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Maintenance Process Improvement Framework Using Lean Six Sigma: A Case Study

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Abstract: The main goal of the maintenance function in any organization is to maximize asset performance and optimize the use of maintenance resources. Lean six sigma (LSS) is a continuous improvement tools for improving process efficiency and effectiveness. This work discusses the importance of LSS tools in maintenance management (LSS-MM). A generic LSS-MM framework has been proposed and validated with a case study conducted in a petrochemical company in Egypt. A case study of a feedwater pump station in a steam system has been used to illustrate the proposed framework. Results indicate that the proposed methodology is successful in identifying the critical equipment and improving maintenance efficiency and effectiveness. For example, overall equipment effectiveness (OEE) improved from 50% to 68%, sigma level improved from 2.53 to 2.88, and maintenance process efficiency improved from 62.3% to 69.7 %.

Keywords: *LSS, DMAIC, LSS-MM, maintenance improvement, TQM, manufacturing.*

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INTRODUCTION

Maintenance operations share a significant amount of the operating costs of any industrial organization. One of the main goals of maintenance management (MM) is to reduce component failure and improve systems availability, with the premise that these systems operate in an efficient and effective ways. Accordingly, maintenance strategy selection became one of the most important decision-making activities in the industry. To achieve these goals, many organizations have turned to the powerful Lean Six Sigma (LSS) methodology. LSS provides a comprehensive toolkit (DMAIC - Define, Measure, Analyze, Improve and Control) and many tools for process continuous improvement. As shown in Fig. (1) and Table (1), there are four common maintenance management approaches for continuous improvement, which are reliability centered maintenance (RCM), total productive maintenance (TPM), risk-based inspection (RBI), and lean six sigma for maintenance management (LSSM), (Gomaa, 2024), (Gomaa, 2023c), (Gomaa, 2023b), (Gomaa, 2023a).

RCM is one of the best known and most widely used approach for maintaining operational reliability in critical sectors. RCM is a proactive and systematic approach for improving system reliability by optimizing maintenance activities based on risk analysis of system failure. RCM selects the most appropriate and tailored maintenance strategy for all equipment in the plant based on the degree of criticality and reliability criteria. Implementing RCM requires collecting and analyzing historical failure and maintenance data to determine the current condition of the equipment.

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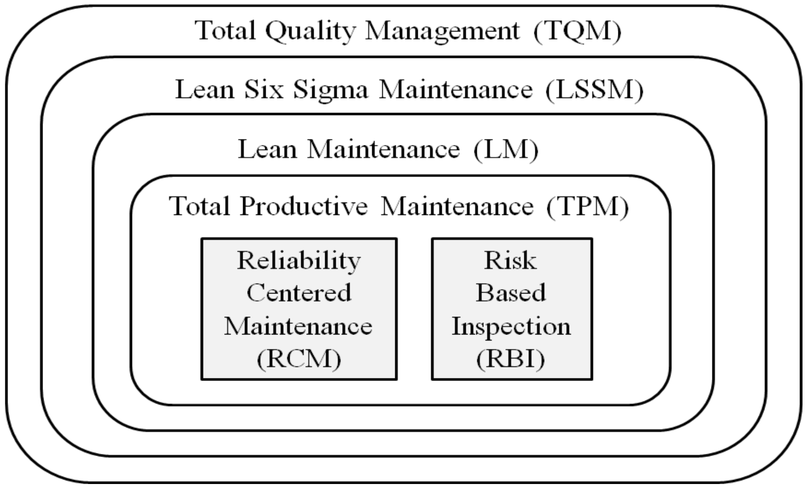


Figure 1 *Continuous Improvement Approaches for Maintenance Management*

Table 1 *CONTINUOUS IMPROVEMENT APPROACHES FOR MAINTENANCE MANAGEMENT*

	Reliability Centered Maintenance (RCM); 1978	Total Productive Maintenance (TPM); 1988	Risk Based Inspection (RBI); 1994	Lean Six Sigma Maintenance (LSSM); 2000
Main Objective	Improving Reliability & Safety	Improving Effectiveness & Availability	Improving HSE	Improving maintenance effectiveness & efficiency
Focus on	Failure Prevention	Culture Change	Hazard Prevention	Continuous Improvement
Phase	Design, Operation, Maintenance	Operation, Maintenance	Design, Operation, Maintenance	Operation, Maintenance
Criticality filter	ABC (Reliability & Safety)	ABC (Effectiveness)	ABC (HSE)	ABC (Effectiveness & Efficiency)
Main KPIs	R%, MTBF, MTTR, Breakdown %	OEE % (A%, P%, Q%)	MTBF & Safety	RAMS (R%, A%, M%, S%)

MTBF: Mean time between failure MTTR: Mean time to repair A: Availability %
R: Reliability % P: Performance % Q: Quality % M: Maintainability% S: Safety%
HSE: Health - Safety- Environmental RAMS: Reliability – Availability – Maintainability -

As shown in Fig. (2), RCM approach is composed of a set of activities that support to define and periodically update the maintenance plans of an engineering system. (Da Silva & de Souza, 2023), (Al Farihi & Herdiman, 2023), (Shannon & Olivia, 2023).

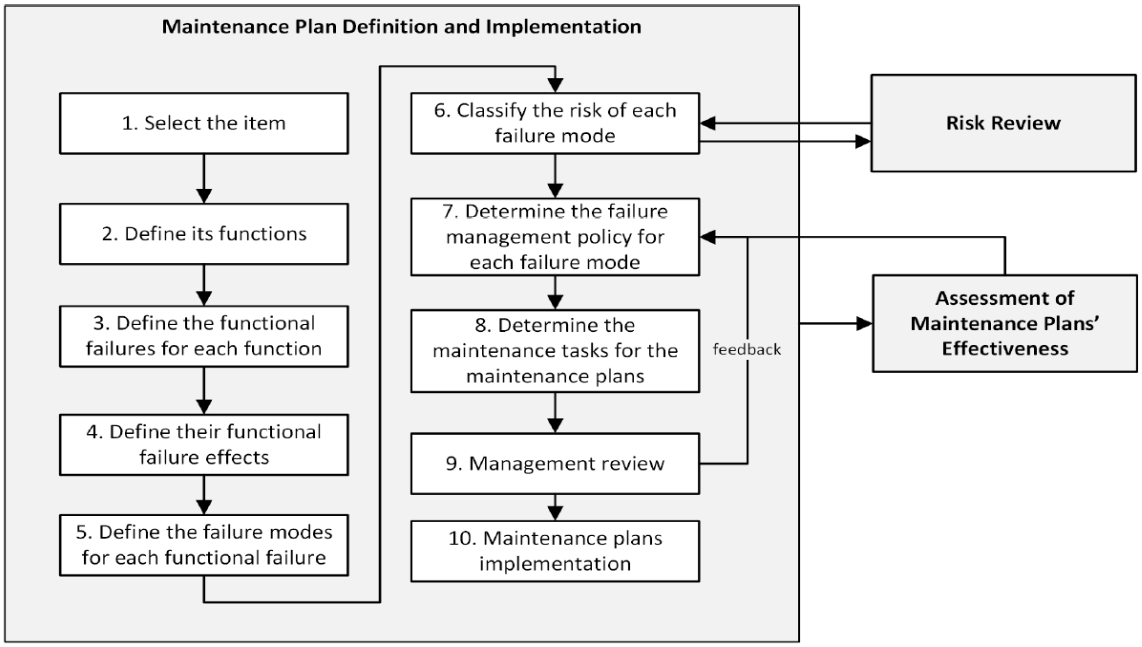


Figure 2 *RCM Methodology*

Total productive maintenance (TPM) is a methodology designed to improve overall equipment effectiveness. The focus of TPM is on processes and people as integral parts of TQM. TPM includes all employees, from department leaders, operations staff, and maintenance staff. At the core of TPM is the 5S method, which aims to keep a clean and well-organized work environment. As shown in Fig. (3), there are eight pillars of TPM, as follows: (Al Farihi & Herdiman, 2023), (Shannon & Olivia, 2023), (Wolska, Gorewoda, Roszak, & Gajda, 2023):

- Autonomous Maintenance: Empowers operators to conduct basic equipment care and routine maintenance tasks on their assigned equipment.
- Focused Improvement: Drives cross-functional teams to address targeted or chronic losses through coordinated efforts
- Planned Maintenance: Shifts the focus of the professional maintenance team from reactive firefighting to planned preventive maintenance activities.
- Development Management: Enhances equipment design and manufacture for easier operation, simplified maintenance, and optimal sizing for intended usage.
- Quality Management: Addresses the root causes of defects and enhances product quality by maintaining equipment throughout the production process.
- Training and Education: Ensures that staff possesses the necessary skills and understanding to effectively support TPM initiatives.
- Health, Safety, Environment (HSE): Prioritizes preventing human errors, eliminating accidents, addressing workplace hazards, and reducing resource waste.
- Office TPM: Extends TPM principles to administrative functions, strengthening departments through continuous improvement activities.

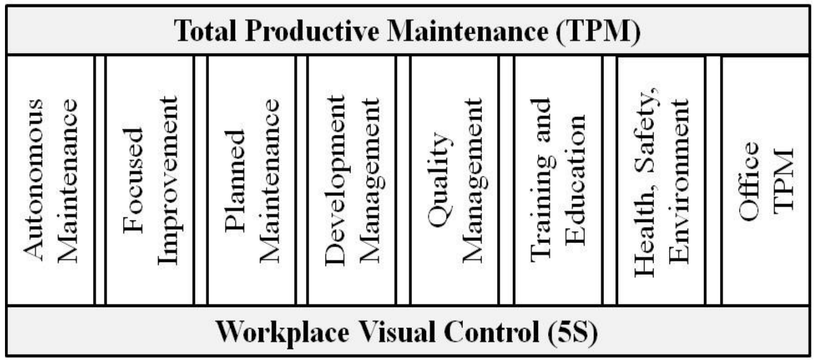


Figure 3 *TPM Pillars*

Risk based inspection (RBI) is a systematic proactive approach to optimize inspection activities based on risk analysis of a system failures. As shown in Fig. (4), refer to API 580 (2016), RBI methodology, provides quantitative procedures for establishing an inspection programme using risk-based methods for equipment such as pressure vessels, piping, tanks, heat exchangers. the purpose of the RBI is to create an efficient inspection plan and to continuously monitor and test the system., (Bitchikh, Kertous, Khanous, & Hammal, 2023).

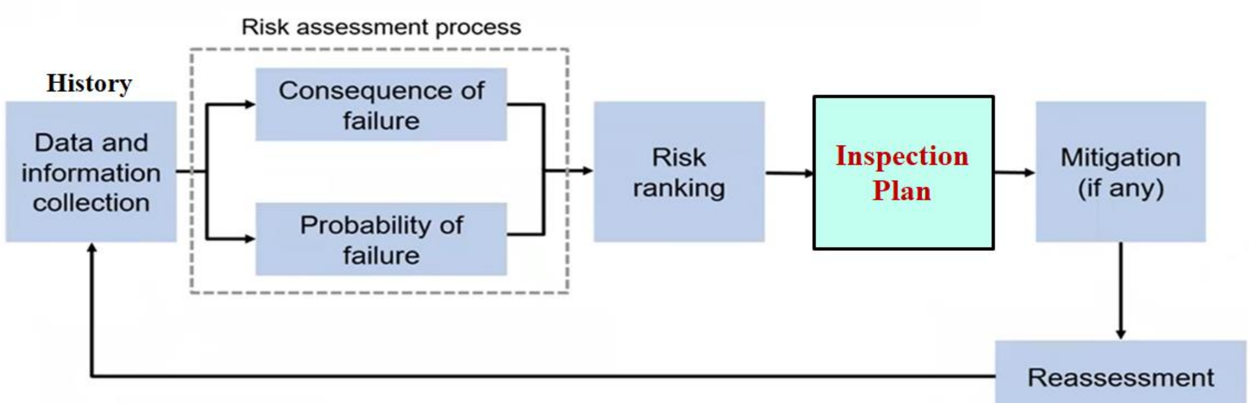


Figure 4 *Block Diagram of the RBI Approach in API 580 (2016).*

Lean six sigma in maintenance process (LSSM), sometimes called lean maintenance; (LM) approach integrates TPM with LSS tools to improve maintenance effectiveness and efficiency through continuous improvement, as shown in Fig. (5). LSS can run in parallel with a TPM strategy and will be easier to understand by operators. As shown in Fig. (6), the situation is completely different when implementing LSS solutions that improve the organization of the work of existing devices. Maximum efficiency can be achieved thanks to a well-prepared maintenance plan and proper operator training. Finally, Fig. (7) shows the main maintenance approaches., (Al Farihi & Herdiman, 2023), (Shannon & Olivia, 2023), (Antosz, Jasiulewicz-Kaczmarek, Waszkowski, & Machado, 2022), (Antosz, Pasko, & Gola, 2020), (West & Okafor, 2023).

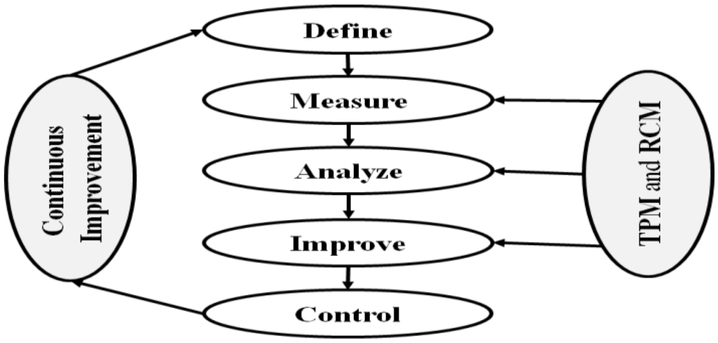


Figure 5 *LSS Maintenance (or Lean Maintenance).*

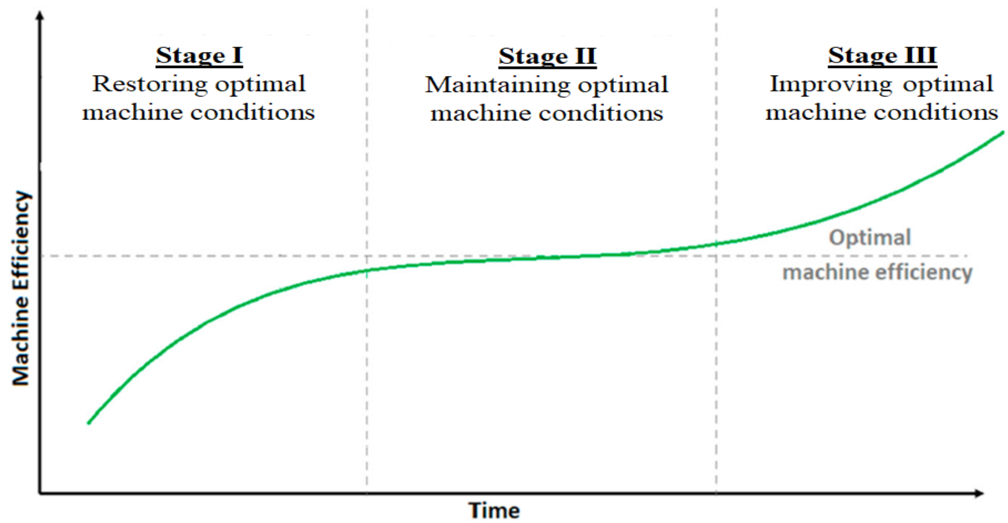


Figure 6 *LSS Maintenance Stages*

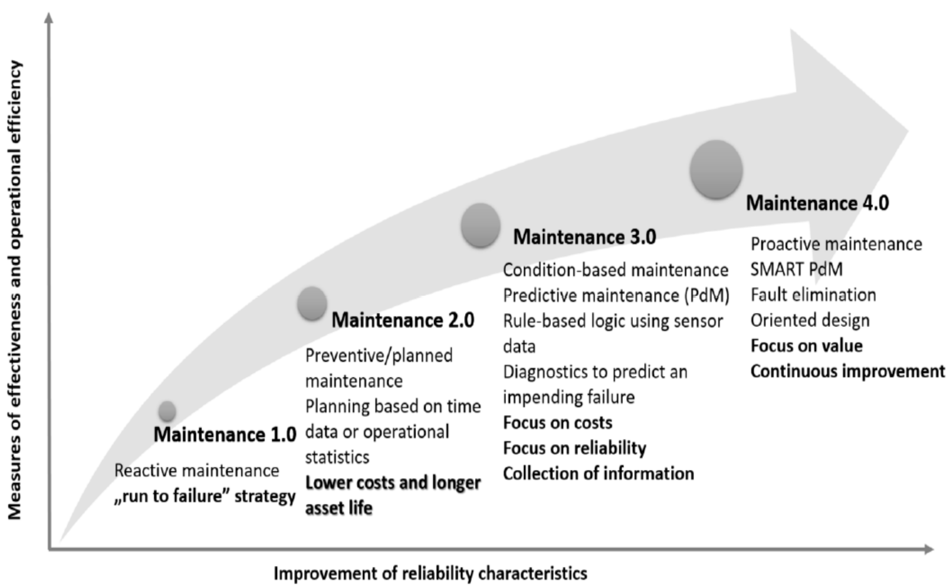


Figure 7 *Main maintenance approaches*

LITERATURE REVIEW

Several previous studies demonstrated the use of LSS tools in the maintenance activities. For example, Table (2) presents a comprehensive survey of LSS-MM studies, and they are classified based on contribution, application, main objectives and main LSS tools, from (Al Farihi & Herdiman, 2023); (Shannon & Olivia, 2023); (Wolska et al., 2023); (Bitchikh et al., 2023); (Antosz et al., 2022); (Antosz et al., 2020); (West & Okafor, 2023); (Trubetskaya, Ryan, Powell, & Moore, 2023); (Korchagin, Deniskin, Pocebneva, & Vasilyeva, 2022); (Imanov, Yildiz, & Koruyucu, 2021); (Chinhengo, Goriwondo, & Sarema, 2020); (Arrascue-Hernandez, Cabrera-Brusil, Chavez-Soriano, Raymundo-Ibañez, & Perez, 2020); (Hassan, Barakat, & Sobh, 2020); (Rashidifar, 2020); (Pinto et al., 2020).

Based on this review, the most important critical failure factors of LSS in maintenance process are as follows, (Gomaa, 2024), (Al Farihi & Herdiman, 2023), (Wolska et al., 2023), (Antosz et al., 2020), (West & Okafor, 2023):

- Lack of management support, commitment and involvement
- Lack of employee motivation and loyalty to achieve specific goals
- Lack of awareness and understanding of LSS tools and principles
- Lack of effective external and internal benchmarking of best practices
- Lack of performance evaluation, KPIs and monitoring
- Lack of standardization and standard operating procedures (SOPs)
- Inadequate system for assessing and improving machine availability and reliability
- Inadequate computerized maintenance management systems (CMMS)
- Lack of adequate training in diagnosing failures and problems for critical equipment
- Lack of additional resources at the beginning of LSS implementation

Measuring the effectiveness of LSS in maintenance process is vital to understand its impact on manufacturing operations. Key Performance Indicators (KPIs) help track the success of LSS initiatives and identify areas for improvement. The most common KPIs are as follows, (Al Farihi & Herdiman, 2023), (Shannon & Olivia, 2023), (Wolska et al., 2023), (Antosz et al., 2022), (Antosz et al., 2020), (Rashidifar, 2020), (Zasadzień, 2017):

- Overall Equipment Effectiveness (OEE)
- Mean Time Between Failures (MTBF)
- Mean Time to Repair (MTTR)
- Mean maintenance lead time (MMLT)
- Equipment Failure Rate (EFR)
- Planned Maintenance (PM) %
- Sigma Level
- Operational Reliability %
- Maintenance Process Efficiency %
- RAM (Reliability, availability, and maintainability)

Table 2 *CONTINUOUS IMPROVEMENT APPROACHES FOR MAINTENANCE MANAGEMENT*

Reference	Contribution	Application	Main objectives	Main LSS Tools
Trubetskaya, 2024	Proposed DMAIC framework for maintenance	A case study in dairy industry	- Reducing maintenance downtime	DMAIC, Project charter, VOC, Process mapping, SIPOC, TPM, 5S.
Al Farihi, 2023	Developed lean maintenance framework	A case study in wiring harness production	- Reducing unplanned downtime. - Reducing MTTR	TPM, RCM, VSM, RCA, 5S.
Shannon, 2023	Proposed LSS for maintenance	A case study in a pharmaceutical ingredient plant	- Improving OEE - Reducing corrective maintenance	DMADV, TPM, RCM, FMEA, OEE, CTQ, VSM, RCA, 5S, Pareto chart, KPIs.
West, 2023	Developed LSS for maintenance process	A case study in oil service company	- Improving maintenance process efficiency - Increasing machine availability	DMAIC, TPM, SIPOC, Statistical tests.
Antosz, 2022	Reported LSS for sustainable maintenance	A case study in floor coverings company.	- Improving machine availability - Reducing failure time	DMAIC, CTQ, TPM, 5S, SIPOC, Charts, Statistical tests.
Korchagin, 2022	Developed a framework for lean maintenance	A case study in aviation industry	- Improving maintenance process efficiency	JIT, TPM, Poka-Yoke, Simulation, Process flow chart
Imanov, 2021	Proposed a framework for lean maintenance	A case study in aircraft maintenance	- Reducing aircraft downtime	VOC, VSM, TPM, 5S, Kaizen, Poka-Yoke, PDCA.
Chinhengo, 2020	Developed a framework for lean maintenance	A case study in a coal handling plant	- Improving overall plant availability	TPM, VSM, Pareto Chart, 5S.
Arrascue-Hernandez, 2020	Reported a framework for lean maintenance	A case study in a textile company	- Increasing equipment availability	Takt time, VSM, OEE, 5S, SMED, Process flow chart.
Hassan, 2020	Developed a framework for lean maintenance	Three case study in oil and gas fields	- Improving planned maintenance (PM) % - Improving production	TPM, VSM, 5S, KPIs, Process flow chart.
Rashidifar, 2020	Proposed a framework for lean maintenance	A case study in die maintenance process	- Reducing maintenance downtime	VSM, Process flow map, 5S.
Pinto, 2020	Developed a TPM framework	A case study in CNC Lathes	- Reducing maintenance downtime - Improving OEE	TPM, 5S, 5Why.
Zasadzień, 2017	Proposed a six sigma framework	A case study in production machines	- Improving equipment availability	Process map, FMEA, SIPOC, SW.

PROPOSED LSSMM FRAMEWORK

The primary objective of this study is to improve the effectiveness and efficiency of the maintenance process. Based on in-depth analysis of the literature review, a Lean Six Sigma Maintenance Management (LSSMM) framework was developed using various analysis and improvement tools. Table (3) shows the LSSMM roadmap for the maintenance process and Table (4) shows the proposed LSS-DMAIC framework for maintenance management. Details of the DMAIC framework are provided in the following subsections.

Define Phase

The purpose of this phase is to clarify the project scope of work and identify the objectives and problems. This phase can be summarized in the following main steps:

- Step #1: Defining scope of work and main objectives.
- Step #2: Building process improvement teamwork
- Step #3: Defining system selection and required information
- Step #4: Identifying Problem Statement.
- Step #5: Defining maintenance process mapping.
- Step #6: Defining the current maintenance program.

Measure Phase

This phase aims to document and understand the current state of the system and identify important metrics related to maintenance quality and performance. This phase can be summarized in the following main steps:

- Step #7: Designing standard templates & collecting the required information.
- Step #8: Measuring the current performance evaluation.
- Step #9: Measuring the current Sigma Level.
- Step #10: Preparing the maintenance value stream mapping (Before improvement).
- Step #11: Identifying the top failures for the critical equipment

Analyze Phase

The purpose of this stage is to analyze the problems and shortcomings of the system and determine the root cause of the problems. This phase can be summarized in the following main steps:

- Step #7: Designing standard templates & collecting the required information.
- Step #8: Measuring the current performance evaluation.
- Step #9: Measuring the current Sigma Level.
- Step #10: Preparing the maintenance value stream mapping (Before improvement).
- Step #11: Identifying the top failures for the critical equipment

Improve Phase

This phase begins by listing the recommendations and solutions obtained during the analysis phase. The project team works together to develop, test, and implement an improvement plan that provides continuous improvements to the maintenance process. This phase can be summarized in the following main steps:

- Step #18: Constructing equipment trouble shooting.
- Step #19: Preparing the proposed PM program.
- Step #20: Preparing the proposed condition-based maintenance program.
- Step #21: Training the teamwork groups.
- Step #22: Implementing kaizen & lean principles.
- Step #23: Implementing changes and monitoring progress.
- Step #24: Updating the Maintenance Value Stream Mapping (After improvement).

Control Phase

In this phase, the project team develops a control plan to monitor and maintain the improvement plan. The control plan explains how processes will be standardized as well as how procedures will be documented. Actions taken to improve the maintenance process and best practices should also be well documented. The final activity in this phase is to close the project and prepare the final project closure report (annual report). This phase can be summarized in the following main steps:

- Step #25: Controlling before/after KPIs analysis.
- Step #26: Creating a culture of continuous improvement.
- Step #27: Documenting and standardizing the pest practice.
- Step #28: Providing advanced training and support.
- Step #29: Preparing project close-out report (annual report).
- Step #30: Communicating results & learned lessons.

Table 3 *PROPOSED LSS ROADMAP FOR MAINTENANCE PROCESS (BRAINSTORMING SESSION).*

Approach	Objectives	Most Common Tools
Current Situation Analysis	- Maintenance Process Description - KPIs Dashboard	• Process Mapping (process flow chart & SIPOC diagram) • Performance Evaluation & KPIs
Kaizen Approach	- Improving People Culture & Productivity	• 5S (Visual Control) • Standard Work (SW) • Root Cause Failure Analysis (RCFA) • Mistake Proofing (Poka-yoka)
Lean Approach	- Improving Value Added - Reducing Wastes	• Total Productive Maintenance (TPM) • Overall Equipment Effectiveness (OEE) • Value Added Time Analysis • Value Stream Mapping (VSM) • Lean Waste Analysis (8 wastes)
Six Sigma Approach	- Reducing Failures - Reducing Variance	• Sigma Level • SQC for failure Analysis • Root Cause Failure Analysis (RCFA) • Failure Mode Effect Analysis (FMEA) • Reliability Analysis

Table 4 *PROPOSED LSS-DMAIC FRAMEWORK FOR MAINTENANCE PROCESS (BRAINSTORMING SESSION).*

Phase	Objectives	Key Activities	Used Tools
Define	Studying process, product and problems in detail.	1) Defining scope of work and main objectives	Brainstorming
		2) Building process improvement teamwork	Brainstorming
		3) Defining system selection and required information	Brainstorming
		4) Identifying problem statement	Brainstorming
		5) Defining maintenance process mapping	Process flow chart SIPOC diagram
		6) Defining the current maintenance program	Work orders
Measure	Designing and collecting the required information.	7) Designing standard templates & collecting the required information	Brainstorming
		8) Measuring the current performance evaluation	KPIs & OEE
		9) Measuring the current sigma level	Sigma level
		10) Preparing the maintenance value stream mapping	VSM
		11) Identifying the top failures for the critical equipment	Brainstorming Rule 80/20
Analyze	Applying analysis tools and identifying root causes	12) Constructing risk assessment & maintenance strategies	Risk assessment
		13) Analyzing equipment risk & identifying the maintenance strategies	Risk matrix
		14) Root Cause Failure Analysis	Pareto chart RCFA
		15) Constructing fishbone diagram for equipment failures	Fishbone diagram
		16) Failure mode effect analysis	FMEA
		17) Equipment reliability analysis	Reliability
Improve	Implementing solutions according to priorities	18) Constructing equipment trouble shooting	Brainstorming
		19) Preparing the proposed PM program	Brainstorming
		20) Preparing the proposed condition based maintenance program	Brainstorming
		21) Training the teamwork groups	Advanced training program
		22) Implementing kaizen & lean principles	Kaizen, 5S, SW, 8 lean wastes
		23) Implementing changes and monitoring progress	Brainstorming
		24) Updating the maintenance value stream mapping	VSM
Control	Monitoring the process and achieving daily improvements	25) Controlling before/after KPIs analysis	KPIs, OEE
		26) Creating a culture of continuous improvement	Kaizen events
		27) Documenting and standardizing the pest practice	Auditing
		28) Providing advanced training and support	Brainstorming
		29) Preparing project close-out report	Annual report
		30) Communicating results & learned lessons	Brainstorming

CASE STUDY

The proposed framework is validated with a case study conducted in one of the petrochemical companies in Egypt. A case study of a feedwater pumping station in a steam system is used to illustrate the proposed framework. Furthermore, this section discusses the results obtained before and after applying the LSS approach in the maintenance process. The project charter is the first step in an LSSMM project. It is a roadmap consisting of details of the problem statement, scope, objectives, timeline, and teamwork. Details of the DMAIC framework are provided in the following subsections.

Define Phase

The purpose of this stage is to clarify the scope of work and identify the main objectives and problems. The scope of work of this study was to improve the maintenance process of the feedwater pumping station in the steam system. The main objectives were to improve planned maintenance percentage, improve sigma level, improve MTBF of critical items, reduce MTTR of critical items, improve OEE%, improve operational reliability%, and improve maintenance process efficiency%. As shown in Fig. (8), the process improvement task force included all staff related to process improvement, especially the LSSM specialist, site facilitator, maintenance engineer, inspection engineer, planning engineer, safety engineer, process engineer, and materials engineer. As shown in Figures (9), The selected process unit was a feedwater pumping station in a steam system. The station includes four pumps, three of which are running and the other is standby. Fig. (10) shows the required information based on maintenance history data collected from the company's log book. The main problem of this system is frequent breakdowns of pumps, which reduces the reliability and availability of equipment in the service process. Fig (11) and Fig. (12) shows the maintenance process mapping for the selected case. Table (5) shows the current maintenance program.

Measure Phase

This phase aims to document and understand the current status of the maintenance process and identify important metrics related to maintenance quality and maintenance process performance. As shown in Fig. (13) and Table (6), based on equipment history, the equipment maintenance KPIs are PM%, MTBF, MTTR, OEE and sigma level. Fig. (14) shows maintenance value stream mapping (before improvement). Based on rule 80/20, Fig. (15) shows the top failures for the critical equipment.

Analysis Phase

The purpose of this stage is to analyze problems and identify root causes. Risk analysis is a tool used to evaluate how equipment failure will impact organizational performance in order to systematically classify plant assets for the purpose of prioritizing work, material classification, FTM/CBM development, and reliability improvement initiatives. Based on several brainstorming sessions, Fig. (16) shows the proposed risk assessment and Fig. (17) shows the proposed maintenance strategies. Table (7) shows the equipment risk level and maintenance strategies for the different items. Based on the failure frequency, Fig. (18) shows Pareto chart for the top failures. For example; Fig. (19) shows Why-Why Analysis for pump bearing failure. Fig. (20) shows Fishbone diagram for pump station failure based on equipment items. Fig. (21) shows Fishbone diagram for pump station failure based on maintenance process inputs. Table (8) shown for the centrifugal pump Fig. (22) shows reliability analysis curves for the main items of centrifugal pump.

Improve Phase

This stage focuses on listing the recommendations and solutions obtained during the analysis stage. Based on several brainstorming sessions and for example, Fig. (23) shows the proposed trouble shooting for the centrifugal pump. Table (9) shows the Main recommendations to update the PM Program. Table (10) shows the proposed PM program for the centrifugal pump. Finally, Table (11) shows the proposed condition-based maintenance program.

Control Phase

At this stage, the brainstorming team developed a control plan to monitor and maintain the improvement plan. This plan explained how processes would be standardized as well as how procedures would be documented. Furthermore, actions taken for continuous process improvement and best practices should also be well documented. The final activity in this phase was to close the project and prepare the final project closure report. Based on several brainstorming sessions and for example, Table (12) shows Implementation of 5S in maintenance process. Table (13) shows lean wastes (DWONTIME) analysis for maintenance process. Fig. (24) shows maintenance value stream mapping (after improvement). Finally, Table (14) and Fig. (25) show a summary of maintenance performance indicators (after 2 years continuous improvement).

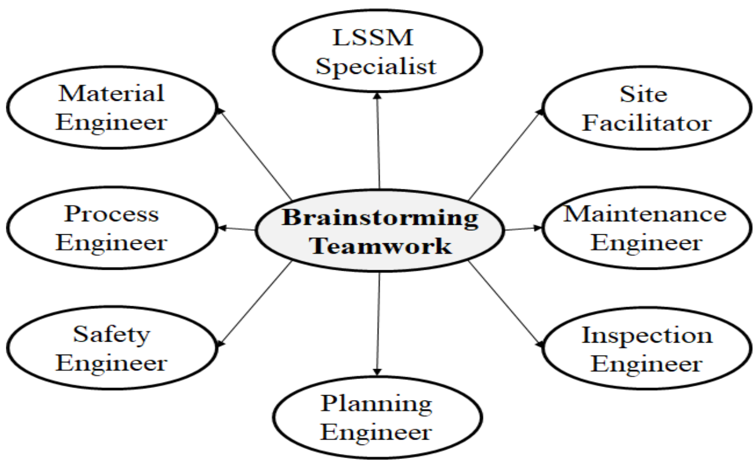


Figure 8 *Continuous improvement teamwork (brainstorming teamwork).*

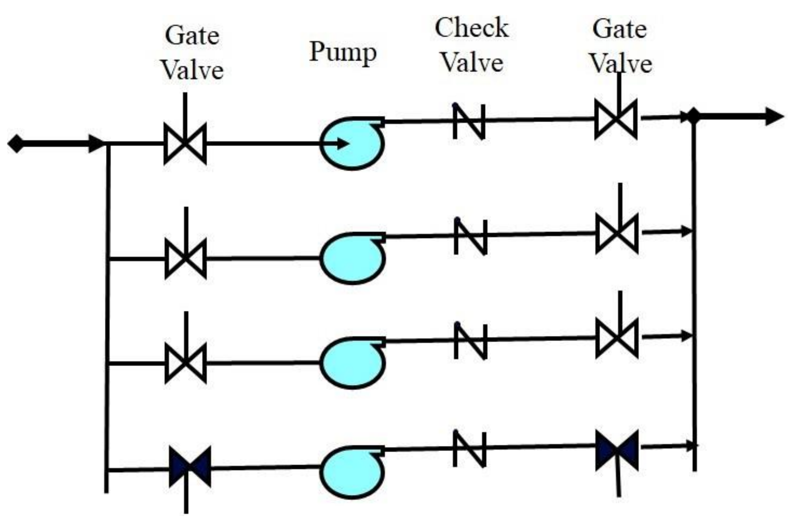


Figure 9 *Process flow diagram (PFD) – (4 pumps: 3 running + 1 standby).*

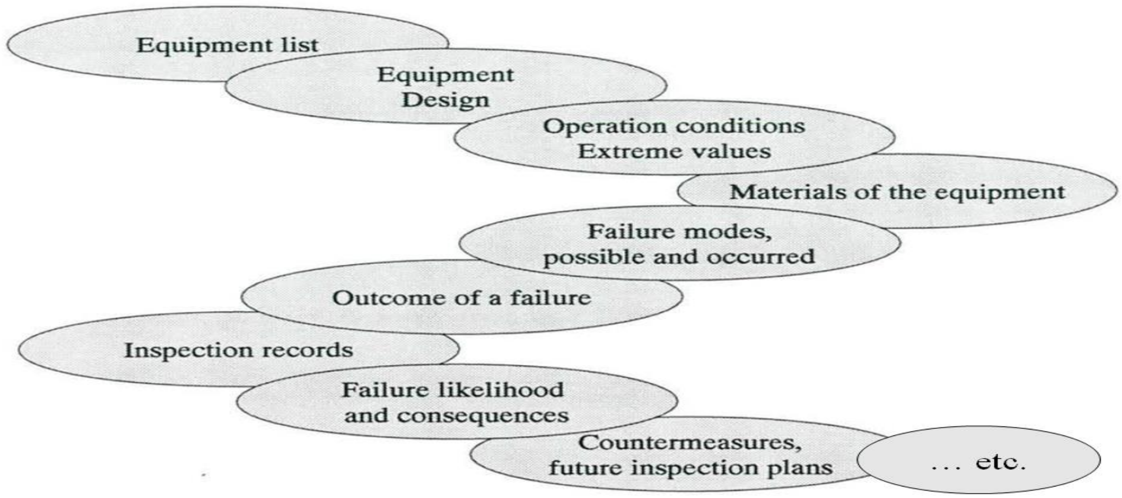


Figure 10 *Required information*

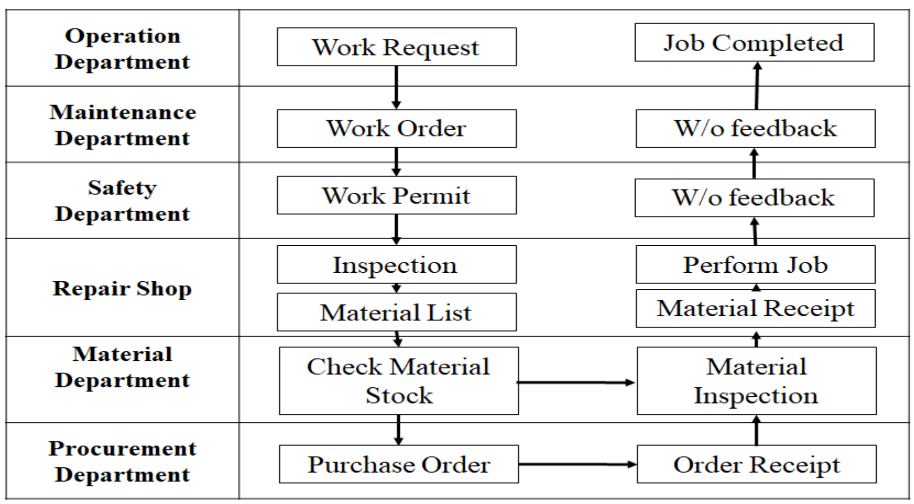


Figure 11 *Process flow chart for maintenance process (brainstorming).*

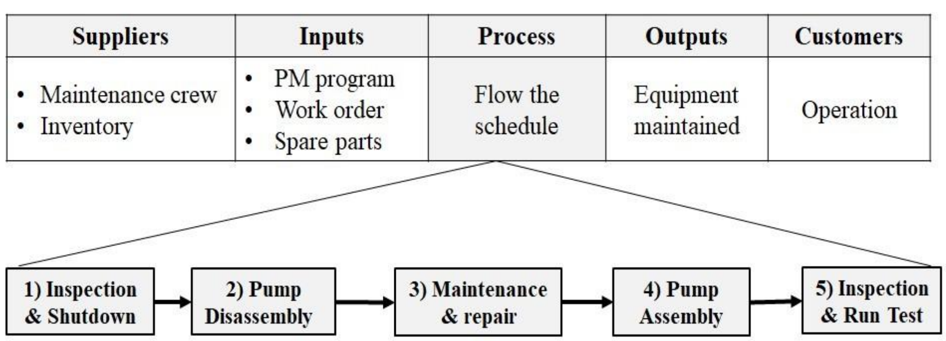


Figure 12 *SIPOC diagram for maintenance process (brainstorming).*

Table 5 *CURRENT MAINTENANCE PROGRAM PER PUMP (BRAINSTORMING & WORK ORDERS).*

PM Level	Monthly Activities	Annual (~ 8000 RH) Activities
Check	• Cleaning • Check operation • Check noise • Check seals • Check bearing • Check valves	• Cleaning • Check operation • Check noise • Check seals • Check bearing • Check valves • Check coupling • Check impeller • Check casing • Check shaft • Check strainers • Check motor
Replace	-	• Replace mechanical seal • Replace pump bearing
Maintenance Type	Running	Shutdown
Responsibility	Maintenance	Maintenance

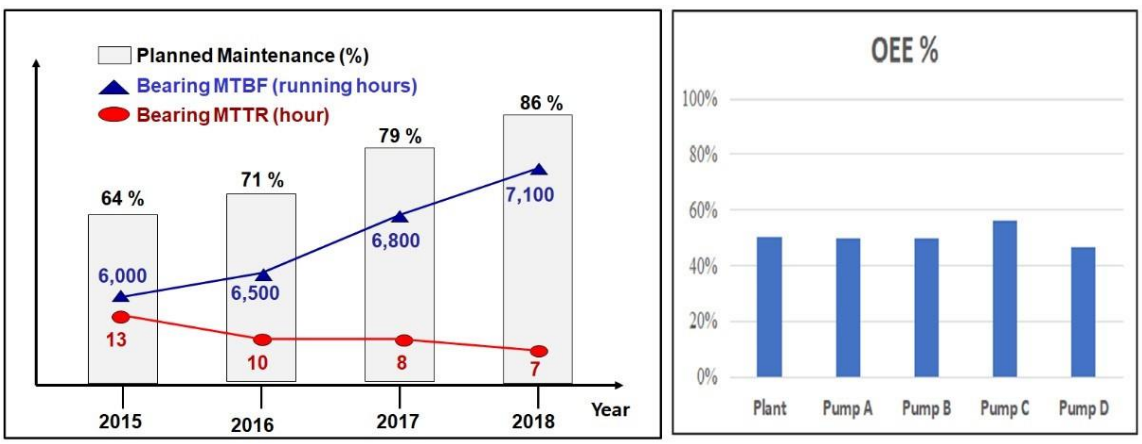


Figure 13 *History equipment maintenance KPIs, for example.*

Table 6 *HISTORY PLANNED MAINTENANCE % AND SIGMA LEVEL, FOR EXAMPLE.*

Period	2015	2016	2017	2018
Planned Maintenance %	64%	71%	79%	86%
Sigma Level	1.86	2.05	2.31	2.58

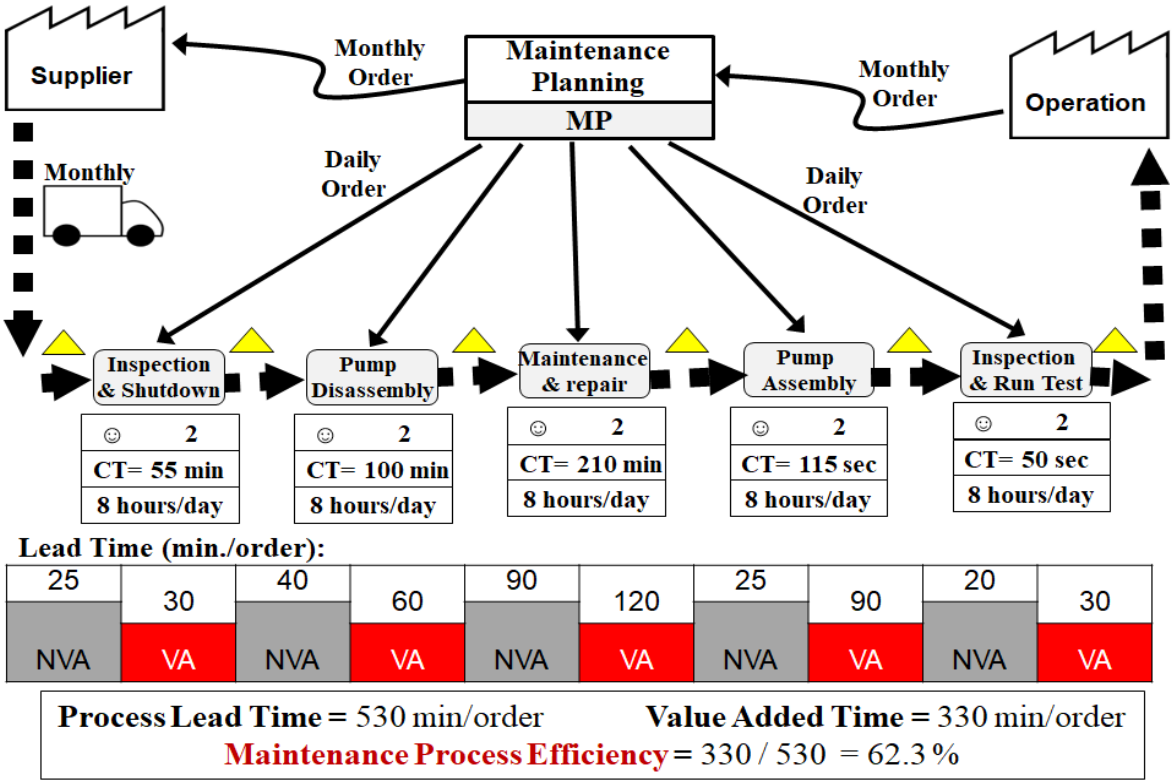


Figure 14 *Maintenance value stream mapping (before improvement).*

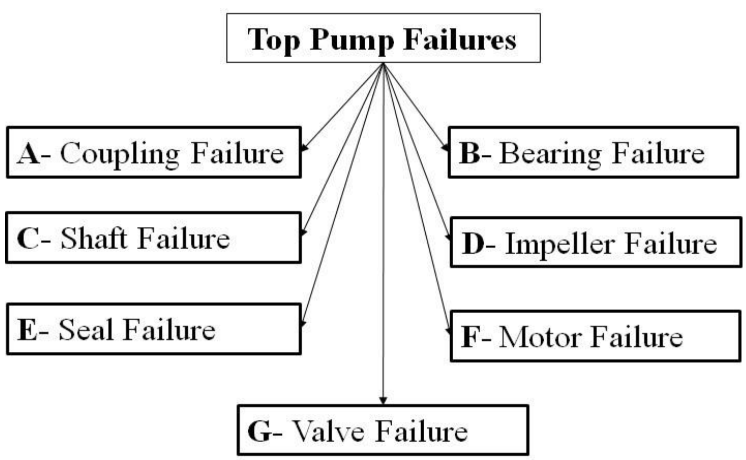


Figure 15 *Top failures based on rule 80/20.*

Probability						
	Very High	M	H	H	VH	VH
	High	L	M	H	H	VH
	Medium	L	L	M	M	H
	Low	VL	L	L	M	H
	Very Low	VL	VL	L	L	M
		Very Low	Low	Medium	High	Very High
		Consequence				

Probability:

Failure Frequency	Probability
> 10 Annually	Very High
6 – 10	High
3 – 5	Medium
1 – 2	Low
< 1	Very Low

Consequence:

Unplanned Downtime	Consequence
> 10 hours	Very High
6 – 10	High
3 – 5	Medium
1 – 2	Low
< 1	Very Low

Figure 16 *Proposed risk assessment, (brainstorming).*

Probability (Failure Frequency)						
	Very High	CBM	CBM+	CBM+	DOM	DOM+
	High	FTM+	CBM	CBM+	CBM+	DOM
	Medium	FTM	FTM+	CBM	CBM	CBM+
	Low	RTF	FTM	FTM+	CBM	CBM+
	Very Low	RTF	RTF	FTM	FTM+	CBM
Oil Plant		Very Low	Low	Medium	High	Very High
		Consequence (Failure Downtime)				

DOM: Design Out Maintenance
CBM: Condition Based Maintenance
FTM: Fixed Time Maintenance
RTF: Run To Fail & Routine Maintenance
DOM+: Advanced Design Out Maintenance
CBM+: Advanced Condition Based Maintenance
FTM+: Advanced Fixed Time Maintenance

Figure 17 *History equipment maintenance KPIs, for example.*

Table 7 *EQUIPMENT RISK LEVEL & MAINTENANCE STRATEGIES, FOR EXAMPLE.*

Item	Motor		Coupling	Pump				Valves	Pipeline
	Bearing	Stator		Seal	Bearing	Impeller	Sleeve		
MTBF	15,000	15,000	3,750	3,750	7,500	15,000	15,000	15,000	30,000
Downtime	8	8	4	6	8	6	6	4	4
Risk	M	M	M	M	H	L	L	L	VL
Policy	CBM	CBM	CBM	CBM	CBM+	FTM	FTM	FTM	RTF

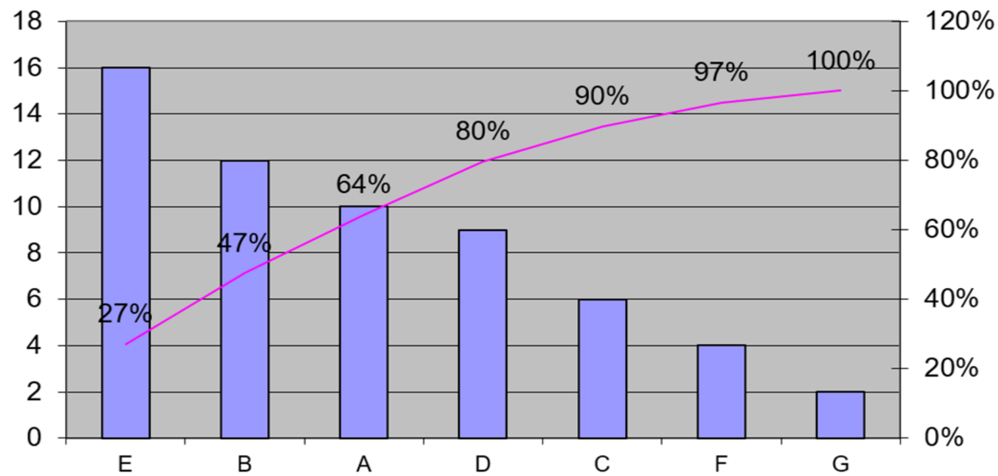


Figure 18 *Pareto Chart for the top failures, for example.*

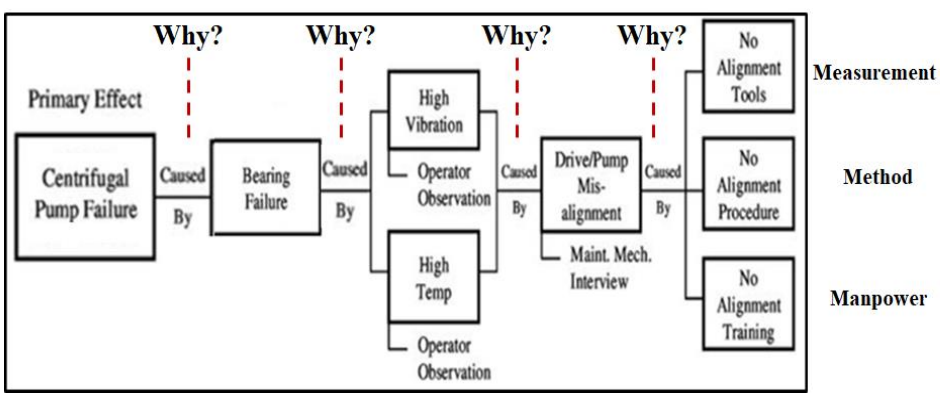


Figure 19 *Why-Why Analysis, for example.*

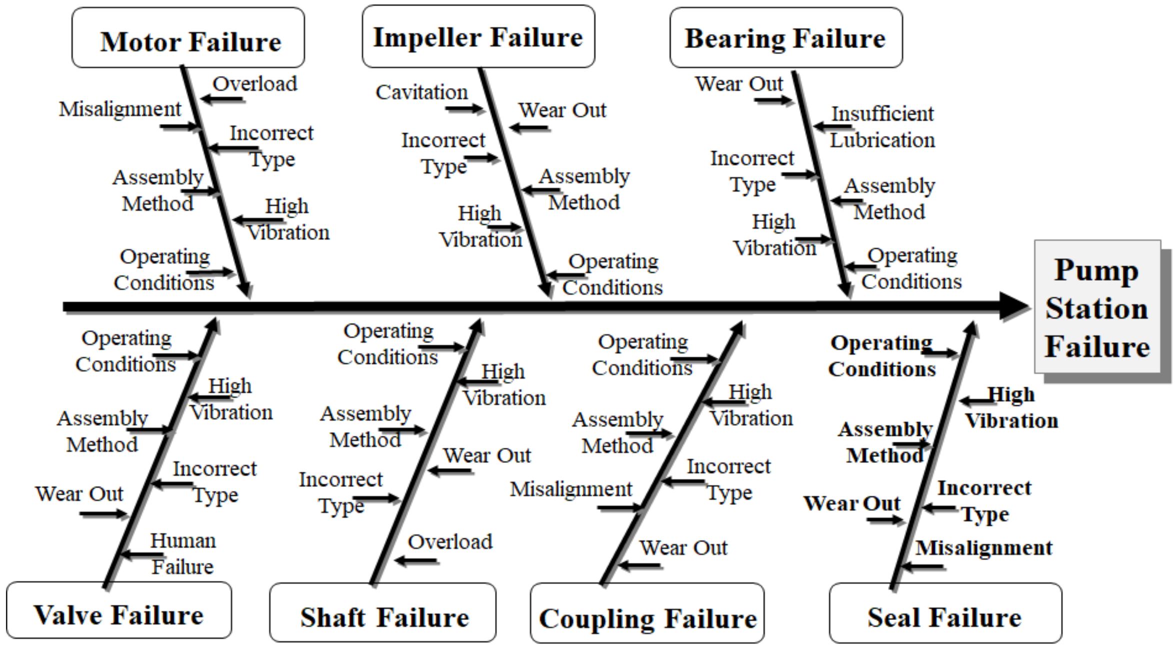


Figure 20 *Fishbone diagram based on equipment items, for example.*

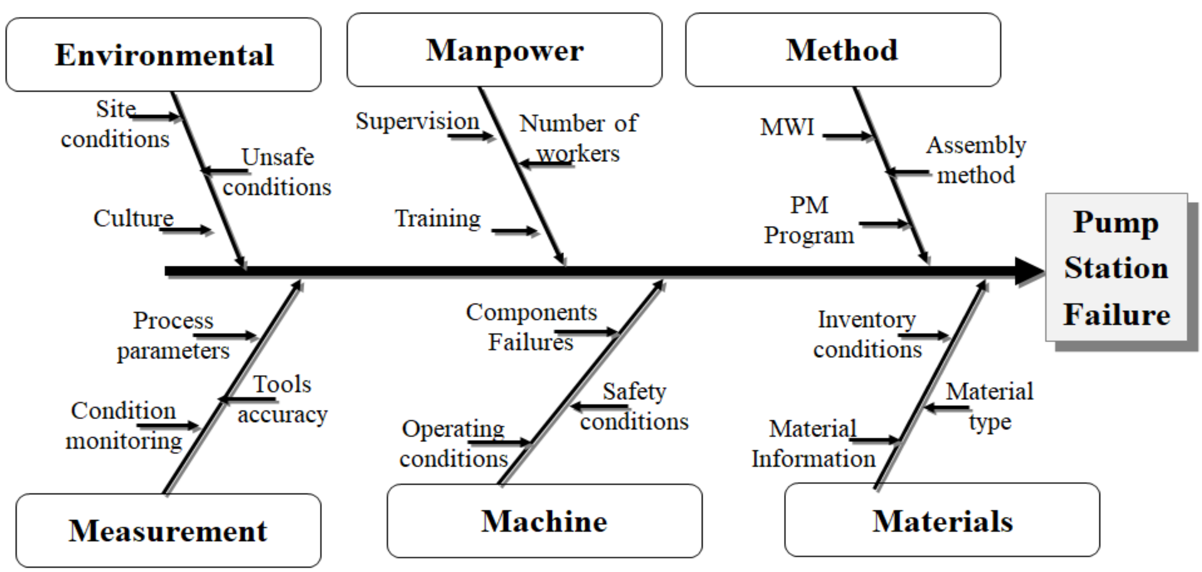


Figure 21 *Fishbone diagram based on maintenance process inputs, for example.*

Table 8 *FMEA FOR CENTRIFUGAL PUMP, FOR EXAMPLE.*

Identify			Analysis			Control
	Function	Failure Mode	Failure Cause	Failure Effect	Risk Level	Recommendations
Functions	Fluid Flow	No flow	- Overloaded motor	Motor failure	H	- Check misalignment - Check motor
		Insufficient flow	- Cavitation on impeller - Insufficient NPSH	Low pump efficiency	M	- Check impeller - Check NPSH
	Fluid Head	Insufficient head	- Cavitation on impeller - Insufficient NPSH	Low pump efficiency	M	- Check impeller - Check NPSH
Main Items	Mechanical Seal	Fluid leakage	- Seal fails - Poor maintenance	Leakage Low pump efficiency	M	- Check seal - Material selection
	Pump Bearing	Excessive vibration	- Bearing fails - High bearing temp. - Poor maintenance	Bearing failure	M	- Check misalignment - Check bearing temp. - Check bearing vib.
	Impeller	Insufficient head	- Cavitation - Insufficient NPSH - Poor maintenance	Low pump efficiency	M	- Check impeller - Check NPSH
	Coupling	Excessive vibration	- Coupling damage	Misalignment	M	- Check misalignment

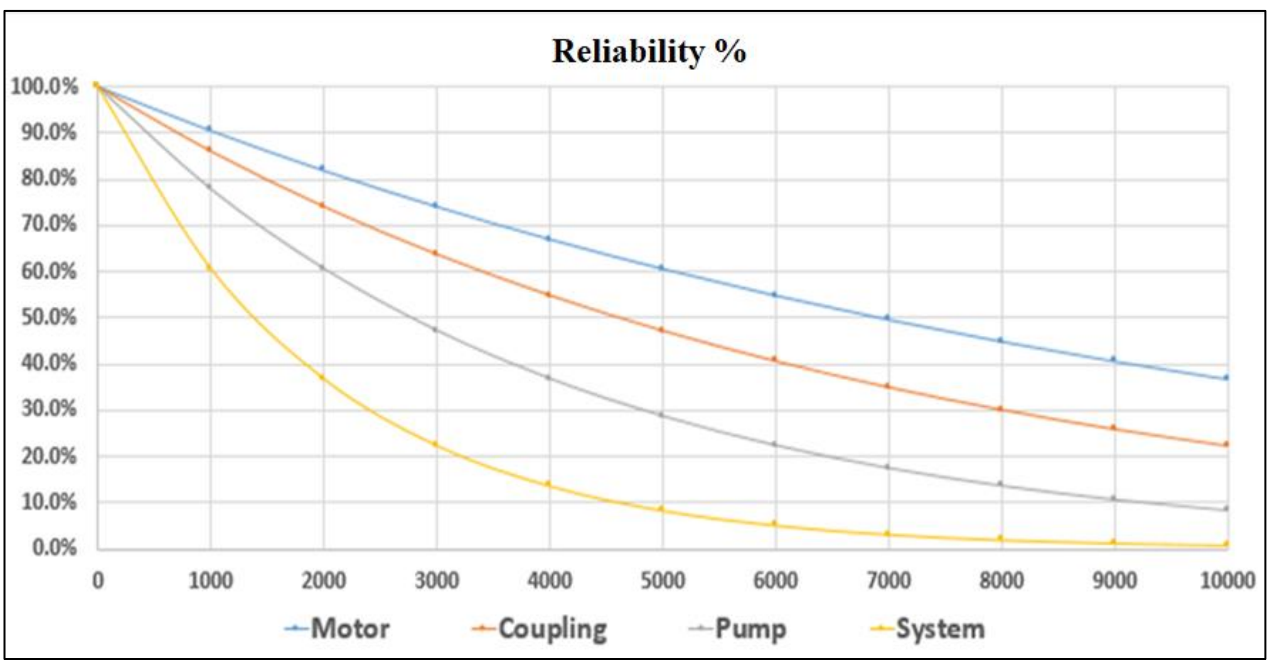
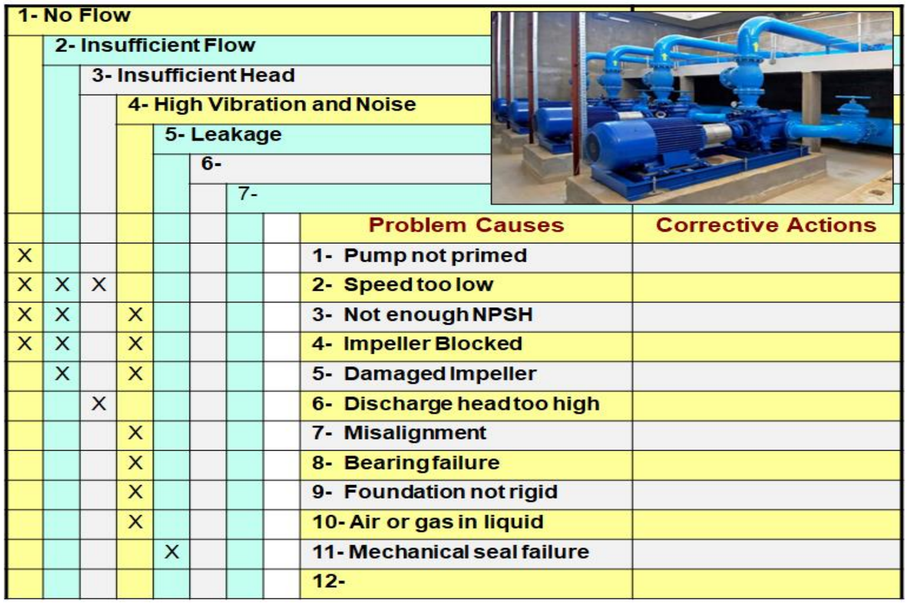


Figure 22 *Reliability analysis curves for the main items, for example.*



1- No Flow	2- Insufficient Flow	3- Insufficient Head	4- High Vibration and Noise	5- Leakage	6-	7-		Problem Causes	Corrective Actions
X								1- Pump not primed	
X	X	X						2- Speed too low	
X	X		X					3- Not enough NPSH	
X	X		X					4- Impeller Blocked	
	X		X					5- Damaged Impeller	
		X						6- Discharge head too high	
			X					7- Misalignment	
			X					8- Bearing failure	
			X					9- Foundation not rigid	
			X					10- Air or gas in liquid	
				X				11- Mechanical seal failure	
								12-	

Figure 23 *Proposed PUMP Trouble Shooting, for example.*

Table 9 *MAIN RECOMMENDATIONS TO UPDATE THE PM PROGRAM, FOR EXAMPLE.*

PM Level	Pump	Coupling	Motor	Valves	Pipeline
Every 1,000 RH	Check	Check	Check	Check	Check
Every 2,000 RH	Check	Check	Check	Check	Check
Every 4,000 RH	Replace Seal	Check	Check	Check	Check
Every 8,000 RH	Replace Seal & Bearing	Repair / Replace	Check	Check	Check
Every 16,000 RH	Replace Seal & Bearing	Repair / Replace	Replace Bearing	Check	Check
Every 32,000 RH	Replace Seal & Bearing	Repair / Replace	Replace Bearing	Repair / Replace	Check

Table 10 *PROPOSED PM PROGRAM FOR CENTRIFUGAL PUMP, FOR EXAMPLE.*

PM Level	Weekly	Monthly	Quarter (2000 RH)	Semi-Annual (4000 RH)	Annual (8000 RH)
Check	Cleaning Check operation Check seals Check noise	Cleaning Check operation Check seals Check noise Check valves	Cleaning Check operation Check seals Check noise Check valves Check bearing Check motor	Cleaning Check operation Check seals Check noise Check valves Check bearing Check motor Check coupling Check impeller Check casing Check strainers	Cleaning Check operation Check seals Check noise Check valves Check bearing Check motor Check coupling Check impeller Check casing Check strainers
Replace	-	-	-	Replace mechanical seal	Replace mechanical seal Replace bearing
Maintenance Type	Running	Running	Running	Shutdown	Shutdown
Target Maintenance Time, hours	1	2	3	5	7
Target Downtime; hours	-	-	-	3	5
MWI	410-P-W	410-P-M	410-P-Q	410-P-S	410-P-A
Responsibility	Operation		Maintenance		

Table 11 *PROPOSED CONDITION-BASED MAINTENANCE PROGRAM, FOR EXAMPLE.*

Item	Pump Bearing	Mechanical Seal	Pump Unit	Motor
Inspection Activities	Check vibration Check temperature Check oil	Check leakage Check temperature	Check flow rate Check flow head Check pump efficiency	Check vibration Check temperature Check current
Inspection Frequency	Every 2,000 RH	Every 1,000 RH	Every 1,000 RH	Every 2,000 RH

Table 12 *LEAN WASTES (DWONTIME) ANALYSIS FOR MAINTENANCE PROCESS, FOR EXAMPLE.*

5S Steps	Before Improvement	After Improvement
Sort	• There is a lot of unnecessary or outdated information.	• Remove all unnecessary or outdated information.
	• Rejected parts are kept inside the workshop.	• Rejected parts are removed and space is freed.
Set in order	• Previous stains on the floor hinder the movement of materials using the cart.	• The patches are filled with cement, which helps the material flow smoothly.
	• Spare parts and tools are placed randomly in the shelves and no labels are placed on them.	• Spare parts and tools are stored in their designated places with labels.
	• No labels	• Create labels for all components.
Shine	• Work place not very tidy and clean.	• Clean and tidy work place. • Floor garbage removal.
Standardize	• There are no standard documents (work order, work permit, quality inspection list, etc.)	• Create standard work order • Create standard safety permit • Create standard quality inspection • Create standard maintenance work procedures
Sustain	---	• Maintenance objectives and KPIs are presented in Arabic and English. • Keep all changes

Table 13 *LEAN WASTES (DWONTIME) ANALYSIS FOR MAINTENANCE PROCESS, FOR EXAMPLE.*

#	Waste Type	Waste Description	Root Cause	Solution Tools
1	Defects	Equipment failures	Lack of motivation	• Pareto chart • Cause–effect diagram
2	Waiting	Waiting times between maintenance activities Waiting times for materials Waiting times for handling	Poor coordination	• VA & NVA analysis • VSM • TPM
3	Over-production	Over maintenance	Poor maintenance planning	• Maintenance planning • Standard work
4	Not utilizing talent	Unused talent and skills of people	Resistance to change	• Advanced training • Motivation program
5	Transportation of materials	Spare parts and tools transportation	Poor housekeeping	• 5S (Visual control) • VSM
6	Inventory excess	Overstocked of spare parts	Poor material planning	• Material classification • Material planning
7	Motion of people	Unnecessary motion of people	Poor housekeeping	• 5S (Visual control) • Standard work
8	Excess processing	Excessive or too frequent maintenance activities	Lack of standardization	• Standard work • Advanced training

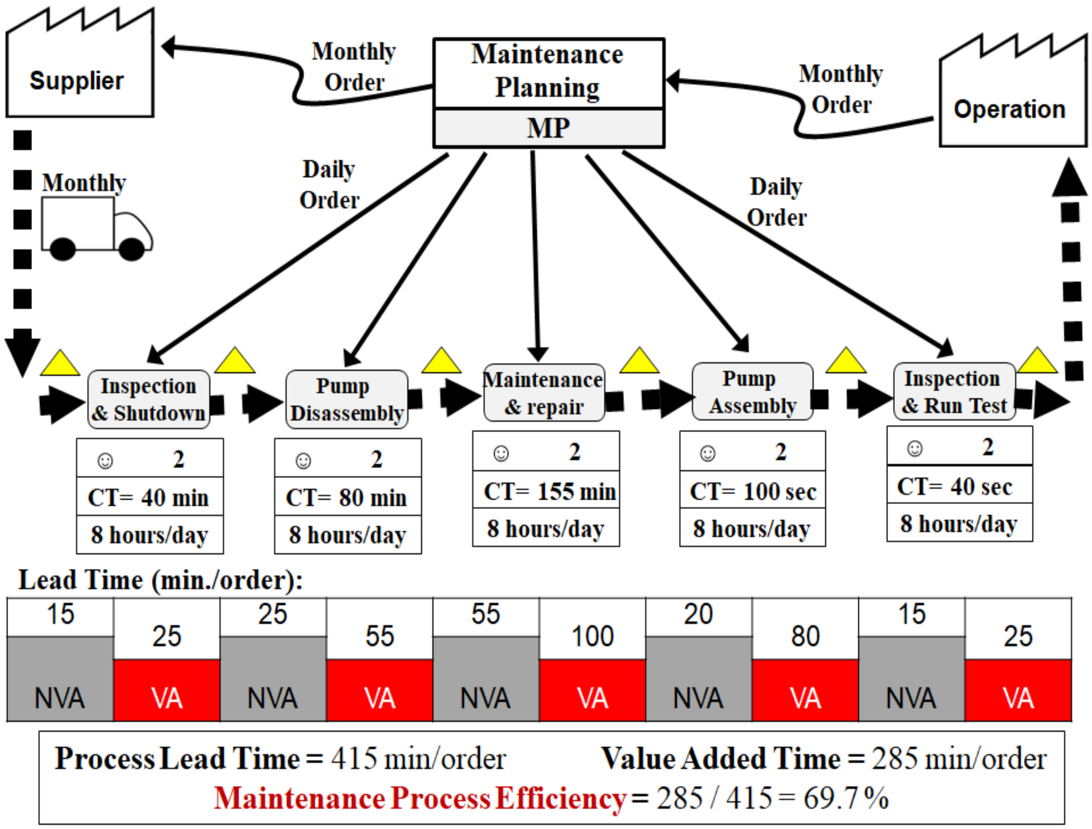


Figure 24 *Maintenance value stream mapping (after improvement).*

Table 14 *A SUMMARY OF MAINTENANCE PERFORMANCE INDICATORS (AFTER 2 YEARS CONTINUOUS IMPROVEMENT)*

KPIs	Target	Before Improvement	After Improvement
Planned maintenance %	≥ 95%	86%	93%
Sigma level	≥ 3.50	2.53	2.98
Bearing MTBF, hours	≥ 8,200	7,100	7,800
Bearing MTTR, hours	≤ 5.0	7.0	6.0
Plant OEE %	≥ 72%	50%	68%
Operational reliability %	≥ 95%	72%	89%
Maintenance process efficiency %	≥ 75%	62.3 %	69.7 %

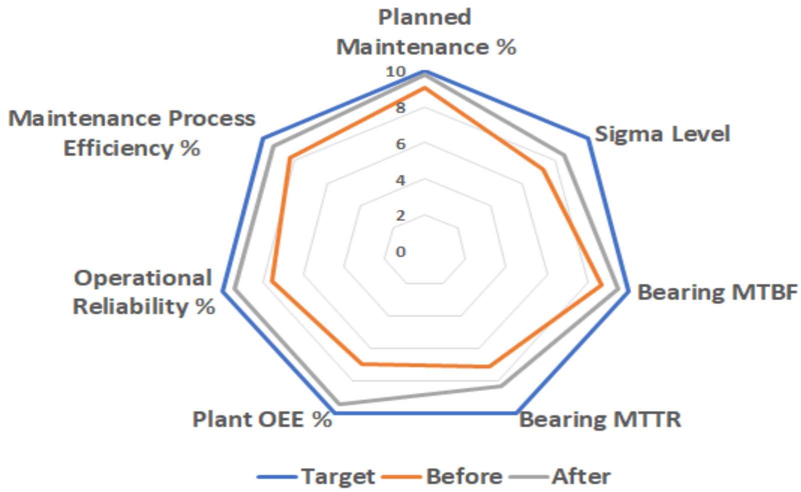


Figure 25 *Maintenance KPIs dashboard*

CONCLUSION

The importance of the maintenance function has increased due to its role in maintaining and improving process availability, product quality, safety requirements and operating cost levels of processing plants. Accordingly, choosing a maintenance strategy has become one of the most important decision-making activities in industry. In this study, some important LSS in maintenance case studies, tools and techniques are discussed, which will be useful for maintenance managers and leaders. LSSMM framework is proposed using various analysis and improvement tools. The study was conducted in one of the petrochemical companies in Egypt. A case study of a feedwater pumping station in a steam system is used to illustrate the proposed framework. Results indicate that the proposed methodology is successful in identifying the critical equipment and improving maintenance efficiency and effectiveness. For example, overall equipment effectiveness (OEE) improved from 50% to 68%, sigma level improved from 2.53 to 2.88, and maintenance process efficiency improved from 62.3% to 69.7 %.

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