

= 416388 mins/year

(T_o) Productive time = $(T_e$ - Breakdown time) = 444468 mins/year

$A = T_o / T_e$ = 444468/449280   = 0.989

$R = N / N_{max}$ = 1565368.42/1689022.55   = 0.926

$Y = N_Q / N$ = 1487100/1565368.42   = 0.950

$N = 416388/0.266 = 1565368.42$ pieces; $N_{max} = 449280/0.266 = 1689022.55$ pieces

$E = A * R * Y$…………………………………………….………….(Ron and Rooda, 2006)

Equipment effectiveness (E) = 87 %

3.13.3.2   Total maintenance time

The total maintenance time spent for straightening process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY…………………………...……(Kannan et al., 2007)

MMLT = 9.10 + 71.10 = 80.20 hrs/year

Mean maintenance lead time (MMLT) = 80.20 hrs/year

<u>Note</u>: (MTTO + MTTY = 9.10 hrs/year & MTTR = 71.10 hrs/year)

3.13.3.3 Efficiency of maintenance process

Maintenance efficiency of straightening process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100……..…………..…(Kannan et al., 2007)

= (71.10/80.20) * 100

Maintenance efficiency = 88.65 %

3.13.4 Centreless grinding

The spindle blade is sent to Cincinnati centreless grinding machine where the outer surface is grinded after the straightening process. Cycle time for centreless grinding process is 42 seconds. Changeover time for centreless grinding process is 81000 seconds. The work time of this machine is about 27000 seconds per shift and is operated for 3 shifts per day.

3.13.4.1 Effectiveness of the equipment

Equipment effectiveness is calculated for centreless grinding process as shown below:

Total shifts / day   = 3   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 42 sec   = 0.7 mins

Changeover time   = 81000 sec   = 1350 mins

Total time consumed for 1 component   = 1350.7 mins

Breakdown time (unplanned)   = 290.5 hrs/year   = 17430 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working days/month)] * 12

$$= [(24 * 26) * 60 *12] \text{ mins/year}$$

$$= 449280 \text{ mins/year}$$

Actual time $= [(\text{no. of working hrs/day} - \text{break time}) * \text{no. of working days/month}] * 12 -$

breakdown time

$$= \{[(24 - 1.5)* 26 * 60]* 12\} \text{ mins/year} - 17430 \text{ mins/year}$$

$$= 403770 \text{ mins/year}$$

(T_o) Productive time $= (T_e - \text{Breakdown time}) = 431850 \text{ mins/year}$

$A = T_o / T_e$ $= 431850/449280$ $= 0.961$

$R = N / N_{max}$ $= 298.93/332.62$ $= 0.898$

$Y = N_Q / N$ $= 283.98/298.93$ $= 0.950$

$N = 403770/1350.7 = 298.93 \text{ pieces}$; $N_{max} = 449280/1350.7 = 332.62 \text{ pieces}$

$E = A * R * Y$…………………………………………………….………….(Ron and Rooda, 2006)

Equipment effectiveness (E) = 81.99 %

3.13.4.2   Total maintenance time

The total maintenance time spent for centreless grinding process is calculated as shown below:

$MMLT = MTTO + MTTR + MTTY$…………………………...…………(Kannan et al., 2007)

MMLT = 103.15 + 187.35 = 290.50 hrs/year

Mean maintenance lead time (MMLT) = 290.50 hrs/year

<u>Note</u>: (MTTO + MTTY = 53.70 hrs/year & MTTR = 175.80 hrs/year)

3.13.4.3   Efficiency of maintenance process

Maintenance efficiency of centreless grinding process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100……..…………...…(Kannan et al., 2007)

= (187.35/290.50) * 100

Maintenance efficiency = 64.49 %

3.13.5   Lapping

After centreless grinding process spindle blade is sent to lapping machine. The machine is used to lap the blades outer surface. Cycle time for lapping process is 7.5 seconds. The work time of the machine is about 27000 seconds per shift and is operated for 3 shifts per day.

3.13.5.1   Effectiveness of the equipment

Equipment effectiveness is calculated for lapping process as shown below:

Total shifts / day   = 3   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 7.5 sec   = 0.125 mins

Total time consumed for 1 component   = 0.125 mins

Breakdown time (unplanned)   = 77 hrs/year   = 4620 mins/year

Effective time (T_e) = [(no. of working hrs/day * no. of working days/month)] * 12

$$= [(24 * 26) * 60 *12] \text{ mins/year}$$

$$= 449280 \text{ mins/year}$$

Actual time   = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

breakdown time

$$= \{[(24 - 1.5)* 26 * 60]* 12\} \text{ mins/year} – 4620 \text{ mins/year}$$

$$= 416580 \text{ mins/year}$$

(T_o) Productive time $= (T_e - \text{Breakdown time}) = 444660 \text{ mins/year}$

$A = T_o / T_e$ $= 444660/449280$ $= 0.989$

$R = N / N_{max}$ $= 3332640/3594240$ $= 0.927$

$Y = N_Q / N$ $= 3166008/3332640$ $= 0.950$

$N = 416580/0.125 = 3332640$ pieces; $N_{max} = 449280/0.125 = 3594240$ pieces

$E = A * R * Y$……………………………………………….……….(Ron and Rooda, 2006)

Equipment effectiveness (E) = 87.17 %

3.13.5.2   Total maintenance time

     The total maintenance time spent for lapping process is calculated as shown below:

$MMLT = MTTO + MTTR + MTTY$……………………………...…………(Kannan et al., 2007)

MMLT = 22.35 + 54.65 = 77 hrs/year

Mean maintenance lead time (MMLT) = 77 hrs/year

<u>Note</u>: (MTTO + MTTY = 22.35 hrs/year & MTTR = 54.65 hrs/year)

3.13.5.3 Efficiency of maintenance process

Maintenance efficiency of lapping process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100…………….……(Kannan et al., 2007)

$$= (54.65/77) * 100$$

Maintenance efficiency = 70.97 %

3.13.6 Grinding

Machined spindle blade is sent to R30 grinding machine where radius grinding operation is performed. Cycle time for radius grinding process is 15 seconds. The work time of the machine is about 27000 seconds per shift and is operated for 3 shifts per day.

3.13.6.1 Effectiveness of the equipment

Equipment effectiveness is calculated for grinding process as shown below:

Total shifts / day   = 3   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 15 sec   = 0.25 mins

Total time consumed for 1 component   = 0.25 mins

Breakdown time (unplanned)   = 186 hrs/year = 11160 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working days/month)] * 12

$$= [(24 * 26) * 60 * 12] \text{ mins/year}$$

$$= 449280 \text{ mins/year}$$

Actual time   = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

breakdown time

$$= \{[(24 - 1.5) * 26 * 60] * 12\} \text{ mins/year} – 11160 \text{ mins/year}$$

$$= 410040 \text{ mins/year}$$

(T_o) Productive time = (T_e - Breakdown time) = 438120 mins/year

$A = T_o / T_e$ = 438120/449280   = 0.975

$R = N / N_{max}$ = 1640160/1797120   = 0.912

$Y = N_Q / N$ = 1558152/1640160   = 0.950

N = 410040/0.25 = 1640160 pieces; N_{max} = 449280/0.25 = 1797120 pieces

$E = A * R * Y$…………………………………………….…………….(Ron and Rooda, 2006)

Equipment effectiveness (E) = 84.53 %

3.13.6.2   Total maintenance time

     The total maintenance time spent for radius grinding process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY…………………………………...…(Kannan et al., 2007)

MMLT = 33.60 + 152.40 = 186 hrs/year

Mean maintenance lead time (MMLT) = 186 hrs/year

<u>Note</u>: (MTTO + MTTY = 33.60 hrs/year & MTTR = 152.40 hrs/year)

3.13.6.3   Efficiency of maintenance process

Maintenance efficiency of radius grinding process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100……..…………...…(Kannan et al., 2007)

= (152.40/186) * 100

Maintenance efficiency = 81.93 %

3.13.7   Polishing

After the radius grinding process spindle blade is sent to Gala polishing machine and then finally inspected. This machine gives a glossy surface finish and the functions are automatically synchronized by means of an advanced control panel to machine the component. Cycle time for polishing process is 30 seconds. Changeover time for polishing process is 900 seconds. The work time of the machine is about 27000 seconds per shift and is operated for 3 shifts per day.

3.13.7.1   Effectiveness of the equipment

Equipment effectiveness is calculated for polishing process as shown below:

Total shifts / day   = 3   (1 shift = 8 hrs)

Cycle time (for 1 component) $\qquad$ = 30 sec $\qquad$ = 0.5 mins

Changeover time $\qquad$ = 900 sec $\qquad$ = 15 mins

Total time consumed for 1 component $\qquad$ = 15.5 mins

Breakdown time (unplanned) $\qquad$ = 161.53 hrs/year $\qquad$ = 9691.8 mins/year

Effective time (T_e) $\quad$ = [(no. of working hrs/day * no. of working days/month)] * 12

$\qquad$ = [(24 * 26) * 60 *12] mins/year

$\qquad$ = 449280 mins/year

Actual time $\quad$ = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

$\qquad$ breakdown time

$\qquad$ = {[(24 - 1.5)* 26 * 60]* 12} mins/year – 9691.8 mins/year

$\qquad$ = 411508.2 mins/year

(T_o) Productive time = (T_e - Breakdown time) = 4395288.2mins/year

$A = T_o / T_e$ $\qquad$ = 439588.2/449280 $\qquad$ = 0.978

$R = N / N_{max}$ $\qquad$ = 26548.91/28985.80 $\qquad$ = 0.915

$Y = N_Q / N$ $\qquad$ = 25221.47/26548.91 $\qquad$ = 0.950

N = 411508.2/15.5 = 26548.91 pieces; $\qquad$ N_{max} = 449280/15.5 = 28985.80 pieces

$E = A * R * Y$……………………………………………….……….(Ron and Rooda, 2006)

Equipment effectiveness (E) = 85.13 %

3.13.7.2 Total maintenance time

The total maintenance time spent for polishing process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY……………………………...……(Kannan et al., 2007)

MMLT = 33.53 + 128 = 161.53 hrs/year

Mean maintenance lead time (MMLT) = 161.53 hrs/year

Note: (MTTO + MTTY = 33.53 hrs/year & MTTR = 128 hrs/year)

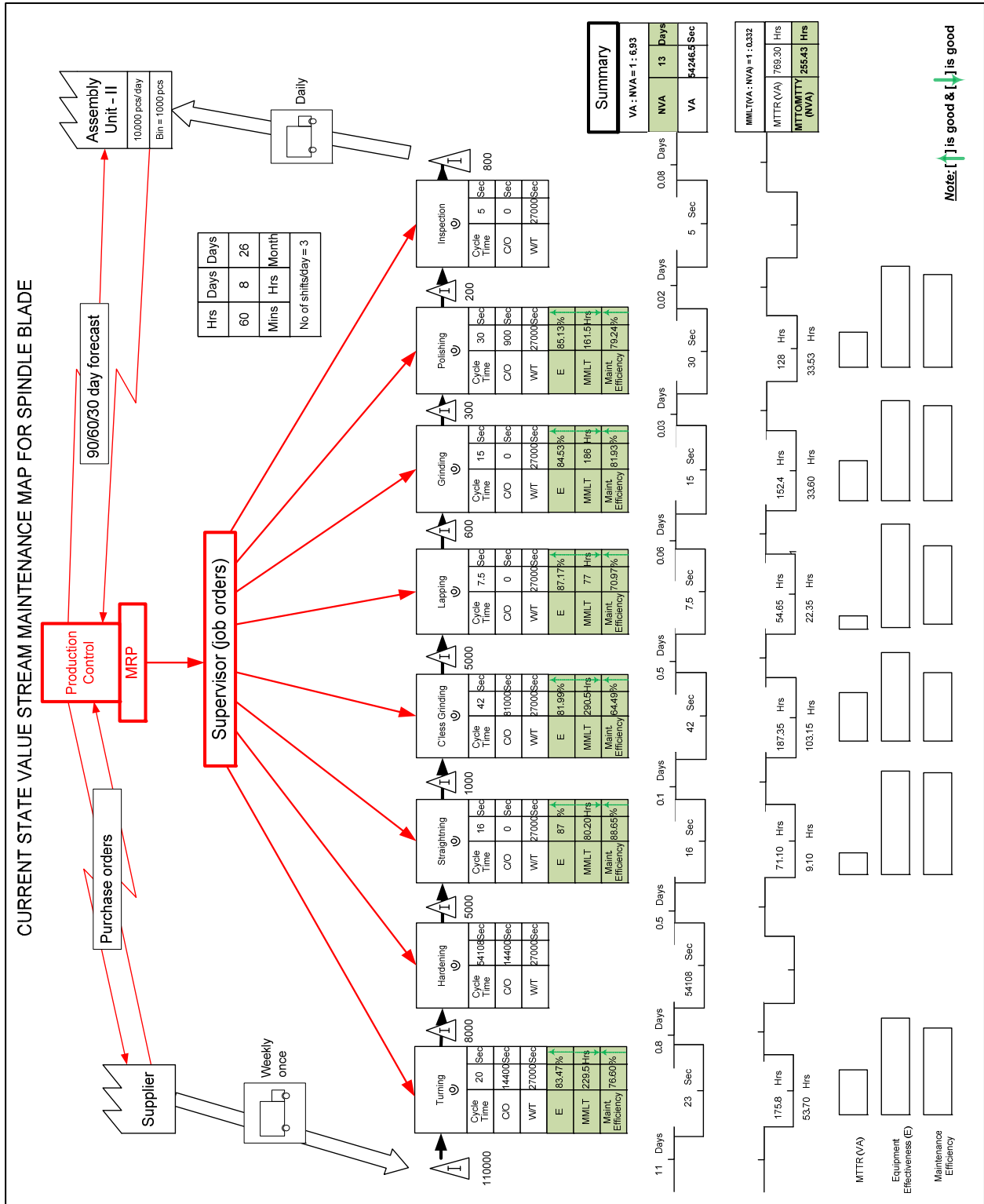### 3.13.7.3 Efficiency of maintenance process

Maintenance efficiency of polishing process is calculated as shown below:

% Maintenance efficiency = (MTTR/MMLT) * 100…..…………...……(Kannan et al., 2007)

= (128/161.53) * 100

Maintenance efficiency = 79.24 %
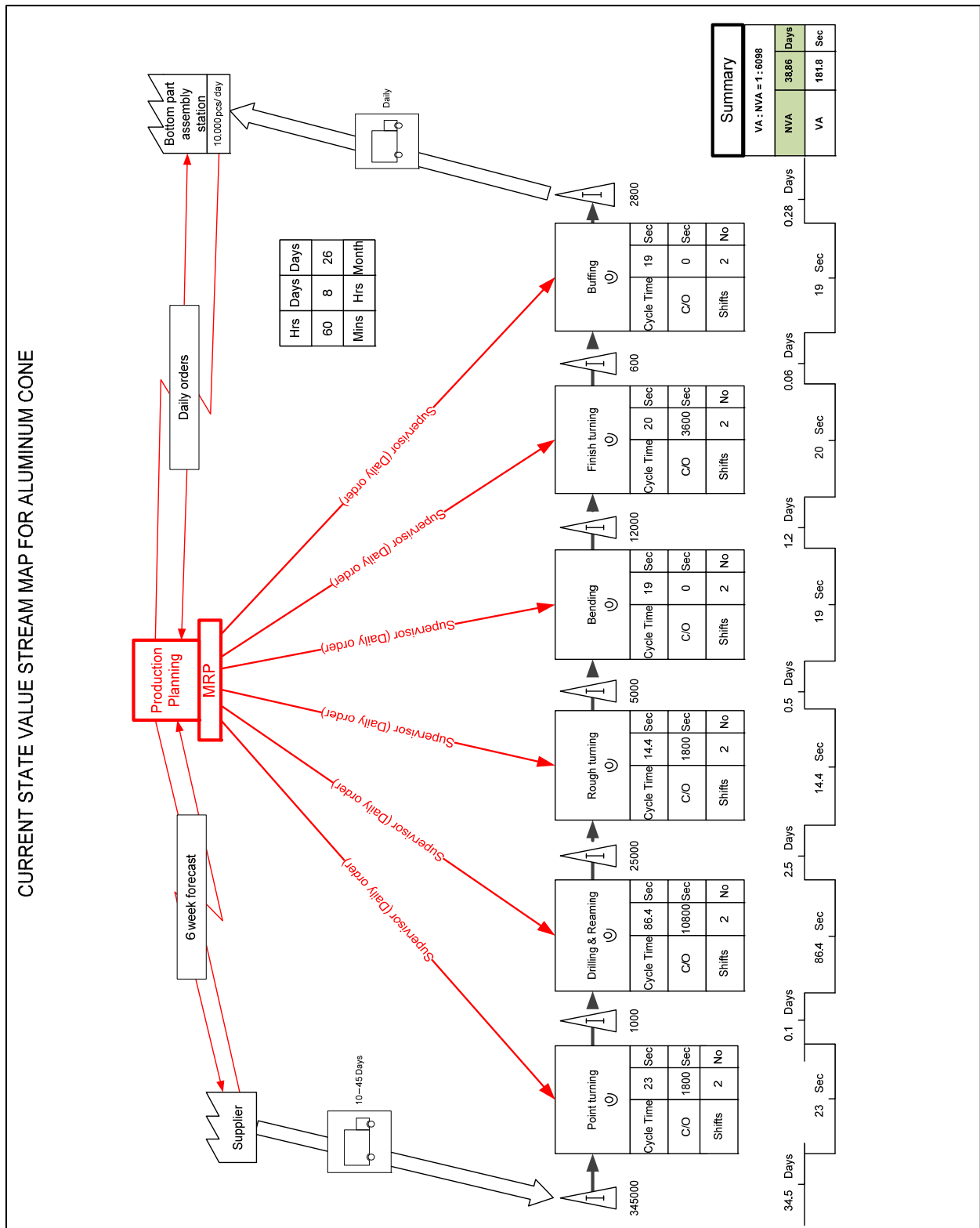
Figure 3.9 Current state value stream maintenance map (VSMM) for spindle blade production line

3.14 Company Y overview

Company Y produces various special purpose machines for chemical, paper and fiber industries. The company has two manufacturing plants in the southern part of India. The company was started in the year 1985 and it provides employment for about 250 skilled employees. The products are mainly sold in the domestic market and export its products to Brazil, Austria, Indonesia and Turkey.

3.14.1 Manufacturing line of a fiber machine aluminum cone

The machines that are associated in the production line of an aluminum cone are taken into account for performing this case study. The current state VSM is shown in figure 3.10. The company gets aluminum raw material from its supplier. The raw material inventory is stored for about 34.5 days before it gets processed. The demand for the aluminum cone is 10,000 pieces per day. The company operates 2 shifts per day and 26 days per month. The raw material is converted into an aluminum cone through a series of processes and is shipped daily to bottom part assembly station. Workstations examined in this case study are explained in detail in the sub sections below. The defect rate is 3 percentage of the total number of produced items. A current state VSMM illustrates how the maintenance factors are incorporated as shown in figure 3.11.

CURRENT STATE VALUE STREAM MAP FOR ALUMINUM CONE

Figure 3.10 Current state value stream map (VSM) for aluminum cone production line

3.14.2 Point turning

CNC turning center is used for machining the aluminum rod. In this machine, the outer surface is angle turned to form a cone. The machine is pre-programmed to machine the component. Cycle time for point turning process is 23 seconds. Changeover time for point turning process is 1800 seconds. The machine is operated for 2 shifts per day.

3.14.2.1 Effectiveness of the equipment

Equipment effectiveness is calculated for point turning process as shown below:

Total shifts / day $\qquad$ = 2 (1 shift = 8 hrs)

Cycle time (for 1 component) = 23 sec = 0.383 mins

Changeover time = 1800 sec = 30 mins

Total time consumed for 1 component = 30.383 mins

Breakdown time (unplanned) = 270.49 hrs/year = 16229.40 mins/year

Effective time (T_e) = [(no. of working hrs/day * no. of working days/month)] * 12

$\qquad$ = [(16 * 26) * 60 *12] mins/year

$\qquad$ =299520 mins/year

Actual time = [(no. of working hrs/day – break time) * no. of working days/month] * 12 – breakdown time

$\qquad$ = {[(16 - 2)* 26 * 60]* 12} mins/year – 16229.40 mins/year

$= 245850.60$ mins/year

(T_o) Productive time $= (T_e$ - Breakdown time$) = 283290.60$ mins/year

$A = T_o / T_e$ $= 283290.60/299520$ $= 0.945$

$R = N / N_{max}$ $= 8091.63/9858.04$ $= 0.820$

$Y = N_Q / N$ $= 7848.88/8091.63$ $= 0.970$

$N = 245850.6/30.3833 = 8091.63$ pieces; $N_{max} = 299520/30.3833 = 9858.04$ pieces

$E = A * R * Y$……………………………………………………......(Ron and Rooda, 2006)

Equipment effectiveness (E) = 75.30 %

3.14.2.2   Total maintenance time

The total maintenance time spent for point turning process is calculated as shown below:

$MMLT = MTTO + MTTR + MTTY$……………………………………(Kannan et al., 2007)

$MMLT = 55.95 + 207.15 + 7.39 = 270.49$ hrs/year

Mean maintenance lead time (MMLT) = 270.49 hrs/year

Note: (MTTO = 55.95 hrs/yr, MTTR = 207.15 hrs/yr & MTTY = 7.39 hrs/yr)

3.14.2.3   Efficiency of maintenance process

Maintenance efficiency of point turning process is calculated as shown below:

% Maintenance efficiency $= (MTTR/MMLT) * 100$…………..….……(Kannan et al., 2007)

$$= (207.15/270.49) * 100$$

Maintenance efficiency = 76.58%

3.14.3   Drilling and reaming

The machined aluminum rod after turning operation is sent to CNC drilling and milling machine. In this machine, inner diameter (ID) drilling and reaming operation is performed. The machine is pre-programmed to machine the component as per the drawing. Cycle time for drilling and reaming process is 86.4 seconds. Changeover time for drilling and reaming process is 10800 seconds. The machine is operated for 2 shifts per day.

3.14.3.1   Effectiveness of the equipment

Equipment effectiveness is calculated for drilling process as shown below:

Total shifts / day = 2   (1 shift = 8 hrs)

Cycle time (for 1 component) = 86.4 sec   = 1.44 mins

Changeover time = 10800 sec   = 180 mins

Total time consumed for 1 component = 181.44 mins

Breakdown time (unplanned) = 124.68 hrs/year = 7480.80 mins/year

Effective time (T_e) = [(no. of working hrs/day * no. of working days/month)] * 12

= [(16 * 26) * 60 *12] mins/year

= 299520 mins/year

74

Actual time = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

breakdown time

= {[(16 - 2)* 26 * 60]* 12} mins/year – 7480.80 mins/year

= 254599.20 mins/year

(T_o) Productive time = $(T_e$ - Breakdown time) = 292039.20 mins/year

$A = T_o / T_e$ = 292039.20/299520   = 0.975

$R = N / N_{max}$ = 1403.21/1650.79   = 0.850

$Y = N_Q / N$ = 1361.11/1403.21   = 0.970

N = 254599.20/181.44 = 1403.21 pieces; N_{max} = 299520/181.44 = 1650.79 pieces

E = A * R * Y………………………………………………….......(Ron and Rooda, 2006)

Equipment effectiveness (E) = 80.38 %

3.14.3.2 Total maintenance time

The total maintenance time spent for drilling process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY…………………………..………(Kannan et al., 2007)

MMLT = 33.06 + 80.95 + 10.67 = 124.68 hrs/year

Mean maintenance lead time (MMLT) = 124.68 hrs/year

Note: (MTTO = 33.06 hrs/yr, MTTR = 80.95 hrs/yr & MTTY = 10.67 hrs/yr)

3.14.3.3 Efficiency of maintenance process

Maintenance efficiency of drilling process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100……………......……(Kannan et al., 2007)

= (80.95/124.68) * 100

Maintenance efficiency = 64.92%

3.14.4 Rough turning

After the drilling operation, rough turning operation is performed using a special purpose CNC turning center. In this machine the inner surface of the aluminum component is turned at an angle parallel to its outer surface. The machine is pre-programmed to machine the component. Cycle time for point rough turning process is 14.4 seconds. Changeover time for rough turning process is 1800 seconds. The machine is operated for 2 shifts per day.

3.14.4.1 Effectiveness of the equipment

Equipment effectiveness is calculated for rough turning process as shown below:

Total shifts / day   = 2   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 14.4 sec   = 0.24 mins

Changeover time   = 1800 sec   = 30 mins

Total time consumed for 1 component   = 30.24 mins

Breakdown time (unplanned)   = 101.31 hrs/year = 6078.60 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working days/month)] * 12

                     = [(16 * 26) * 60 *12] mins/year

                     = 299520 mins/year

Actual time   = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

                breakdown time

                = {[(16 - 2)* 26 * 60]* 12} mins/year – 6078.60 mins/year

                = 256001.40 mins/year

(T_o) Productive time = (T_e - Breakdown time) = 293441.40 mins/year

$A = T_o / T_e$ = 293441.4/299520   = 0.9797

$R = N / N_{max}$ = 8465.65/9904.76   = 0.820

$Y = N_Q / N$ = 8211.68/8465.65   = 0.970

N = 256001.40/30.24 = 8465.65 pieces; N_{max} = 299520/30.24 = 9904.76 pieces

$E = A * R * Y$………………………………………………………......(Ron and Rooda, 2006)

Equipment effectiveness (E) = 81.22 %

3.14.4.2   Total maintenance time

    The total maintenance time spent for rough turning process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY……………………………...……(Kannan et al., 2007)

MMLT = 25.91 + 68.33 + 7.07 = 101.31 hrs/year

Mean maintenance lead time (MMLT) = 101.31 hrs/year

<u>Note:</u> (MTTO = 25.91 hrs/yr, MTTR = 68.33 hrs/yr & MTTY = 7.07 hrs/yr)

3.14.4.3   Efficiency of maintenance process

Maintenance efficiency of rough turning process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100…..…………..……(Kannan et al., 2007)

= (68.33/101.31) * 100

Maintenance efficiency = 67.44%

3.14.5   Bending

The rough turned aluminum cone piece is sent to an automatic CNC bending machine for removing minor bends on its surface. The machine is pre-programmed to machine the component. Cycle time for bending process is 19 seconds. The machine is operated for 2 shifts per day.

3.14.5.1   Effectiveness of the equipment

Equipment effectiveness is calculated for bending process as shown below:

Total shifts / day   = 2   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 19 sec   = 0.3166 mins

Total time consumed for 1 component   = 0.3166 mins

Breakdown time (unplanned)   = 234.50 hrs/year   = 14070 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working days/month)] * 12

           = [(16 * 26) * 60 *12] mins/year

           = 299520 mins/year

Actual time   = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

           breakdown time

           = {[(16 - 2)* 26 * 60]* 12} mins/year – 14070 mins/year

           = 248010 mins/year

(T_o) Productive time = (T_e - Breakdown time) = 285450 mins/year

$A = T_o / T_e$ = 285450/299520   = 0.953

$R = N / N_{max}$ = 783354.39/946051.80   = 0.828

$Y = N_Q / N$ = 759853.75/783354.39   = 0.970

$N = 248010/0.3166 = 783354.39$ pieces; $N_{max} = 299520/0.3166 = 946051.80$ pieces

E = A * R * Y………………………………………………….......(Ron and Rooda, 2006)

Equipment effectiveness (E) = 76.54 %

3.14.5.2   Total maintenance time

The total maintenance time spent for bending process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY………………………………..………(Kannan et al., 2007)

MMLT = 62.55 + 165.25 + 6.70 = 234.50 hrs/year

Mean maintenance lead time (MMLT) = 234.50 hrs/year

<u>Note:</u> (MTTO = 62.55 hrs/yr, MTTR = 165.25 hrs/yr & MTTY = 6.70 hrs/yr)

3.14.5.3 Efficiency of maintenance process

Maintenance efficiency of bending process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100……..…………...…(Kannan et al., 2007)

= (165.25/234.50) * 100

Maintenance efficiency = 70.46%

3.14.6 Finish turning

A special purpose CNC turning center is used for machining the aluminum cone. In this machine, fine turning operation is performed. The machine is pre-programmed to machine the component. Cycle time for finish turning process is 20 seconds. Changeover time for finish turning process is 3600 seconds. The machine is operated for 2 shifts per day.

3.14.6.1 Effectiveness of the equipment

Equipment effectiveness is calculated for finish turning process as shown below:

Total shifts / day   = 2   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 20 sec   = 0.333 mins

Changeover time $\qquad$ = 3600 sec $\qquad$ = 60 mins

Total time consumed for 1 component $\qquad$ = 60.333 mins

Breakdown time (unplanned) $\qquad$ = 61.80 hrs/year $\qquad$ = 3708 mins/year

Effective time (T_e) = [(no. of working hrs/day * no. of working days/month)] * 12

$\qquad$ = [(16 * 26) * 60 *12] mins/year

$\qquad$ = 299520 mins/year

Actual time = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

breakdown time

$\qquad$ = {[(16 - 2)* 26 * 60]* 12} mins/year – 3708 mins/year

$\qquad$ = 258372 mins/year

(T_o) Productive time = (T_e - Breakdown time) = 295812 mins/year

$A = T_o / T_e$ $\qquad$ = 295812/299520 $\qquad$ = 0.987

$R = N / N_{max}$ $\qquad$ = 4282.43/4964.44 $\qquad$ = 0.820

$Y = N_Q / N$ $\qquad$ = 4153.95/4282.43 $\qquad$ = 0.970

$N = 258372/60.333 = 4282.43$ pieces; $\qquad$ $N_{max} = 299520/60.333 = 4964.44$ pieces

$E = A * R * Y$……………………………………………………………......(Ron and Rooda, 2006)

Equipment effectiveness (E) = 82.63 %

3.14.6.2 Total maintenance time

The total maintenance time spent for finish turning process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY…………………………...………(Kannan et al., 2007)

MMLT = 11.72 + 48.09 + 1.99 = 61.80 hrs/year

Mean maintenance lead time (MMLT) = 61.80 hrs/year

Note: (MTTO = 11.72 hrs/yr, MTTR = 48.09 hrs/yr & MTTY = 1.99 hrs/yr)

3.14.6.3 Efficiency of maintenance process

Maintenance efficiency of finish turning process is calculated as shown below:

% Maintenance efficiency = (MTTR/MMLT) * 100…..…………...……(Kannan et al., 2007)

= (48.09/61.80) * 100

Maintenance efficiency = 77.81%

3.14.7 Buffing

Finally, the aluminum cone is buffed using a buffing machine for removing the burrs attached to its surface and polishing. After the buffing operation the aluminum cone is shipped to the bottom part assembly station. Cycle time for buffing process is 19 seconds. The machine is operated for 2 shifts per day.

3.14.7.1 Effectiveness of the equipment

Equipment effectiveness is calculated for buffing process as shown below:

Total shifts / day $= 2$ (1 shift = 8 hrs)

Cycle time (for 1 component) $= 19$ sec $= 0.3166$ mins

Total time consumed for 1 component $= 0.3166$ mins

Breakdown time (unplanned) $= 135.70$ hrs/year $= 8142$ mins/year

Effective time (T_e) $= [(\text{no. of working hrs/day} * \text{no. of working days/month})] * 12$

$= [(16 * 26) * 60 *12]$ mins/year

$= 299520$ mins/year

Actual time $= [(\text{no. of working hrs/day} – \text{break time}) * \text{no. of working days/month}] * 12 –$

breakdown time

$= \{[(16 - 2) * 26 * 60] * 12\}$ mins/year $– 8142$ mins/year

$= 253938$ mins/year

(T_o) Productive time $= (T_e - \text{Breakdown time}) = 291378$ mins/year

$A = T_o / T_e$ $= 291378/299520$ $= 0.972$

$R = N / N_{max}$ $= 802078.33/946051.80$ $= 0.847$

$Y = N_Q / N$ $= 778015.98/802078.33$ $= 0.970$

$N = 253938/0.3166 = 802078.33$ pieces; $N_{max} = 299520/0.3166 = 946051.80$ pieces

$E = A * R * Y$………………………………………………….......(Ron and Rooda, 2006)

Equipment effectiveness (E) = 79.99 %

3.14.7.2 Total maintenance time

The total maintenance time spent for buffing process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY……………………………...……(Kannan et al., 2007)

MMLT = 29.40 + 100.60 + 5.70 = 135.70 hrs/year

Mean maintenance lead time (MMLT) = 135.70 hrs/year

Note: (MTTO = 29.40 hrs/yr, MTTR = 100.60 hrs/yr & MTTY = 5.70 hrs/yr)

3.14.7.3 Efficiency of maintenance process

Maintenance efficiency of buffing process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100………………..……(Kannan et al., 2007)

= (100.60/135.70) * 100

Maintenance efficiency = 74.13%

3.15 Company Z overview

Company Z was started in the year 1960. The company is involved in producing various types of aircrafts such as business aircraft, commercial aircraft and also provides specialized aircraft solutions. The aerospace division of the company operates with a huge workforce of around 28,000 employees and is serving in several markets globally in more than 60 countries. In USA it has six manufacturing sites including one in Wichita, Kansas where the company manufacturers and services its business as well as regional aircrafts.
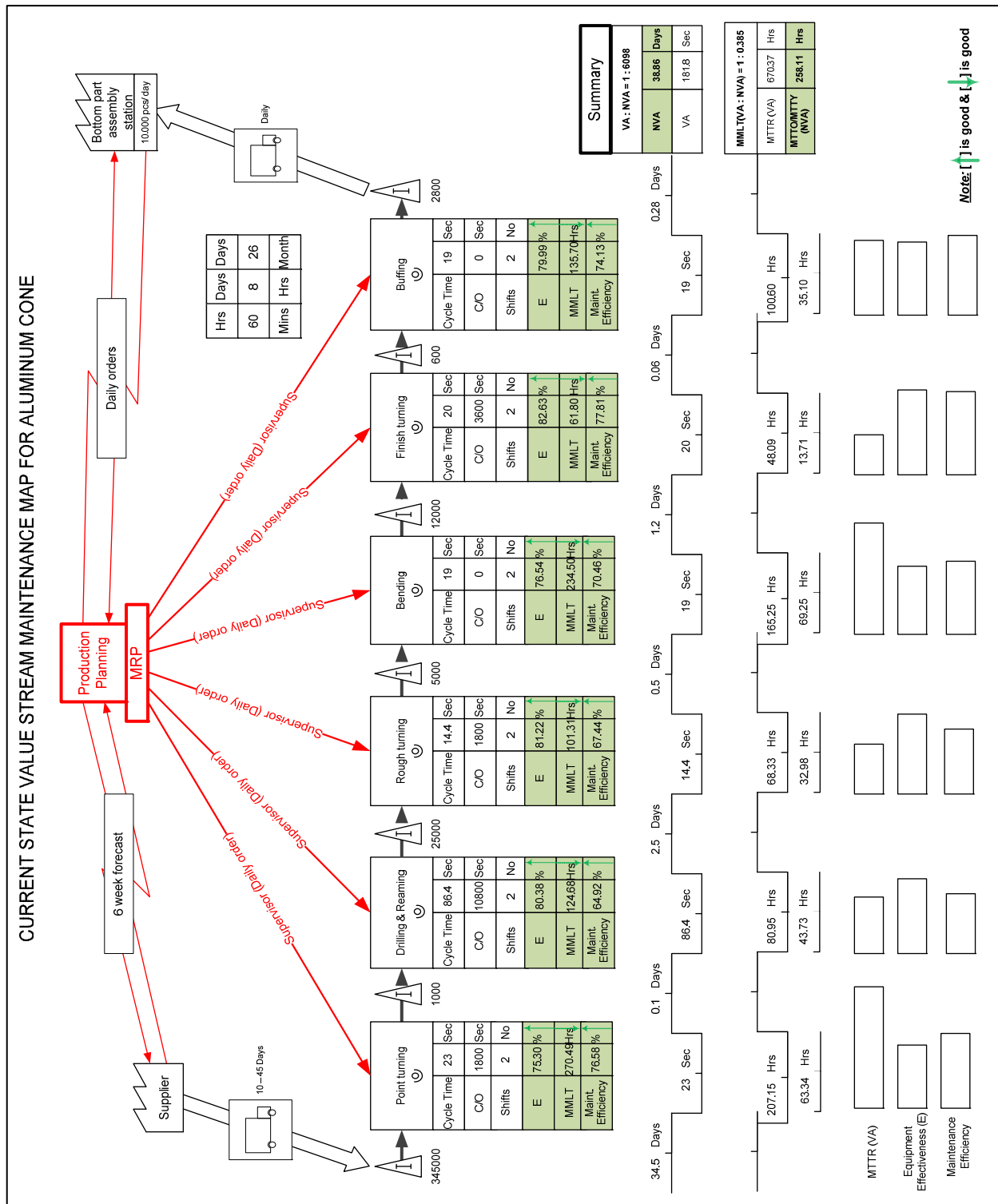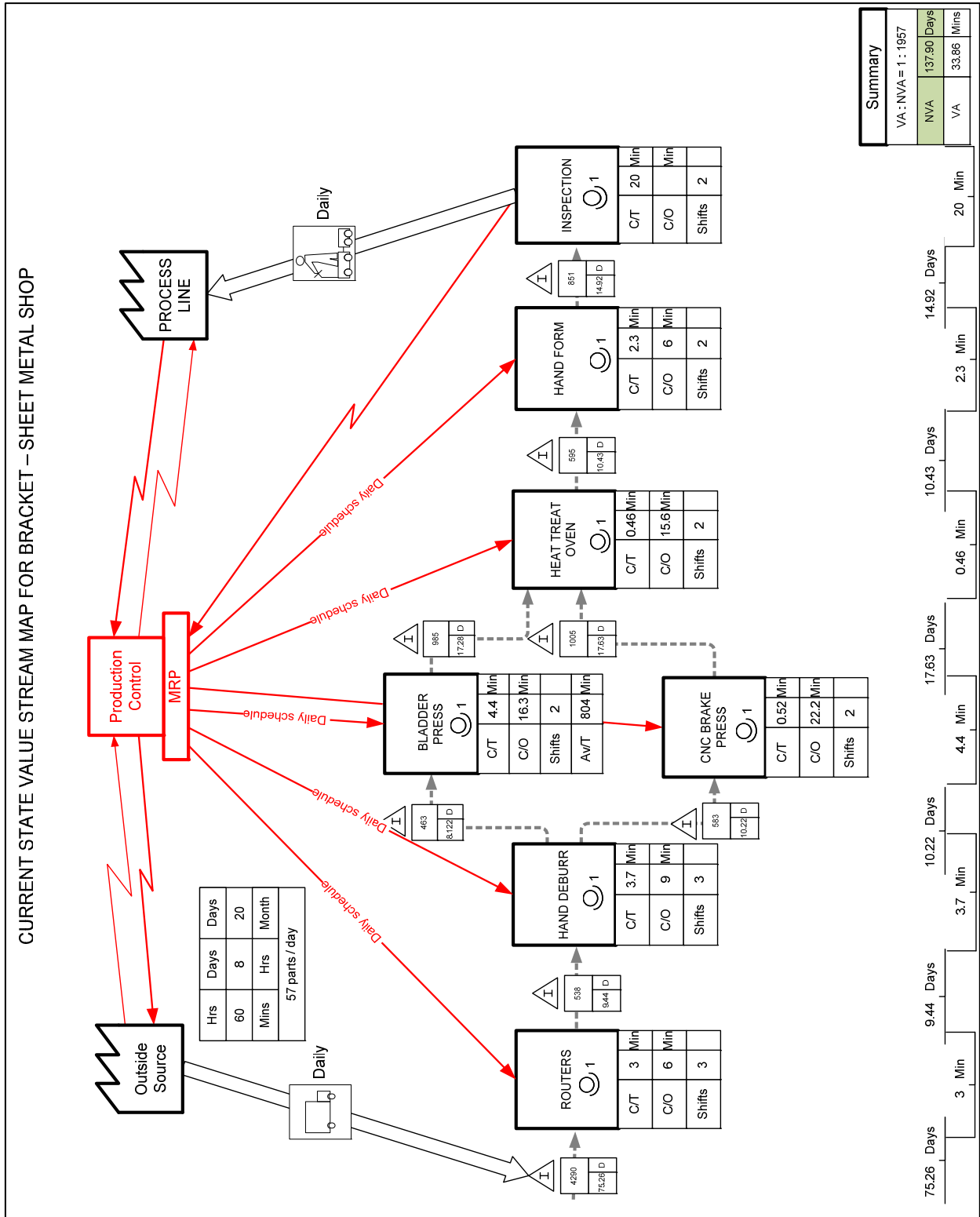
Figure 3.11 Current state value stream maintenance map (VSMM) for aluminum cone production line

3.15.1 Production line of a sheet metal shop

The machines that are associated in the production line of a sheet metal shop are taken into account in this case study. The current state VSM is shown in figure 3.12. Mild steel (MS) brackets are manufactured in the sheet metal shop. The company gets raw material from its supplier with a lead time of about 75.26 days. The demand for the brackets is 57 pieces per day. The company operates 20 days per month. The raw material is converted into a bracket through a series of processes and is shipped daily to next process line. Workstations examined in this case study are explained in detail in the sub sections below. The defect rate is 0.003 percentage of the total number of produced items. (MTTO + MTTY) and MTTR is 25 percentage and 75 percentage of the total breakdown time respectively is assumed the same for all processes. A current state VSMM illustrates how the maintenance factors are incorporated as shown in figure 3.13.

3.15.2 Router

Komo router is used for machining mild steel sheets. The machine is pre-programmed to machine the component. Cycle time for router process is 3 minutes. Changeover time for router process is 6 minutes which includes the time for fixing the component over the work surface by the operator. The machine is operated for 3 shifts per day.

Figure 3.12 Current state value stream map (VSM) for bracket production line

3.15.2.1 Effectiveness of the equipment

Equipment effectiveness is calculated for router process as shown below:

Total shifts / day = 3 (1 shift = 8 hrs)

Cycle time (for 1 component) = 3 mins

Changeover time = 6 mins

Total time consumed for 1 component = 9 mins

Breakdown time (unplanned) = 184 hrs/year = 11040 mins/year

Effective time (T_e) = [(no. of working hrs/day * no. of working days/month)] * 12

= [(24 * 20) * 60 *12] mins/year

= 345600 mins/yr

Actual time = [(no. of working hrs/day – break time) * no. of working days/month] * 12 – breakdown time

= {[(24 - 3)* 20 * 60]* 12} mins/year – 11040 mins/year

= 291360 mins/year

(T_o) Productive time = (T_e - Breakdown time) = 334560 mins/year

A = T_o / T_e = 334560/345600 = 0.968

R = N / N_{max} = 32373.33/38400 = 0.843

$Y = N_Q \; / \; N$ $= 32276.21/32373.33$ $= 0.997$

$N = 291360/9 = 32373.33$ pieces; $N_{max} = 345600/9 = 38400$ pieces

E = A * R * Y……………………………………………………..…(Ron and Rooda, 2006)

Equipment effectiveness (E) = 81.35 %

3.15.2.2 Total maintenance time

The total maintenance time spent for router process is calculated as shown below:

$MMLT = MTTO + MTTR + MTTY$……………………………………...(Kannan et al., 2007)

$MMLT = 138 + 46 = 184$ hrs/year

Mean maintenance lead time (MMLT) = 184 hrs/year

Note: (MTTO + MTTY = 46 hrs/year & MTTR = 138 hrs/year)

3.15.2.3 Efficiency of maintenance process

Maintenance efficiency of router process is calculated as shown below:

% Maintenance efficiency $= (MTTR/MMLT) * 100$……………..…(Kannan et al., 2007)

$= (138/184) * 100$

Maintenance efficiency = 75%

3.15.3 CNC brake press

After the hand deburr operation, mild steel sheets are machined using a Cincinnati CNC

brake press. The machine is pre-programmed to machine the component as per the drawing. Cycle time for brake press process is 0.52 minutes. Changeover time for brake press process is 22.2 minutes which includes the setup time for fixing the component on the working table. The machine is operated for 2 shifts per day.

3.15.3.1 Effectiveness of the equipment

Equipment effectiveness is calculated for brake press process as shown below:

Total shifts / day   = 2   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 0.52 mins

Changeover time   = 22.2 mins

Total time consumed for 1 component   = 22.72 mins

Breakdown time (unplanned)   = 43 hrs/year   = 2580 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working hrs/month)] * 12

                    = [(16 * 20) * 60 *12] mins/year

                    = 230400 mins/yr

Actual time   = [(no. of working hrs/day – break time) * no. of working days/month] * 12 – breakdown time

                    = {[(16 - 2)* 20 * 60]* 12} mins/year – 2580 mins/year

                    = 199020 mins/year

(T_o) Productive time = $(T_e$ - Breakdown time) = 227820 mins/year

$A = T_o / T_e$ = 227820/230400   = 0.988

$R = N / N_{max}$ = 8759.68/10140.84   = 0.863

$Y = N_Q / N$ = 8733.40/8759.68   = 0.997

N = 199020/22.72 = 8759.68 pieces; N_{max} = 230400/22.72 = 10140.84 pieces

E = A * R * Y………………………………………………………..…(Ron and Rooda, 2006)

Equipment effectiveness (E) = 85.15 %

3.15.3.2 Total maintenance time

The total maintenance time spent for brake press process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY………………………………………...(Kannan et al., 2007)

MMLT = 34.4 + 8.6 = 43 hrs/year

Mean maintenance lead time (MMLT) = 43 hrs/year

Note: (MTTO + MTTY = 8.6 hrs/year & MTTR = 34.4 hrs/year)

3.15.3.3 Efficiency of maintenance process

Maintenance efficiency of brake press process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100……………….……(Kannan et al., 2007)

                      = (34.4/43) * 100

Maintenance efficiency = 80%

3.15.4   Bladder press

After the hand deburr operation mild steel sheets are machined using a CNC bladder press. The machine is pre-programmed to machine the component as per the drawing. Cycle time for bladder press process is 4.4 minutes. Changeover time for bladder press process is 16.3 minutes which includes the setup time for fixing the component on the working table. The machine is operated for 2 shifts per day.

3.15.4.1   Effectiveness of the equipment

Equipment effectiveness is calculated for bladder press process as shown below:

Total shifts / day   = 2   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 4.4 mins

Changeover time   = 16.3 mins

Total time consumed for 1 component   = 20.7 mins

Breakdown time (unplanned)   = 353 hrs/year = 21180 mins/year

Effective time (T_e)   = [(no. of working hrs/day * no. of working hrs/month)] * 12

= [(16 * 20) * 60 *12] mins/year

= 230400 mins/yr

Actual time $\quad$ = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

breakdown time

$= \{[(16 - 2) * 20 * 60] * 12\}$ mins/year – 21180 mins/year

= 180420 mins/year

(T_o) Productive time = $(T_e$ - Breakdown time) = 209220 mins/year

$A = T_o / T_e \quad\quad\quad = 209220/230400 \quad\quad\quad = 0.908$

$R = N / N_{max} \quad\quad\quad = 8715.94/11130.43 \quad\quad\quad = 0.843$

$Y = N_Q / N \quad\quad\quad = 8689.79/8715.94 \quad\quad\quad = 0.997$

N = 180420/20.7 = 8715.94 pieces; $\quad$ N_{max} = 230400/20.7 = 11130.43 pieces

E = A * R * Y……………………………………………………..…(Ron and Rooda, 2006)

Equipment effectiveness (E) = 70.88 %

3.15.4.2 Total maintenance time

The total maintenance time spent for bladder press process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY…………………………………...(Kannan et al., 2007)

MMLT = 247.10 + 105.90 = 353 hrs/year

Mean maintenance lead time (MMLT) = 353 hrs/year

**Note:** (MTTO + MTTY = 105.90 hrs/year & MTTR = 247.10 hrs/year)

3.15.4.3   Efficiency of maintenance process

Maintenance efficiency of bladder press process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100…………...…..……(Kannan et al., 2007)

= (247.10/353) * 100

Maintenance efficiency = 70%

3.15.5   Heat treatment oven

The components from CNC bladder press and bladder press are placed inside an oven where heat treatment process is performed. The heat treatment time is pre-programmed. Cycle time for heat treatment process is 0.46 minutes. Changeover time for heat treatment process is 15.6 minutes which includes the setup time for placing the component inside the oven. The machine is operated for 2 shifts per day.

3.15.5.1   Effectiveness of the equipment

Equipment effectiveness is calculated for heat treatment process as shown below:

Total shifts / day   = 2   (1 shift = 8 hrs)

Cycle time (for 1 component)   = 0.46 mins

Changeover time   = 15.6 mins

Total time consumed for 1 component   = 16.06 mins

Breakdown time (unplanned)   = 330 hrs/year = 19800 mins/year

Effective time (T_e) = [(no. of working hrs/day * no. of working days/month)] * 12

= [(16 * 20) * 60 *12] mins/year

=230400 mins/yr

Actual time = [(no. of working hrs/day – break time) * no. of working days/month] * 12 –

breakdown time

= {[(16 - 2)* 20 * 60]* 12} mins/year – 19800 mins/year

= 181800 mins/year

(T_o) Productive time = (T_e - Breakdown time) = 210600 mins/year

$A = T_o / T_e$ = 210600/230400 = 0.914

$R = N / N_{max}$ = 11320.04/14346.20 = 0.789

$Y = N_Q / N$ = 11286.07/11320.04 = 0.997

$N = 181800/16.06 = 11320.04$ pieces; $N_{max} = 230400/16.06 = 14346.20$ pieces

$E = A * R * Y$………………………………………………………..….(Ron and Rooda, 2006)

Equipment effectiveness (E) = 71.89 %

3.15.5.2 Total maintenance time

The total maintenance time spent for heat treatment process is calculated as shown below:

MMLT = MTTO + MTTR + MTTY…………………………………...(Kannan et al., 2007)

MMLT = 237.60 + 92.40 = 330 hrs/year

Mean maintenance lead time (MMLT) = 330 hrs/year

**Note:** (MTTO + MTTY = 92.40 hrs/year & MTTR = 237.60 hrs/year)
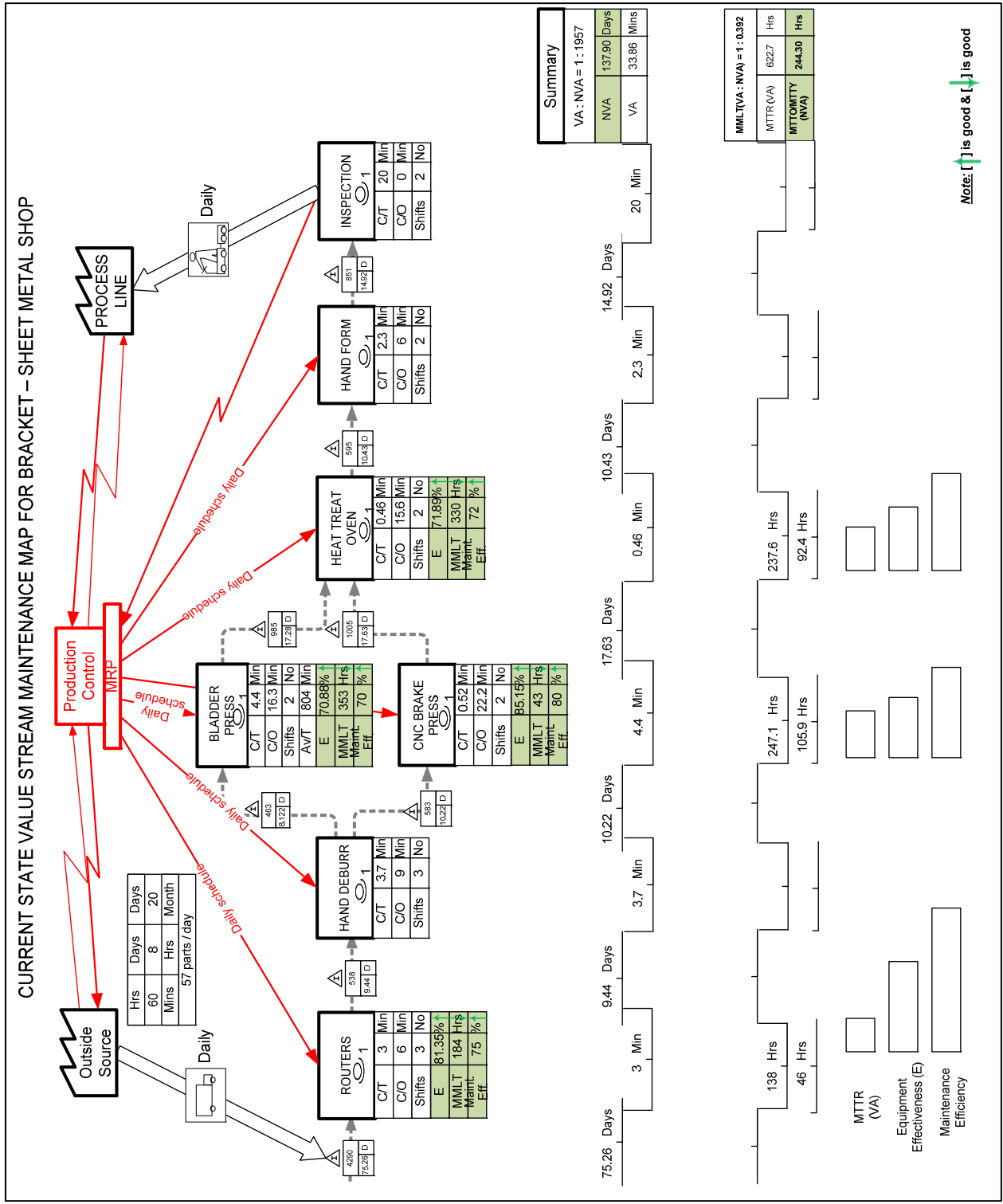
3.15.5.3   Efficiency of maintenance process

Maintenance efficiency of heat treatment process is calculated as shown below:

% Maintenance efficiency   = (MTTR/MMLT) * 100………………….……(Kannan et al., 2007)

= (237.60/330) * 100

Maintenance efficiency = 72%

Figure 3.13 Current state value stream maintenance map (VSMM) for bracket production line

97

3.16 Industry specific VSMM

Maintenance managers of a company can choose the necessary breakdown maintenance metrics from the developed framework shown in table 3.1 to assess the effectiveness of their breakdown maintenance activities according to their requirements. For the hypothetical VSM shown in figure 3.3, two different key metrics along with MMLT from the framework is calculated and incorporated in a VSMM along with their respective trends as shown in figure 3.14.

a) Maintenance overtime percentage

Maintenance overtime percentage is the ratio of the total number of overtime hours worked beyond regular working hours by the maintenance staff over a period of time to the total number of hours worked during their usual working hours over the same period of time. If the maintenance overtime percentage trend is decreased it is value added for the company.

$$Overtime = \frac{Total\ overtime\ worked}{Total\ hours\ worked} * 100$$ ……………....(Davies and Greenough, 2004)

Sample calculations for turning process are as follows:

Total overtime worked / month   = 1.5 hours

Total hours worked / month   = 20 hours

$$Overtime = \frac{Total\ overtime\ worked}{Total\ hours\ worked} * 100 = \frac{1.5}{20} * 100$$

98

Overtime = 7.50 %

<u>**Assumed:**</u>

(Total overtime worked / month = 1.5 hrs & Total hours worked / month = 20 hrs)

b) Maintenance wrench time

Maintenance wrench time is the ratio of the total productive time that was spent by the maintenance personnel on repairing equipments over a period of time to the total number of hours scheduled for repairing equipments over a period of time in general. If the maintenance overtime percentage trend is decreased it is value added for the company.

$$\text{Wrench time} = \frac{\text{Productive work time}}{\text{Total work time scheduled}} \times 100$$ …………….......……(SMRP, 2006)

Sample calculations for turning process are as follows:

Productive work time / month   = 12 hours

Total work time scheduled / month   = 20 hours

$$\text{Wrench time} = \frac{\text{Productive work time}}{\text{Total work time scheduled}} \times 100 \quad = \frac{12}{20} \times 100$$

Wrench time = 60%

<u>**Assumed:**</u>

(Productive work time / month = 12 hrs & Total work time scheduled / month = 20 hrs)

Figure 3.14 Other key maintenance metrics incorporated in a hypothetical VSMM

3.17   Summary

In this chapter a hierarchy and a unique framework for calculating the breakdown maintenance factors that was cited in the hierarchy were developed. A method for incorporating significant breakdown maintenance factors and their trends into the VSM adapted from the framework was presented. Then the developed method was tested in a hypothetical and three industrial cases by incorporating few key breakdown maintenance factors in a VSM. It shows the initial current state VSM and also discusses how key breakdown maintenance metrics are calculated and incorporated along with their respective trends in the developed current state VSMM for each case study.

To demonstrate that any of the key maintenance metrics incorporated in the framework can be added in a VSMM, a VSMM is created for the hypothetical case study with two different key metrics along with MMLT. The developed VSMM helps to assess the breakdown maintenance factors of every individual machine in a production line. Moreover the VSMM can be used to assess and record the effectiveness of the breakdown maintenance activities performed in all industrial cases and thus serve as a tool for continuous improvement opportunities.

CHAPTER 4

CONCLUSION AND FUTURE WORK

4.1 Introduction

In today's highly competitive and volatile business environment, companies are attempting to utilize their resources to compete in the market with its competitors. Breakdown maintenance activities performed in an organization play a vital role in improving equipment availability and overall productivity. The primary purpose of this thesis is to assess the maintenance factors using a value stream maintenance map (VSMM) in a clearly measurable method. This chapter discusses the conclusion from this thesis, achievements of this thesis and possible future research work of this thesis.

4.2 Thesis summary

The main intent of this research work was to develop a method for enabling the assessment of maintenance factors using a VSMM in a clearly and precisely measurable technique.

To facilitate the objective, different organizational breakdown maintenance wastes were grouped. With the different types of identified breakdown maintenance wastes a breakdown maintenance performance measures hierarchy was developed.

Then a breakdown maintenance performance measures framework containing about forty maintenance metrics was developed. A method was developed for calculating and incorporating

few key maintenance metrics in a VSMM. The developed method was tested in a hypothetical case study and three real industrial cases.

For each industrial case study, initially the general detail of the company was described and then the information of the considered production line and its current state VSM were explained. Finally, the current state VSMM was developed by calculating and incorporating the key breakdown maintenance performance metrics and their respective trends for each workstation.

4.3   Thesis achievements

To attain the proposed goal of this thesis the following activities were achieved during the course of this research work:

1. Identified and grouped various organizational breakdown maintenance wastes.

2. Developed a hierarchy for breakdown maintenance wastes.

3. Developed a framework containing forty key breakdown maintenance metrics to show how indicators are calculated. It addressed the metrics trend and their specific target level which leads to continuous improvement opportunities.

4. Developed a sample current state value stream maintenance map (VSMM) for a hypothetical case study in order to incorporate the calculated key maintenance performance metrics and their respective trends.

5. Tested proposed method in three real industrial cases in order to assess the breakdown maintenance effectiveness of a production line and to identify the breakdown maintenance improvement opportunities.

4.4 Future work

The improvements that can be added to this thesis work for assessing maintenance factors using the VSMM are as listed below:

1. Develop a key breakdown maintenance performance measures framework exclusively for specific industries such as chemical, processing and mining industries.

2. Further test the method in multiple production lines of a company to augment the amount of non-value added activities spent in terms of money and time that occur due to breakdown maintenance activities for top level management.

3. Create awareness among the maintenance staff in order to perform effective breakdown maintenance and sustain it by utilizing lean tools (Kaizen, 5S, visual management, workflow diagram, etc,.).

REFERENCES

REFERENCES

Alavi, S. (2003). Leaning the right way. *Manufacturing Engineer*, 82(3), 32-35.

Anonymous, (2004). Limitations of value stream mapping, www.strategos.com, *Strategos, Inc*., Kansas City, Missouri.

Atkinson, A.A., Waterhouse, J.H., and Wells, R.B. (1997). A stakeholder approach to strategic performance measurement, *Sloan Management Review*, 38(3), 25-37.

Badiger, A.S., and Gandhinathan, R. (2008). A proposal: evaluation of OEE and impact of six big losses on equipment earning capacity. *International Journal of Process Management and Benchmarking,* 2(3), 234–248.

Bagadia, K. (2008). Asset reliability drives Lean maintenance. *Plant Engineering*, 62(5), 45-47.

Bicheno, J. (2000). The lean toolbox, Second edition, *PICSIE books*.

British Standards Institution (1993). BS 3811: Glossary of Terms Used in Terotechnology, *British Standards Institution*, London.

Campbell, J.D., and Jardine, A.K.S. (2001). Maintenance Excellence, *Marcel Dekker, New York*, NY.

Cholasuke, C., Bhardwa, R., and Antony, J. (2004). The status of maintenance management in the UK manufacturing organisations: results from a pilot survey. *Journal of Quality in Maintenance Engineering*, 10(1), 5-15.

Davies, C., and Greenough, R. (2004). Performance Measures to Identify the Effectiveness of Lean Thinking within Maintenance. *Maintenance and Asset Management*, 19(1), 8-15.

Daya, B.M., and Duffuaa, O.S. (1995). Maintenance and quality: the missing link. *Journal of Quality in Maintenance Engineering*, 1(1), 20 – 26.

Dekker, R. (1996). Applications of maintenance optimization models: a review and analysis, *Reliability engineering and system safety*, 51, 229-240.

Duffuaa, O.S., Raouf, A., and Campbell, D.J. (1999). Planning and Control of Maintenance Systems, *John Wiley and Sons, Inc*.

Fleischer, J., Weismann, U., and Niggeschmidt, S. (2006). Calculation and optimisation model for costs and effects of availability relevant service elements. *Proceedings of LCE, 13th CIRP International Conference on Life Cycle Engineering*, 675-680.

Gulati, R. (2009). Maintenance and Reliability Best Practices, *Industrial Press*, New York, NY.

Haik, E.B. and Aomar, A.R. (2006). Simulation-based lean six-sigma and design for six-sigma, *John Wiley and Sons, Inc*, HOBOKEN, New Jersey.

Hatton. L. and Riches. P. (2008) Using a 'high involvement' model: a strategic planning approach in a state public sector agency. *Journal of Business and Behavioral Sciences*, 19(1), 33-42.

Higgins, L.R., Brautigam, D.P., and Mobley, R.K. (1995). Maintenance Engineering Handbook, Fifth Ed., *McGraw-Hill Inc*., New York, NY.

Hines, P. and Rich, N. (1996). The seven value stream mapping tools, *Proceedings of NAPM annual academic conference*, Portland state university, Portland, USA, 69-86, March 21-23.

Kannan, S., Li, Y., Ahmed, N., and Akkad, E.Z. (2007). Developing a Maintenance Value Stream Map. *Institute of Industrial Engineers, Technical Societies and Divisions Lean Conference Proceedings.*

Kelly, A. (2006). Maintenance Management Auditing In search of Maintenance Management Excellence, *Industrial Press*, New York, NY.

Kennerly, M. and Neely, A. (2003), Measuring performance in a changing business environment, *International journal of operation and production management*, 23(2), 213-29.

Kumar, U., and Parida, A. (2008). Maintenance Performance Measurement (MPM) System. *Complex System Maintenance Handbook*, *Springer Series in Reliability Engineering*, Springer London, 459-478.

Kutucuoglu, K.Y., Hamali, J., Irani, Z. and Sharp, J.M. (2001). A framework for managing maintenance using performance measurement systems. *International Journal of Operations and Production Management*, 21(1), 173-95.

Levitt, J. (1997). The Handbook of Maintenance Management, First Ed., *Industrial Press*, New York, NY.

Levitt, J. (2008). Lean maintenance, First edition, *Industrial press*, NY, USA.

Marquez, C.A. (2007). The maintenance management framework: modules and methods for complex systems maintenance, *Springer Series in Reliability Engineering*, Springer-Verlag London Limited.

Mejabi, O. O. (2003). Framework for a Lean Manufacturing Planning System. *International Journal of Manufacturing Technology and Management*, 5(5), 563 – 578.

Miles, M. B. and Huberman, A. M. (1994). Qualitative Data Analysis, *Sage Publication*, California, USA.

Mitchell, S.J. (2007). Physical Asset Management Handbook, Fourth Edition, *Clarion Technical Publishers*, Texas, USA.

Monden, Y. (1993). Toyota production system: An integrated approach to just-in-time, *Industrial engineering and management press*, Norcross, GA.

Najjar, A.B. and Alsyouf, I. (2003). Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making, *International journal of production economics*, 84, 85-100.

Nakajima, S. (1988). Introduction to total productive maintenance (TPM), *Productivity press*, Cambridge, MA.

Nakajima, S. (1989). TPM development program, *Productivity press*, Cambridge, MA.

Ohno, T. (1985). Kanban: just-in-time at Toyota, *Productivity press*.

Parida, A., (2007). Study and analysis of Maintenance Performance Indicators (MPIs) for LKAB: A Case Study. *Journal of Quality in Maintenance Engineering*, 13(4), 325-337.

Parida, A., and Chattopadhyay, G. (2007). Development of a Multi-criteria Hierarchical Framework for Maintenance Performance Measurement (MPM). *Journal of Quality in Maintenance Engineering*, 13(3), 241 – 258.

Parida, A., and Kumar, U. (2006). Maintenance Performance Measurement (MPM): Issues and Challenges. *Journal of Quality in Maintenance Engineering*, 12(3), 239-251.

Peters, R.W. (2006). Maintenance Benchmarking and Best Practices, *McGraw-Hill*, New York, NY.

Pintelon, L., & Puyvelde, V.F. (1997). Maintenance performance reporting systems: some experiences. *Journal of Quality in Maintenance Engineering*, 3(1), 4-15.

Priel, V.Z. (1962). Twenty ways to track maintenance performance, Factory, *McGraw-Hill*, March, 88-91.

Raouf, A. (1994). Improving capital productivity through maintenance. *International Journal of Operations and Production Management*, 14(7), 44 – 52.

Ron, A. J.E., and Rooda, J.E. (2006). OEE and equipment effectiveness: an evaluation. *International Journal of Production Research*, 44(23), 4987–5003.

Russell, R. S. and Taylor, B. W. (1999). Operations Management, Upper Saddle River, NJ: *Prentice-Hall*, 2nd edition.

Sawhney. R., Kannan. S., and Li. X. (2009). Developing a value stream map to evaluate breakdown maintenance operations. *International Journal of Industrial and Systems Engineering*, 4(3), 229 - 240.

Schnoebelen, C.S., Aerne, J.D., & Miller, G.C. (1999). Leveraging Maintenance Through Strategic Performance Measures: (PART 1). *Journal of Cost Management*, 13(5), 11-22.

SEMI. (2001). Standard for Definition and Measurement of Equipment Reliability, Availability and Maintainability, SEMI E10-0701, *Semiconductor Equipment and Material International*: Mt. View, CA.

Seth, D., Seth, N., and Goel, D. (2008). Application of value stream mapping (VSM) for minimization of wastes in the processing side of supply chain of cottonseed oil industry in Indian context. *Journal of Manufacturing Technology Management*, 19(4), 529 – 550.

Sheu C, Krajewski LJ. (1994). A decision model for corrective maintenance management. *International Journal of Production Research*, 32(6):1365-1382.

Smith, R. and Hawkins, B. (2004). Lean maintenance: Reduce Costs, Improve Quality, and Increase Market Share, *Elsevier Butterworth Heinemann*.

Smith, R., and Mobley, R.K. (2008). Rules of Thumb for Maintenance and Reliability Engineers, *Elsevier/Butterworth-Heinemann*, Boston, USA.

SMRP. (2006). Society for Maintenance and Reliability Professionals. Retrieved March 8, 2009, from web site: *http://www.smrp.org/*

SMRP. (2009). Society for Maintenance and Reliability Professionals. Retrieved August 23, 2009, from web site: *http://www.smrp.org/*

Tapping, D., Luyster, T., & Shuker, T. (2002). Value stream management: Eight steps to planning, mapping, and sustaining lean improvements, New York, NY: *Productivity Press*.

Tsang, H.C.A., Jardine, K.S.A., and Kolodny, H. (1999). Measuring maintenance performance: a holistic approach. *International Journal of Operations and Production Management*, 19(7), 691 – 715.

Wireman, T. (1998). Developing Performance Indicators for Managing Maintenance, *Industrial Press*, New York, NY.

Wireman, T. (2005). Developing performance indicators for managing maintenance. Second edition, *Industrial Press*, New York, NY, USA.