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Improving Productivity and Quality of a Machining Process by Using Lean Six Sigma Approach: A Case Study

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Abstract: Lean six sigma (LSS) is a continuous process improvement approach that focuses on improving quality and eliminating waste, which in turn improves customer satisfaction and reduces operation costs. Some important LSS case studies, tools and techniques are discussed, which will be useful to LSS practitioners. In this context, this study focuses on the implementation of LSS in a spare parts company in Egypt. In this study, a generic LSS-DMAIC framework for implementing LSS in manufacturing is developed using various analysis and improvement tools such as brainstorming, process mapping, SIPOC, KPI analysis, OEE analysis, sigma level, seven QC tools, process time analysis, value stream mapping, waste analysis, DOE, Taguchi method, ANOVA, Takt time, standard time, 7S, standard work and cause–effect diagram. Based on the results of the study, suggestions were made to reduce defect rates, improve sigma level, reduce cycle time, increase value-added, reduce non-value-added time, increase labor productivity, and improve overall equipment effectiveness. For example, Total Effective Equipment Performance (TEEP) improved from 58.4% to 67.6%, Overall Equipment Effectiveness (OEE) improved from 64.5% to 75.7%, sigma level improved from 2.36 to 2.68, and process capability improved from 0.38 to 1.01. Finally, the proposed LSS framework can be used by production managers, leaders, and researchers in different production sectors before embarking on a continuous process improvement journey.

Keywords: LSS, KAIZEN, DMAIC, TQM, Continuous Improvement, Manufacturing.

1. INTRODUCTION

Lean Manufacturing and Six Sigma are two different approaches for continuous process improvement, their integration began and spread rapidly in the late 1990s. Lean Six Sigma (LSS) is a structured, data-driven approach that integrates Lean Manufacturing and Six Sigma. In practice, LSS is a process improvement approach that analyzes quantitative data on process performance to identify, eliminate, and control problems and deficiencies related to customer satisfaction, product quality, resource productivity, and manufacturing cost. This study focuses on the implementation of LSS framework in the production sectors in Egypt.

2. LITERATURE REVIEW:

Several studies have focused on the applications of LSS in the production sector, from [1] to [28]. Table (1) presents a comprehensive survey of LSS studies in the production sector over the past ten years (2013 to 2023), and they are classified based on application, main tools, and key objectives. As shown in this table, the key LSS-objectives in production sector are as follows, [1] to [28]:

1) Reducing defect ratio,
2) Improving production rate,
3) Reducing cycle time,
4) Reducing process wastes,
5) Improving customer satisfaction.

The main LSS-tools in production sector are as follows, [1] to [28]:

1) Process mapping (process flow chart and SIPOC),
2) Seven-Quality-Control tools (7QC),
3) Defect analysis, sigma level and process capability,
4) Value stream mapping (VSM) and Lean wastes analysis,
5) Visual control (5S) and Standardized work (SW).

Based on this review, it was found that the most important success factors for LSS implementation are as follows, [2], [6], [9], [12], [15]:

1) Management commitment, support and involvement,
2) Leadership development and awareness,
3) Effective external and internal benchmarking,
4) Effective goals, objectives, and KPIs,
5) Employee training and education,
6) Employee engagement, empowerment, and satisfaction,
7) Effectives reward and recognition system,
8) Effective information and communication technology infrastructure,
9) Understanding LSS methodology, tools and techniques,
10) Focus on customer, relationship and satisfaction,
11) Effective project planning and control system,
12) Effective change management process,
13) Effective Organizational structure & responsibility matrix.

TABLE 1: Lean six sigma studies in manufacturing domain

Reference		Application	Main Tools	Main objectives
[1]	Atmaca, 2013	Dishwashers industry	FMEA, VSM, Process capability, Pareto analysis, C&E diagram, Takt Time.	- Reducing cycle time - Reducing defect %
[2]	Ben-Ruben, 2017	Automotive Industry	Project charter, Process mapping, SIPOC, Pareto analysis, VSM, Network diagram, C&E diagram, Process capability, Process layout, Kaizen.	- Reducing defect % - Reducing cycle time - Reducing lead time
[3]	Cabrita, 2015	Bolts industry	Project charter, VOC, CTQ, VSM, Kanban, FMEA.	- Reducing costs - Reducing cycle time
[4]	Ghaleb, 2015	Cement bags industry	SIPOC, VSM, Process capability, C&E diagram.	- Reducing time waste - Reducing defect % - Increasing sigma level.
[5]	Girmanova, 2017	Metallurgical operations	Process mapping, SIPOC, Sigma level, Pareto analysis, C&E diagram, FMEA,	- Improving quality - Reducing cost
[7]	Guerrero, 2017	Wood furniture	Takt Time, Value stream analysis, Pareto chart, C&E diagram, DOE, ANOVA, Control charts.	- Reducing defect % - Improving process efficiency
[8]	Gupta, 2018	Tire manufacturing	Process capability, Control charts, C&E diagram.	- Reducing defect %
[9]	Hardy, 2021	Laminated panel production	Process mapping, CTQ, OEE, Takt Time, VSM, Control charts, C&E diagram, Process layout, FMEA.	- Reducing downtime - Improving OEE
[10]	Jie, 2014	Printing company	VSM, Pareto chart, Process mapping, C&E diagram, 5Why analysis.	- Improving production rate - Reducing setup time
[11]	Jimenez, 2019	Food industry	SIPOC, VSM, Waste analysis, Process layout, Material flow, Takt time, Heijunka, Pareto chart, C&E diagram,	- Reducing time waste
[12]	Karam, 2018	Pharmaceutical industry	Control charts, Process capability, Visual control, SMED	- Reducing downtime - Reducing changeover time

Reference		Application	Main Tools	Main objectives
[13]	Kumar, 2021	Engine cylinder	ABC, Pareto chart, Process Mapping, Project charter, Process mapping, Control charts, C&E diagram,	- Reducing defect % - Increasing sigma level.
[14]	Liu, 2020	Footwear manufacturing	VSM, Takt time, VSM, DOE, Taguchi method, Simulation,	- Reducing defect % - Reducing lead time - Reducing WIP
[15]	Mittal, 2023	Rubber weather strips	CTQ, Process mapping, C&E diagram, Cost-benefit analysis	- Reducing rejection rate - Reducing production cost
[16]	Murmura, 2021	Iron Industry	Project charter, Gantt Chart, Risk analysis, SIPOC, Process Mapping, VSM, Sigma level, Statistical analysis, 5 Why	- Reducing lead time - Reducing defect % - Increasing sigma level.
[17]	Nandakumar, 2020	Food industry	SIPOC, VSM, ANOVA, 5S, OEE, C&E diagram,	- Improving OEE
[18]	Nedra, 2019	Clothing industry	SIPOC, Process capability, Process Mapping, C&E diagram, Process layout, waste analysis, control charts,	- Reducing defect % - Increasing sigma level - Reducing lead time
[19]	Panat, 2014	R&D Intel	Process mapping, SIPOC, Pareto chart, FMEA, control process flow.	- Improving time utilization - Improving customer satisfaction
[20]	Patyal, 2021	Chemical company	Project charter, SIPOC, Process capability, Why–why analysis, How–how analysis,	- Reducing customer complaints
[21]	Pereira, 2019	Mold industry – CNC	VSM, Waste analysis, Pareto chart, OEE,	- Improving OEE
[22]	Sharma, 2022	Automobile light manufacturing	Process mapping, Project charter, VSM, Waste analysis, Simulation, Pareto chart, C&E diagram, Sigma level,	- Reducing defect % - Increasing production rate - Reducing idle time
[23]	Singh, 2019	Machining workshop	Takt time, VSM, Process layout, Simulation, Process capability, Control charts,	- Reducing cycle time - Reducing WIP - Reducing lead time
[24]	Sodhi, 2019	Foundry unit - Casting	SIPOC, VSM, Waste analysis, Project charter, Process mapping, Sigma level, C&E diagram,	- Reducing scrape rate - Reducing rework
[25]	Swarnakar, 2016	Automotive Industry	Process mapping, Project charter, Process capability, SIPOC, VSM, Waste analysis, C&E diagram, Pareto chart, OEE	- Reducing defect % - Reducing time waste
[26]	Tiwari, 2020	Cookware manufacturing	Project charter, KPIs, VSM, Pareto chart, C&E diagram, Action plan, Waste analysis,	- Improving sustainability - Minimizing safety incidents
[27]	Trubetskaya, 2023	Compound animal feed	VSM, Spaghetti diagram, Pareto chart, Standard work chart, control	- Reducing inventory stock - Reducing lead time

Reference		Application	Main Tools	Main objectives
		manufacturing	charts,	
[28]	Wang, 2019	Development of Green motor	Process mapping, VOC, VSM, Sigma level, C&E diagram, DOE, Taguchi, Control charts,	- Reducing defect % - Reducing time waste

3. CASE STUDY:

As shown in Fig. (1), the core objective of this study is to improve the effectiveness and efficiency of a machining process. Based on the in-depth analysis of the literature review, the LSS-DMAIC framework was developed using various analysis and optimization tools. Table (2) shows proposed LSS roadmap for a machining process. Table (3) shows the proposed LSS-tools in different steps of DMAIC methodology. Table (4) presents the developed LSS-DMAIC framework for the production sector. The study was conducted in a spare parts manufacturing company in Egypt. Project charter is the first step in a LSS project. It is a roadmap consisting of details of the problem statement, scope, goals, schedule, and teamwork. Details of this study are presented in the following sub-sections., [6], [29], [30], [31].

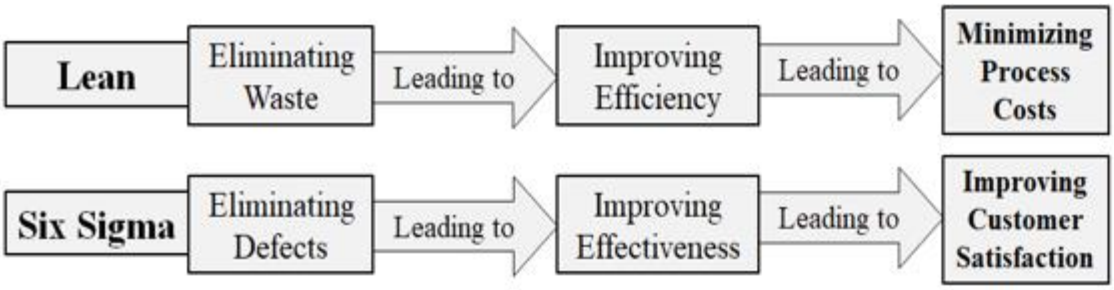

Fig 1. Core objective of this study.

TABLE 2: Proposed LSS roadmap for a machining process.

Approach	Objectives	Most Common Tools
Current Situation Analysis	- 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 Analysis (RCA) • Mistake Proofing (Poka-yoka)
Lean Approach	- Improving Value Added - Reducing Wastes	• Value Added Time Analysis • Value Stream Mapping (VSM) • Lean Waste Analysis (8 wastes)
Six Sigma Approach	- Reducing Defects - Reducing Variance - Optimal Machining Parameters	• SQC for Defect Analysis • SQC for critical to quality (CTQ) Analysis • Design of experiments (DOE) • Taguchi method

TABLE 3: Proposed LSS-tools in different steps of DMAIC methodology.

#	Most common LSS tools	Define	Measure	Analyze	Improve	Control
1	Brainstorming	x		x	x	
2	Project charter	x				
3	Critical To Quality (CTQ)	x			x	
4	Process mapping & SIPOC	x			x	
5	Current performance (KPIs & OEE)		x	x		x
6	Sigma level and process capability		x			x
7	Check Sheet and histogram		x	x		
8	Value Stream Mapping (VSM)		x		x	x
9	Design of experiments (DOE &Taguchi)		x			
10	Lean wastes and non-value added		x			x
11	Takt time		x		x	
12	Pareto Diagram			x		
13	Scatter Diagram			x	x	
14	Process Control Charts			x		x
15	ANOVA and Hypothesis testing			x		
16	Cause & Effect Diagram			x		
17	Visual control (5S)				x	
18	Standard work (SW)				x	
19	Kaizen events				x	
20	Control plan					x
21	Process control charts					x
22	Standard operating procedures (SOP)					x
23	KPIs dashboard					x
24	Before / after analysis					x
25	Internal and external auditing					x
26	Lessons learned					x

TABLE 4. Proposed LSS-DMAIC framework.

Phase	Objectives	Key Activities	Used Tools
Define	Studying process, product and problems in detail.	1) Defining process and product description	Brainstorming
		2) Building teamwork & developing project charter	Brainstorming
		3) Defining current situation (strength & weakness)	Brainstorming
		4) Defining process objectives and problems	Brainstorming
		5) Defining customer requirements & CTQ factors	CTQ and VOC
		6) Defining process mapping (flow chart, SIPOC)	SIPOC
Measure	Designing and collecting the required information.	7) Designing templates & collect information	Brainstorming
		8) Measuring current performance evaluation	KPIs
		9) Measuring overall equipment effectiveness	OEE
		10) Measuring sigma level & process capability	Sigma level, Cpk
		11) Preparing current value stream mapping	VSM
		12) Measuring process wastes	8 Lean wastes
Analyze	Applying analysis tools and identifying root causes	13) Analyzing process defects	Pareto chart
		14) Analyzing of variance	ANOVA
		15) Analyzing critical to quality (CTQ)	SPC & 7QC
		16) Analyzing process wastes	RCA

Phase	Objectives	Key Activities	Used Tools
		17) Analyzing process parameters	DOE
		18) Identifying Root causes	C&E diagram
		19) Determining improvement recommendations	Brainstorming
Improve	Implementing solutions according to priorities	20) Prioritizing the solutions	Brainstorming
		21) Preparing the improvement plan	Brainstorming
		22) Preparing action plans	Brainstorming
		23) Planning for kaizen activities	5S, SW
		24) Training the process teamwork	Training program
		25) Implementing the improvements plans	Kaizen events
		26) Evaluating the results	Brainstorming
Control	Monitoring the process and achieving daily improvements	27) Developing and implementing a control plan	Brainstorming
		28) Designing and document standard practices	QA/QC
		29) Following process control charts	Control charts
		30) Following QA/QC checklists	QA/QC
		31) Following Kaizen improvement	5S, SW
		32) Following KPIs, OEE, Sigma level, … etc.	KPIs
		33) Controlling and evaluating results	8 Lean wastes
		34) Identifying opportunities for future improvements	Kaizen events
		35) Preparing project close-out report	Brainstorming

3.1. Define Phase:
The purpose of this phase is to clarify the project scope of work and identify the problems. Fig. (2) shows the process description and SIPOC diagram for the turning machining process for a roller shaft made of cast alloy steel. The process flow chart of the used product is shown in Fig. (3). After building the study teamwork, an analysis of the current situation was prepared through a brainstorming session to identify the strengths and weaknesses factors of the process under study; as shown in Table (5). According to the company's history of the process performance, a list of problems was identified, as shown in Table (6).

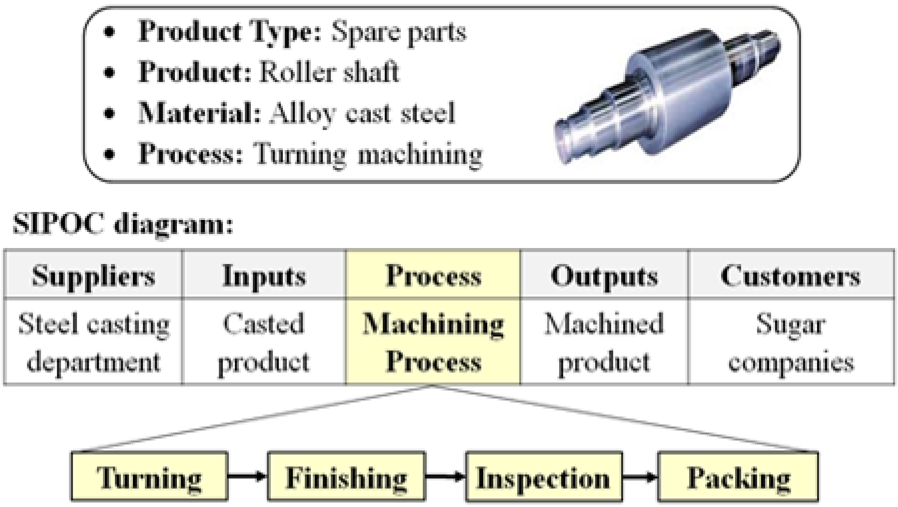

Fig 2. Process description and SIPOC diagram.

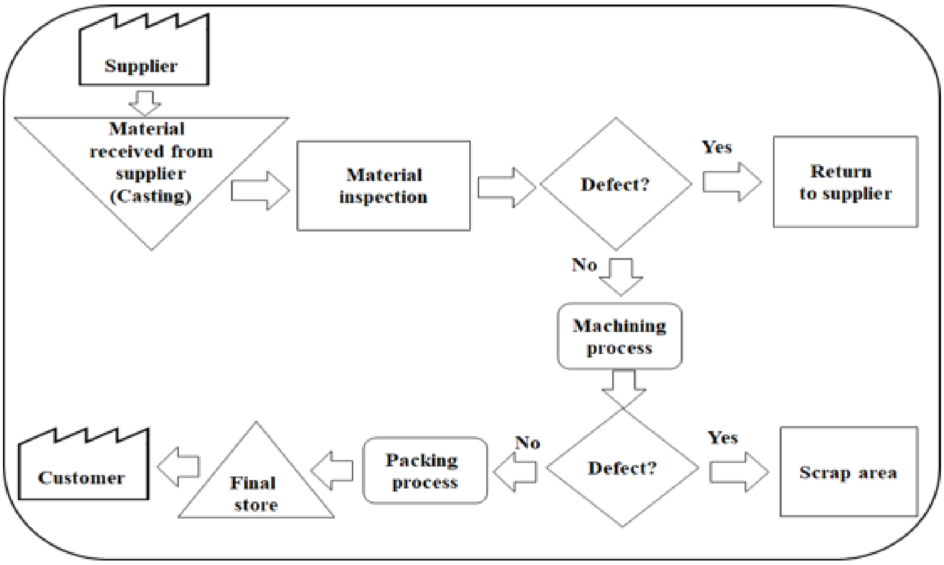

Fig 3. Process flow chart.

TABLE 5. Current situation analysis through brainstorming for the selected process.

#	Factors	Strength Points	Weakness Points
1	Manpower	• Sufficient staff • High employee retention	• Lack of training & education • Lack of motivation • Lack of Kaizen culture
2	Method	• Good information system • Good IT infrastructure	• Lack of process planning • Lack of standardization • Lack of objectives & KPIs
3	Machine	• New Equipment	• Equipment breakdown • Low performance rate • Limited equipment
4	Materials	• High material availability • Good Supplier relationship	• Low material quality • Lack of material control • Poor storage conditions
5	Measurement	• Good inspection plan	• Inefficient inspection tools • Lack of statistical tools • Lack of tools calibration
6	Management System	• Top management support • Good leadership • Focus on customer	• Lack of KPIs dashboard • Lack of knowledge about LSS • Lack of benchmarks
7	Environmental	• Good layout & space	• Unsafe working conditions • Lack of safety PPE • Lack of safety audit

TABLE 6. List of performance problems for the selected process.

#	Problems	Unit	Current	Target
1	Low Customer Satisfaction	%	84.67%	94%
2	Low Quality Ratio	%	80.56%	94%
3	Low Effectiveness Ratio	%	68.18%	90%
4	Low Production Rate	ton/hour	0.725	1.000
5	Low Labor Productivity	man.hour/ton	4.14	3.00
6	Low Machine Productivity	ton/machine.Hour	1.45	1.80
7	Low Time Utilization	%	41.67%	70%
8	Low overall equipment effectiveness (OEE).	%	64.5%	80%

TABLE 7. Defect analysis (Before improvement)

Month #	Quality %	Defect %	DPPM	Sigma Level
1	80.51%	19.49%	194,900	2.360
2	78.46%	21.54%	215,400	2.288
3	80.89%	19.11%	191,100	2.374
4	79.35%	20.65%	206,500	2.319
5	80.23%	19.77%	197,700	2.350
6	80.60%	19.40%	194,000	2.363
Average	**80.01%**	**19.99%**	**199,933**	**2.342**

3.2. Measure Phase:

This phase aims to document and understand the current state of the system and ident ify important metrics related to product quality and process performance. A survey was conducted to collect defect data for a period of six months, as shown in Table (7). It was observed that the current sigma level ranged from 2.288 to 2.374. Fig. (4) shows the quality control chart for the past month, 25 working days.

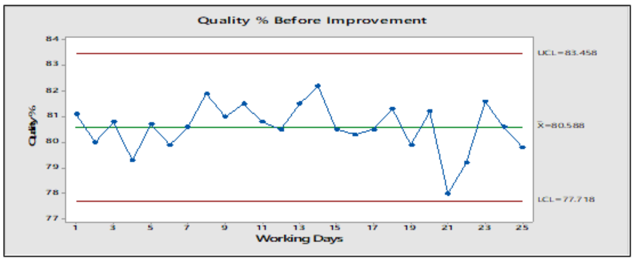

Fig 4. Quality Control Chart (Before improvement).

3.3. Analyze Phase:

The purpose of this phase is to identify the root cause and analyze problems and system inefficiencies. Fig. (5) shows the Pareto chart of the defect types, as shown in this figure, the most common defect in this process is the bad surface finish. Therefore, a brainstorming session was conducted to identify the root causes of the bad surface finish as shown in Fig. (6). Studies were conducted to optimize the processing parameters in order to improve the surface finish and reduce the processing time. To determine the optimal process parameters, Taguchi technique was used to obtain a good surface finish. As shown in Table (8), three main parameters of the lathe process used were speed, feed, and depth of cut. The experimental results were used in analysis of variance (ANOVA) by using MINITAB 18. Fig. (7) shows the scatter diagrams and process parameters analysis. As shown in this figure, the optimal set of lathe parameters to get good surface finish are depth of cut as 0.5 mm, feed rate as 0.1 mm, and spindle speed as 950 rpm.

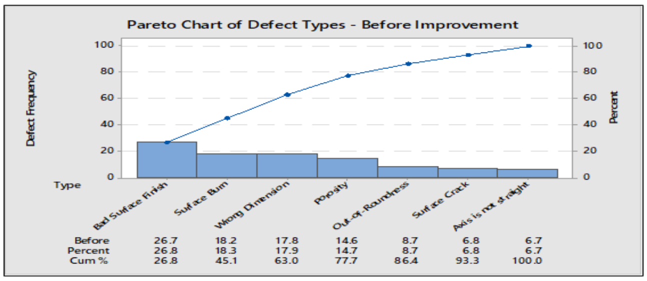

Fig 5. Pareto chart of defect types (Before improvement).

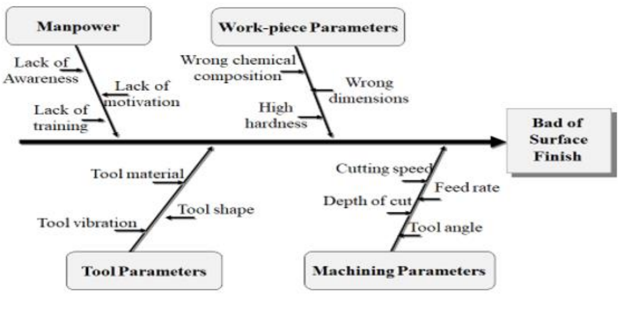

Fig 6. C&E diagram for bad of surface finish

TABLE 8. Experimental data for surface roughness

#	Depth of cut (mm)	Feed rate (mm/rev)	Spindle speed (rpm)	Surface finish (µm)
	D	f	N	Ra
1	0.5	0.10	950	2.20
2	0.5	0.10	625	2.86
3	0.5	0.10	415	3.71
4	1.0	0.15	950	3.48
5	1.0	0.15	625	4.54
6	1.0	0.15	415	5.88
7	1.5	0.20	950	4.42
8	1.5	0.20	625	5.76
9	1.5	0.20	415	7.46

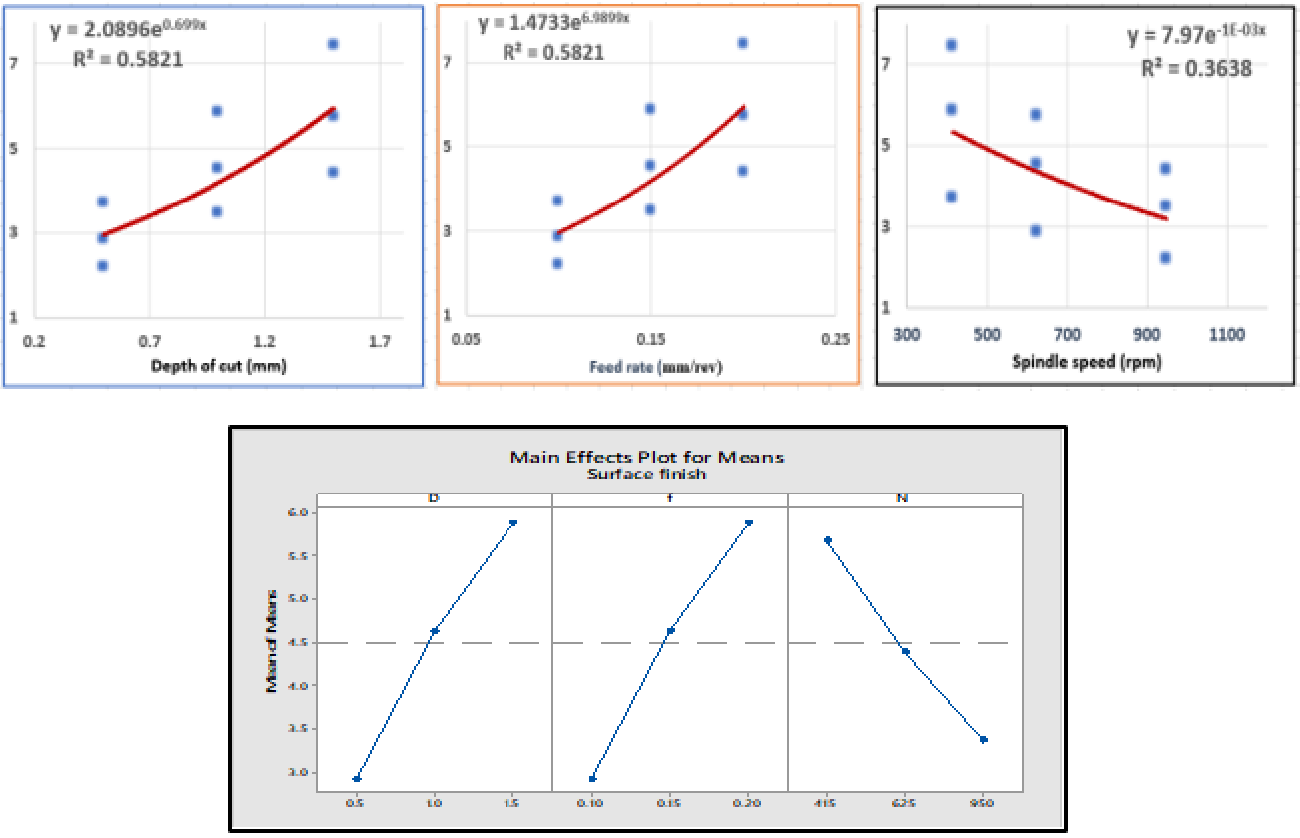

Fig 7. ANOVA results for process parameters analysis

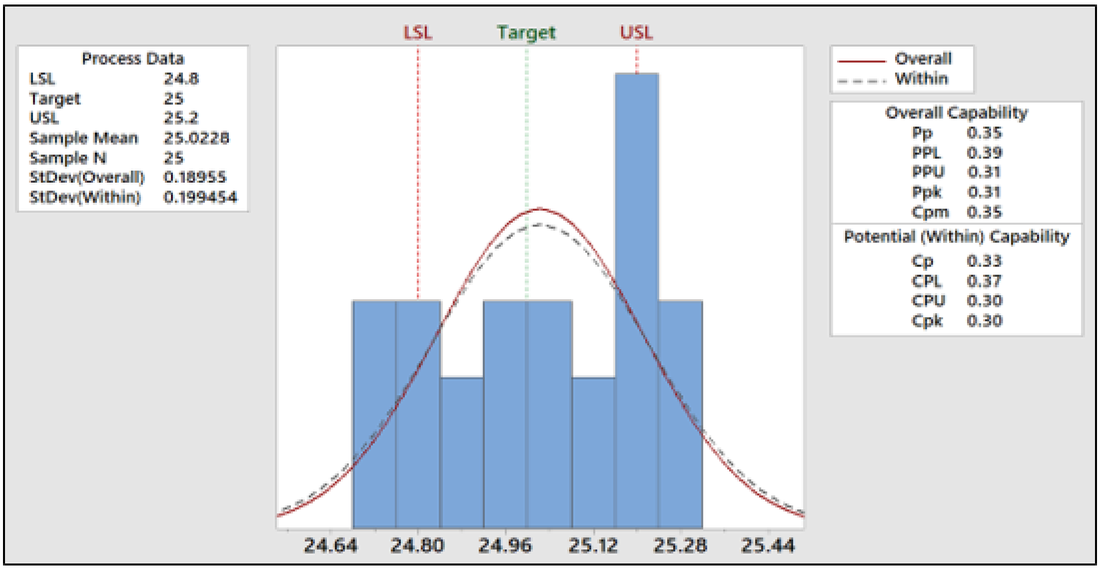

Fig 8. Process capability analysis (before improvement).

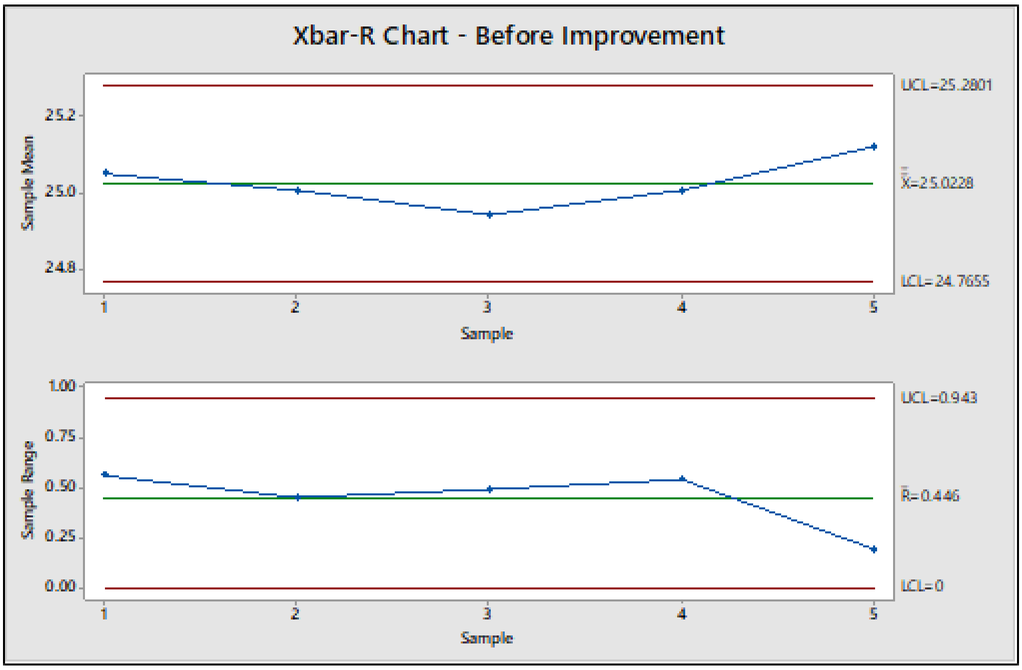

Fig 9. Process control charts (before improvement)

The process capability was analyzed as shown in Fig. (8). Process characterization resulted in a mean of 25.0228, which is higher than the desired mean of 25.0, and the poor value of Cpk = 0.30 indicated that the process was A fishbone diagram is a visual tool used to logically organize the potential root causes of a problem or objective. Based on a lot of brainstorming sessions, the root causes of low performance, low OEE, and waste reduction were identified as shown in Figures (12), (13), and (14).
not on the target and the process was left shifted. Fig. (9) shows process control charts (Xbar-R chart).

A value stream mapping (VSM) was constructed to document the information flow, material flow and lead time flow. As shown in Fig. (10), the process efficiency was about 37.2%. Also, Fig. (11) identifies the value-added time and non-value-added time, the value-added time ratio was about 37%. Through a detailed study of the process, non-value-added activities and process waste analysis were identified as shown in Table (9).

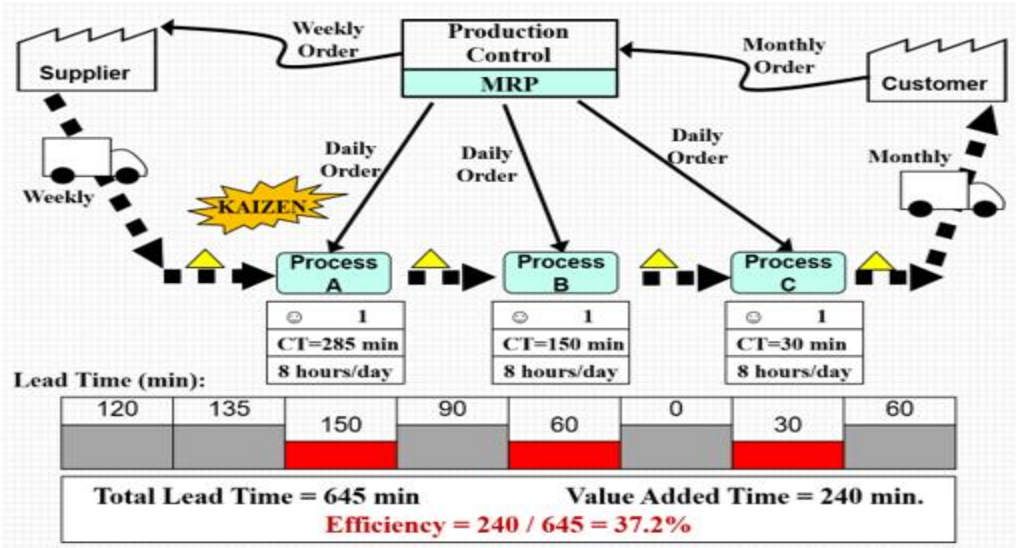

Fig 10. Value stream mapping (before improvement).

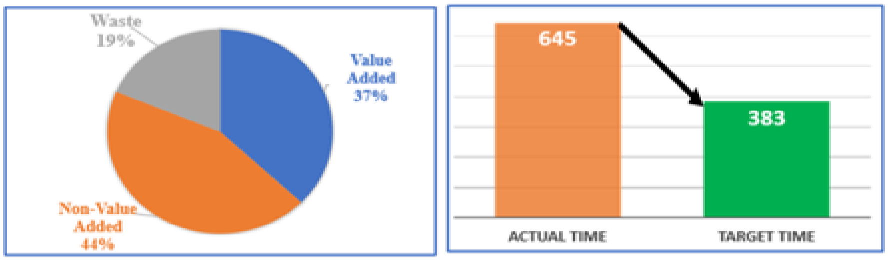

Fig11. Value added analysis for one shift (before improvement).

TABLE 9. Lean wastes (DWONTIME) analysis

#	Waste Type	Waste Description	Root Cause	Solution Tools
1	Defects	Product defects Equipment failures	Lack of motivation	Pareto chart Cause–effect diagram
2	Waiting	Waiting for materials Waiting for handling	Poor coordination	VSM TPM
3	Over-Production	More quantity than customer demand	Poor production planning	Production planning Standard work
4	Not Utilizing Talent	Unused talent and skills of people	Resistance to change	Advanced training Motivation program
5	Transportation of materials	Unnecessary transportation of materials	Poor housekeeping	5S (Visual control) VSM
6	Inventory Excess	Over stock of materials	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	More work or higher quality than required	Lack of standardization	Standard work Advanced training

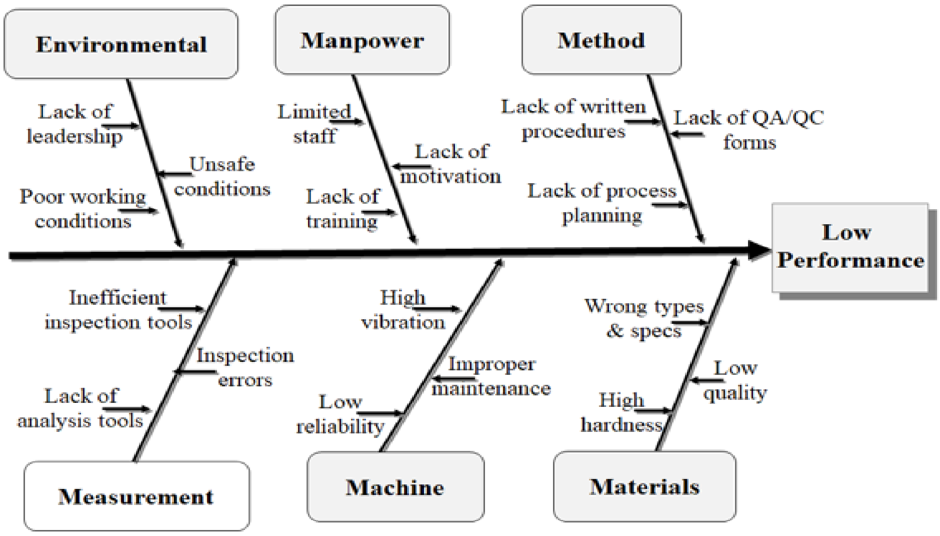

Fig 12. C&E diagram for low process performance.

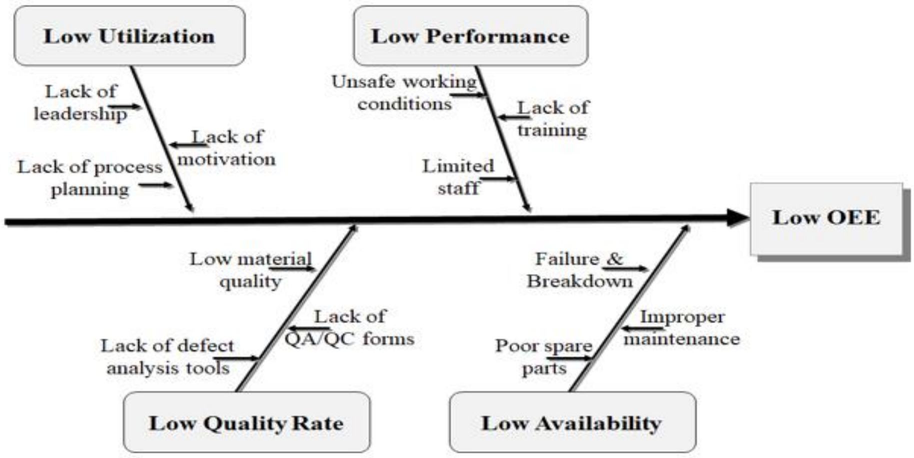

Fig 13. C&E diagram for low overall equipment effectiveness (OEE).

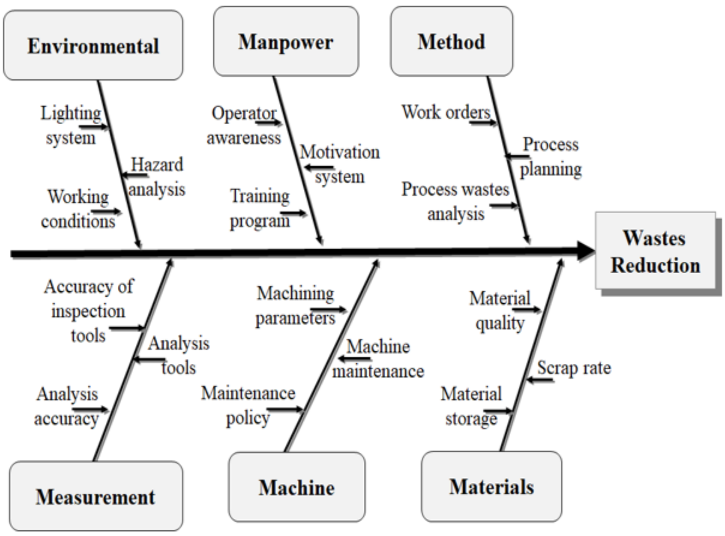

Fig 14. C&E diagram for process wastes reduction.

TABLE 10. A summary of monthly improvement plan

Activity Type	Main Activities	Duration	Frequency of check	Responsibility
Material	- Visual control (7 S) - Material classification - Material Defect Analysis	4 weeks	Daily	Material Leader
Method	- QA / QC check list - Standard procedure & doc. - Standard time analysis	4 weeks	Weekly	Quality Leader
Machine	- Check machining parameters - Process time analysis - Value added time analysis	4 weeks	Daily	Process Leader
Manpower	- KAIZEN training program - Advanced training program - Update motivation program	4 weeks	Weekly	Process Leader
Measurement	- Accuracy of inspection tools - Sampling size and analysis - Auditing system	4 weeks	Weekly	Quality Leader
Environmental	- Visual control (7 S) - Improve working conditions - Job hazard analysis (JHA)	4 weeks	Weekly	Safety Leader

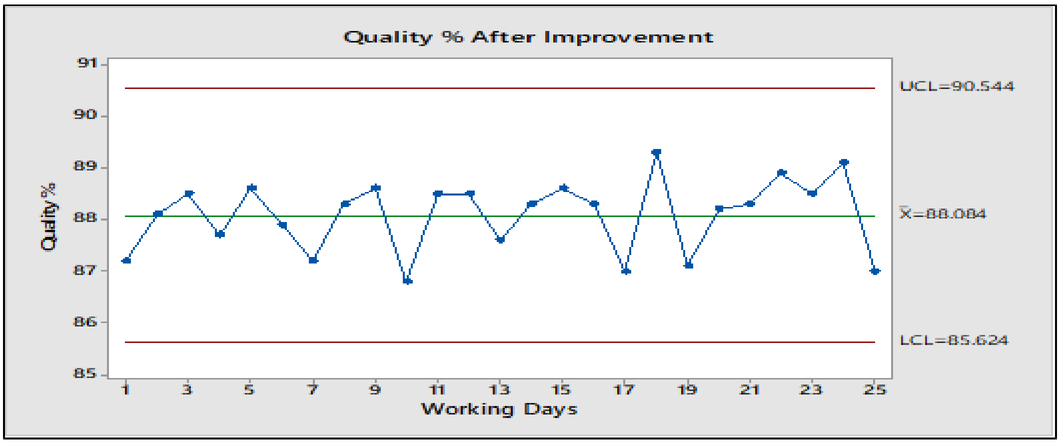

Fig 15. Quality control chart (After improvement).

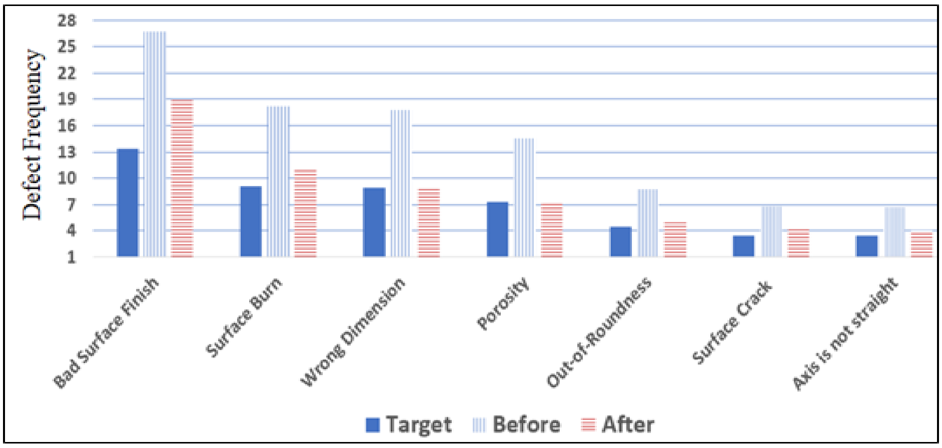

Fig 16. Defect frequency (Before and after improvement).

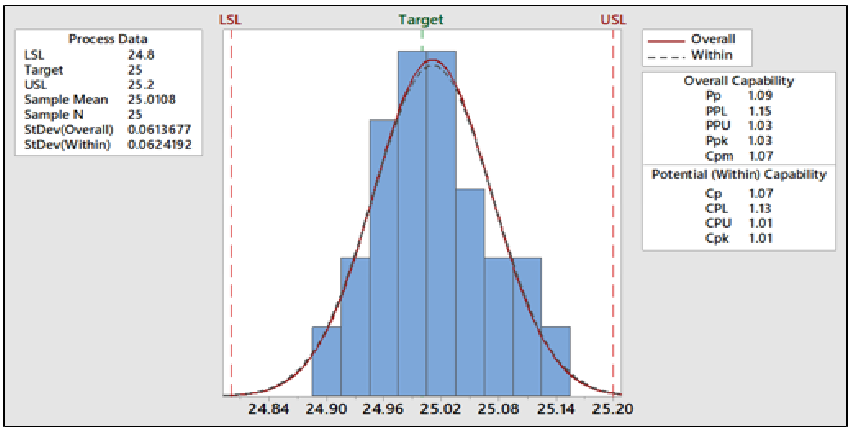

Fig 17. Process capability analysis (After Improvement)

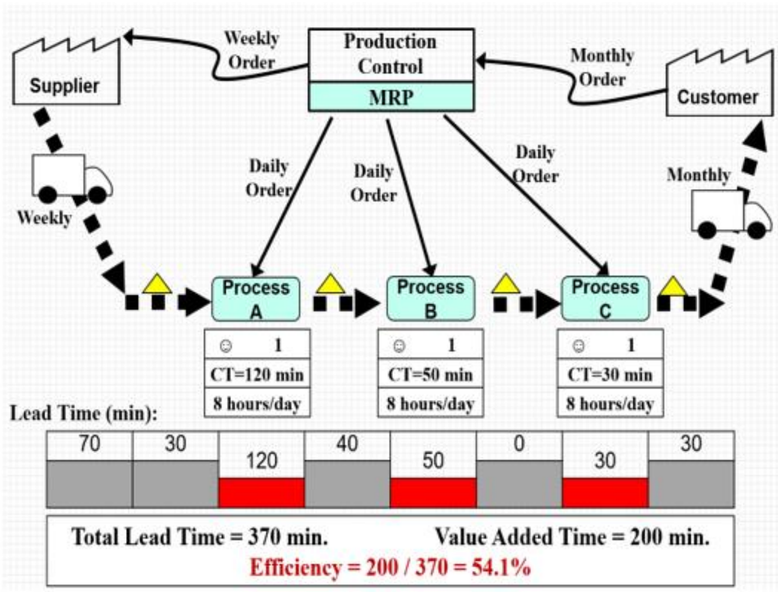

Fig 18. Value stream mapping (After improvement)

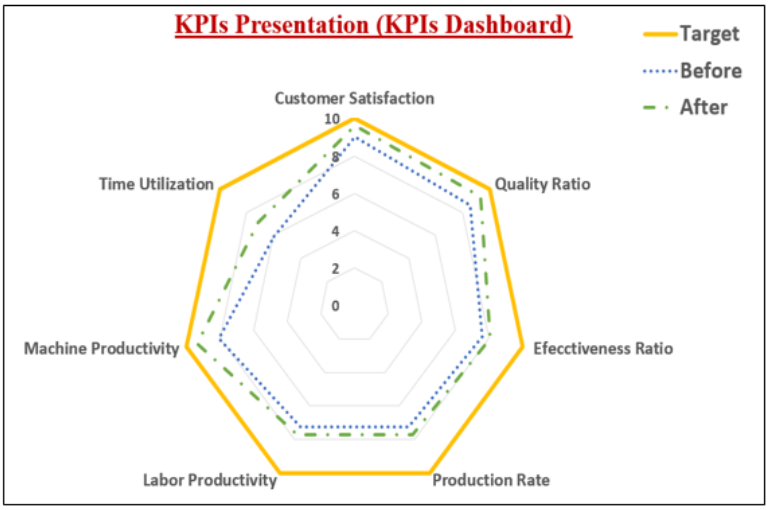

Fig 19. KPIs analysis (Before and after improvement).

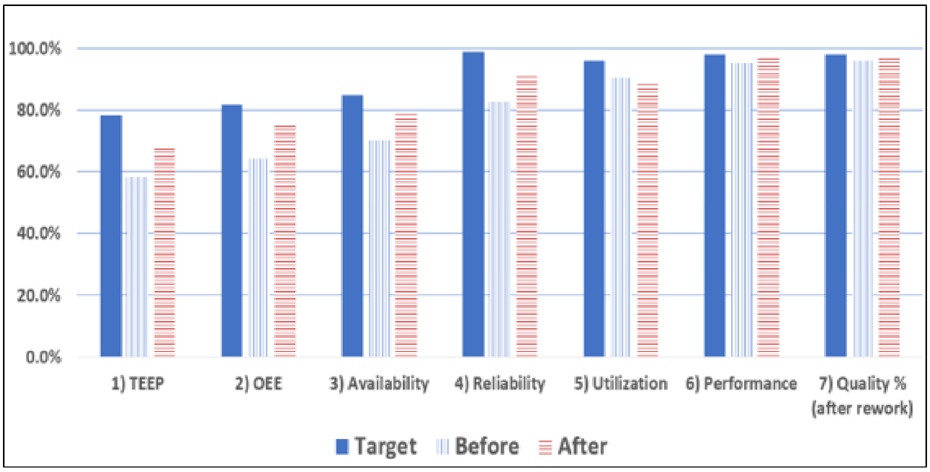

Fig 20. TEEP & OEE analysis (Before and after improvement).

TABLE 11. A summary of process performance indicators (Before and after improvement)

Indicators	Target	Before	After
Quality %	94.0%	80.6%	88.1%
DPPM	60,000	194,000	119,000
Sigma Level	3.05	2.36	2.68
Process Capability (Cp)	1.0	0.33	1.01
Process Efficiency %	60.0%	37.2%	54.1%

3.4. Improve Phase:

This phase begins with listing the recommendations and solutions obtained during the analysis phase. The project team works together to develop, test, and implement an improvement plan that brings continuous improvements to the process. Table (10) shows a summary of the monthly improvement plan. The 7S (5S + Safety + Sustainability) principle has been followed to organize and improve work efficiency and reduce safety risks.

3.5. Control Phase:

In this phase, the project team develops a control plan to monitor and maintain the improvement plan. The control plan shows how the processes will be standardized as well as how the procedures will be documented. Also, the actions taken to improve the process and best practices must be well documented. The last activity involved in this phase is to close the project and prepare the final project close-out report. As shown in Figures (15), (16), and (17), the implementation of the proposed improvements greatly improved in product quality, process variance, and process capability. Fig. (18) shows value stream planning after optimization, value added efficiency increased from 37.2% to 54.1%. Finally, as shown in Figure (19), Figure (20) and Table (11), the overall performance indicators have been improved. For example, Total Effective Equipment Performance (TEEP) improved from 58.4% to 67.6%, Overall Equipment Effectiveness (OEE) improved from 64.5% to 75.7%, sigma level improved from 2.36 to 2.68, and process capability improved from 0.38 to 1.01.

4. CONCLUSION:

In this study, some important LSS case studies, tools and techniques are discussed, which will be useful for production managers and leaders. LSS framework is proposed using various analysis and improvement tools such as brainstorming, process mapping, SIPOC, KPI analysis, OEE analysis, sigma level, seven QC tools, process time analysis, value stream mapping, waste analysis, DOE, Taguchi method, ANOVA, Takt time, standard time, 5S, standard work and cause–effect diagram. In this study, the main causes responsible for the defects and wastes of the process under study were analyzed. Based on the results of this study, the application of the proposed LSS framework helps to reduce defect rates, improve the sigma level, reduce cycle time, increase value-added, reduce non-value-added time, increase labor productivity, and improve overall equipment effectiveness. For example, Total Effective Equipment Performance (TEEP) improved from 58.4% to 67.6%, Overall Equipment Effectiveness (OEE) improved from 64.5% to 75.7%, sigma level improved from 2.36 to 2.68, and process capability improved from 0.38 to 1.01.

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