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Improving Rebar Production Processes Through Six Sigma Methodology

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ABSTRACT

Improving productivity and reducing waste in manufacturing processes is a primary objective for all industrial organizations. Theoretical Six Sigma calculations were applied to actual data collected from the heat-treated and mechanically treated (TMT) steel bar plant of the Libyan Iron and Steel Company (LISCO). This was achieved by applying the Six Sigma (Definition, Measurement, Analysis, Improvement, and Control) methodology and using tools such as control charts, Pareto analysis, cause-and-effect diagrams, and SPSS software, with the aim of optimizing the manufacturing process of heat-treated and mechanically treated steel bars. The results obtained from the applied calculations showed a promising level of improvement, with the production waste rate decreasing to approximately 1.7%. The process parameters affecting the mechanical properties of heat-treated and mechanically treated steel bars were also identified. Therefore, it can be concluded that the study has yielded valuable and encouraging results.

Keywords: Control Maps, Defects, Pareto Analysis, Six Sigma, Steel Bars, Thermo-Mechanically Treated

تحسين عمليات إنتاج حديد التسليح من خلال منهجية ستة سيجما

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ملخـــــــــص البحـــــــــث

يُعدّ تحسين الإنتاجية وتقليل الهدر في عمليات التصنيع هدفًا رئيسيًا لجميع المؤسسات الصناعية. طُبّقت حسابات نظرية لمنهجية ستة سيجما على بيانات فعلية جُمعت من مصنع قضبان الصلب المعالج حراريًا وميكانيكيًا (TMT) التابع للشركة الليبية للحديد والصلب (LISCO). وقد تحقق ذلك من خلال تطبيق منهجية ستة سيجما (التعريف، القياس، التحليل، التحسين، والتحكم) واستخدام أدوات مثل

مخططات التحكم، وتحليل باريتو، ومخططات السبب والنتيجة، وبرنامج SPSS، بهدف تحسين عملية تصنيع قضبان الصلب المعالجة حرارياً وميكانيكياً. أظهرت النتائج المستخلصة من الحسابات المُطبّقة مستوىً واعدًا من التحسين، حيث انخفض معدل الهدر في الإنتاج إلى حوالي 1.7%. كما تم تحديد معايير العملية التي تؤثر على الخواص الميكانيكية لقضبان الصلب المعالجة حرارياً وميكانيكياً. لذلك، يمكن الاستنتاج أن الدراسة قد أسفرت عن نتائج قيّمة ومشجعة.

الكلمات الدالة: خرائط التحكم، العيوب, ستة سيجما، قضبان فولاذية، معالجة حرارية ميكانيكية.

1. INTRODUCTION

Since the 1980's, manufacturing industries processes have been dramatically improved. This change came as a result of the increased demand and the quality concern by consumers [1]. For organizations concerned by manufacturing, they aim to improve their manufacturing processes in order to produce higher quality products with competitive prices [2]. Hence, at present day, achieving the optimum level of products or services quality would be the key factor of survival. Process optimization is an essential request in reducing production variation and achieving optimum products in manufacturing industries. Rebar manufacturing is one of these industries. Globally, in rebar manufacturing, nearly 26% of the steel become waste, whereas by controlling the line scrap, a gain of 17% reduction in CO^2 emissions and the total energy would be achieved [3].

Process optimization in rebar manufacturing, particularly Thermo-Mechanically Treated steel bars (TMT) manufacturing is the main aim of this study. TMT bars production started in 1994 and since then were widely manufactured due to their desired characters such as high strength with high ductility, higher hardness, better weldability and considered to be material saving as they are reproduced [4].

This research work investigates the significant factors that affect the products quality of the TMT steel bars, applies the Six Sigma methodology (Define, Measure, Analyse, Improve, Control) in the sake of obtaining the optimum products of the TMT steel bars manufacturing process and improves the products quality. The study is proposed for the application of Six Sigma in steel bars rolling mills in a Rolling Factory – Libyan Iron & Steel Company, through the introduction and application of the Six Sigma (DAMIC) methodology and using tools such as control maps, Pareto and process capability analysis. Data is collected during the study period and analysed using programs such as Microsoft Excel and SPSS, aiming to improve the production process in accordance with Six Sigma specifications.

2. LITERATURE REVIEW

Recent literature has consistently emphasized the effectiveness of Six Sigma methodology, particularly the DMAIC framework, as a structured approach for improving process quality and reducing variability across industrial systems. Studies such as Gaikwad et al. demonstrated that integrating Statistical Process Control (SPC) within DMAIC enhances monitoring of critical quality characteristics, leading to reduced rejection rates and improved operational performance. This reflects the strong synergy between statistical tools and structured improvement methodologies [5]. Building on this foundation, several studies have extended the application of DMAIC into metallurgical and manufacturing environments. Kumar et al. reported significant reductions in internal rejection rates and notable cost savings in the metal fastener industry through an enhanced DMAIC framework [6]. Similarly, Ishak et al. highlighted the role of DMAIC in improving process stability within carbon steel production, particularly in chemically complex processes such as phosphate coating, by controlling critical process parameters [7]. Deepak et al. further reinforced these findings by demonstrating that the integration of advanced statistical analysis within DMAIC contributes to minimizing variability and improving product quality in modern manufacturing systems [8].

More specifically, within steel and rebar manufacturing, Charles and Umar applied DMAIC to optimize process parameters in TMT rebar production, achieving measurable improvements in process yield and sigma level [1]. Complementarily, Khawar Naeem and Iftikhar Hussain focused on identifying and optimizing key production parameters affecting rebar quality using Six Sigma tools, highlighting the importance of parameter-level optimization [9]. In contrast, Shigemori et al. approached rebar production from a just-in-time and regression modeling perspective, emphasizing efficiency and process design rather than variability reduction [10].

In parallel, broader quality improvement frameworks such as Lean, PDCA, and 5S have been discussed by Ahmad et al., who emphasized the need for integrated approaches tailored to organizational complexity [11]. Linderman et al. provided the theoretical foundation of Six Sigma as a data-driven methodology aimed at reducing defects and improving customer-defined quality, while Gupta et al. demonstrated its effectiveness in enhancing long-term process capability using a combination of qualitative and quantitative tools [12,13].

Additionally, studies such as Hmud et al. focused on metallurgical aspects, particularly the influence of cooling conditions on the mechanical properties of reinforcing steel, indicating that process parameters at the physical level play a crucial role in final product performance [14].

Despite the vast amount of research on Six Sigma and its applications in the manufacturing and metallurgical industries, some significant gaps can be identified:

- There is a separation between Six Sigma studies (which focus on defects) and studies of mechanical properties and operating parameters, without a fundamental integration into a single model.
- The application of DMAIC in the rebar industry remains limited in terms of covering all stages of production.

This study addresses the aforementioned gaps by proposing an integrated Six Sigma-based framework to improve rebar production processes. Unlike previous works, the proposed approach:

- Applies the DMAIC methodology across the entire production cycle of rebar manufacturing,
- Combines statistical quality control tools with process parameter analysis,
- Focuses on simultaneous improvement of process efficiency, defect reduction, and Product quality,
- Provides a systematic and data-driven model suitable for real industrial implementation.

3. METHODOLOGY

DMAIC, which stands for Define, Measure, Analyse, Improve, and Control, is a comprehensive five-phase methodology designed to enhance various organizational processes, including software development and manufacturing. It serves as the primary framework for executing Six Sigma initiatives, although it can also function independently for other improvement efforts. This approach employs a range of tools and techniques to assess projects and derive meaningful insights. Among these tools are process diagrams, Control Charts, Process Capability Analysis, and Pareto Analysis.

3.1 Define

The challenge faced during production is that the mechanical properties, specifically yield strength and tensile strength, frequently fall short of British standards. This deficiency leads to the rejection of rebar products or their sale as defective, resulting in financial losses. Consequently, the focus must be on refining the production process to enhance quality and reduce the rate of rejects. Monthly reports from the Quality Control and Monitoring Department for the first half of 2024 provide data on the production volume of Ø12 mm steel bars, as detailed in Table1.

Table 1: Production quantity of bar Ø12 mm

Product Type	**Total production**	**Acceptable**		**Out of specification**		**Reject**	
		Quantity (tons)	%	Quantity (tons)	%	Quantity (tons)	%
Ø12 mm	68,702.769	59,989.846	87.32 %	8,616.565	12.54 %	96.358	0.14 %

The quantity of defective production attributed to mechanical properties amounted to 5,884.746 tons, representing 8.6% of the total production of Ø12 mm. The Critical to Quality (CTQ) attributes identified for the product include yield strength (YS) and ultimate tensile strength (UTS), both measured in newtons per square millimetre (N/mm^2). In this sector, TMT steel bars are produced in various grades and diameters, including 10mm, 12mm, 14mm, and others. The specific TMT steel bar model chosen for this analysis is the B500B, featuring a diameter of 12mm. The specifications of the TMT steel bar are evaluated against British standards to assess product quality. The British standards for Fe500 TMT bars with a diameter of 12mm are detailed in Table 2. British standards for Fe500 TMT bars with a diameter of 12mm are detailed in Table 2

Table 2. British Standard specification for TMT bar

British Standard 4449 B500B	Yield Stress Points		Tensile Strength	
	Max.	Min.	Max.	Min.
	650 N/mm^2	500 N/mm^2	---	550 N/mm^2

The process flow chart of the industry created in this phase given figure 1.

The data gathered from the Quality Control and Monitoring Department of the LISCO firm, along with the Critical to Quality (CTQ) characteristics, are subjected to measurement and analysis. The CTQ characteristics, specifically yield strength and tensile strength, for the chosen product are evaluated and defined. Various analytical tools, including Control Charts and Capability Analysis, are employed to assess the performance of the manufacturing process based on the collected data.

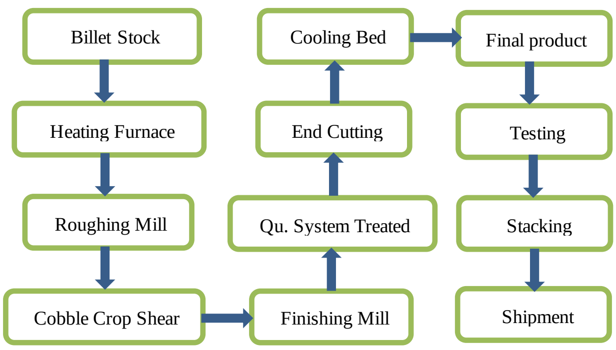

Fig 1. TMT steel bar manufacturing Process map

3.2 Measure

Data was collected from the Quality Department of the Libyan Iron and Steel Company, where Critical to Quality (CTQ) characteristics are measured. These characteristics include yield strength, ultimate tensile strength, and unit length mass of the selected product type. Process performance was then measured using the collected data, employing various tools such as control charts, capacity analysis, and others.

3.2.1 Control Charts

Control charts are developed to ascertain whether the manufacturing process adheres to its design specifications. An example of a control chart for the yield stress of a 12mm steel bar is presented in Figure 2. This figure illustrates the specifications approved by the Libyan Iron and Steel Company, which align with British Standard 4449 B500B. It also displays the yield stress values of the samples, with an average yield stress recorded at 570.41 N/mm². The upper and lower control limits for this process are established at 613.01 N/mm² and 527.82 N/mm², respectively.

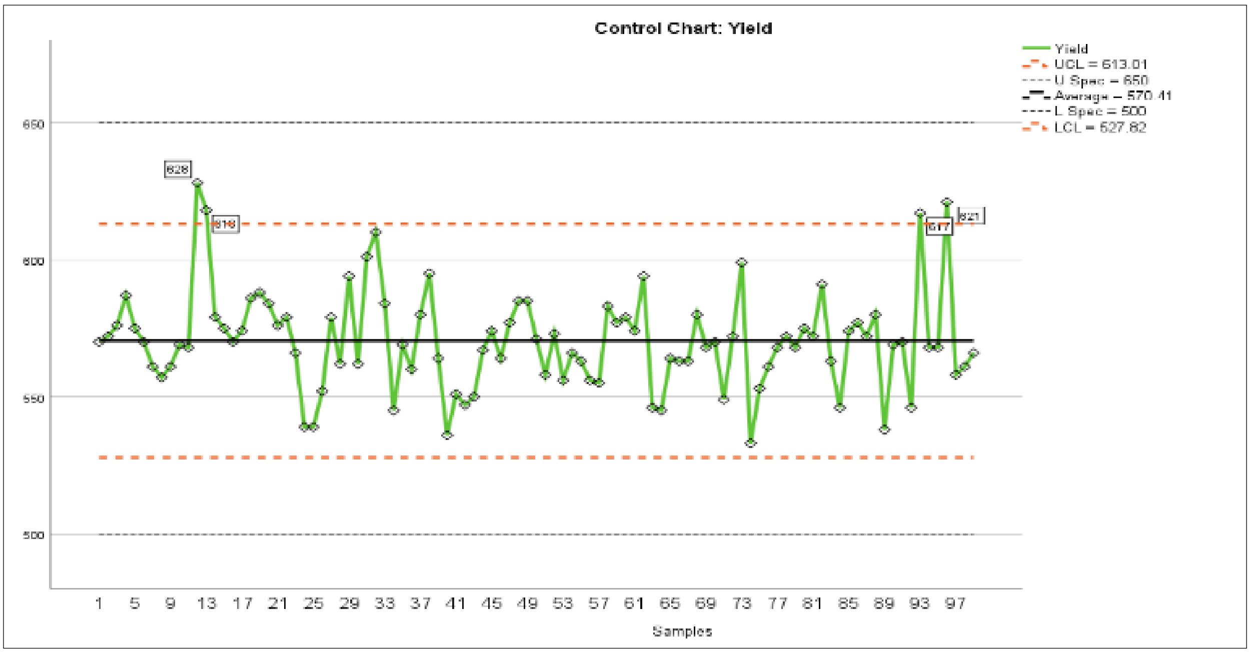

Fig 2. Control chart of yield stress

Figure 3 depicts the same specifications for tensile strength in comparison to the empirical values, where the average tensile strength is also noted at 570.41 N/mm². The upper and lower control limits for this process are set at 721.70 N/mm² and 607.92 N/mm², respectively.

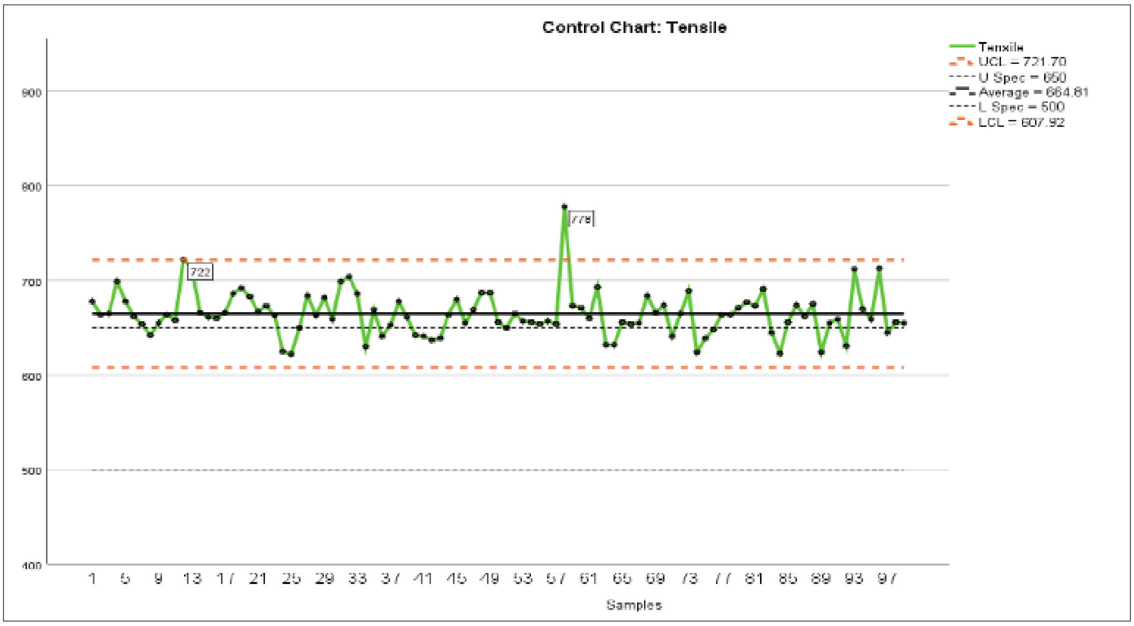

Fig 3. Control chart of tensile strength

3.2.2 Process capability analysis:

The analysis of process capability involves a series of calculations aimed at determining whether a system can statistically fulfil a defined set of specifications or requirements, as well as evaluating its overall performance. In the context of steel bar manufacturing, the performance of the process is assessed through a capability study. Key metrics such as the process capability index (C_{pk}), process performance index (P_{pk}), and defects per million opportunities (DPMO) are calculated for each critical to quality (CTQ) characteristic, culminating in the determination of the current sigma level. Upon completion of the process capability analysis, essential factors including C_{pk} , P_{pk}, and DPMO are carefully examined and recorded. The consolidated findings from the measurement phase are presented in Table 3.

Table 3. Process capability analysis

Process Statistics		**Tensile Strength**	**Yield Stress**
Capability Indices	CP	1.318	1.761
	C_{pk}	0.260	1.653
	CR	0.759	0.568
Performance Indices	PP	1.049	1.388
	P_{pk}	0.207	1.303
	PR	0.954	0.720
Defects per million opportunities (DPMO)		85,689.56	
Per million opportunities (PMO)		1,000,000	
Sigma level		3	

3.3 Analysis

In numerous industries, certain factors contribute to the decision to reject a product. By identifying and quantifying these critical factors, it becomes possible to manage and rectify them, thus reducing the likelihood of rejection and enhancing process yield. A comprehensive analysis was conducted utilizing Pareto Analysis, based on monthly reports detailing common product defects, which are summarized in Table 4.

Table 4. Defects in products under study		
No.	**Defect name**	**Abbreviation**
1	Irregular lengths	IRL
2	Roll mark	ROM
3	H. Yield Stress	HYS
4	Over fill	OVF
5	L. Yield Stress	LYS
6	Scab	SCA
7	Un-systemically	UNS
8	Seams	SEM
9	Twisted Product	TWP
10	Over lap	OLP
11	Under fill	UNF
12	Bad Presentation	BAP

3.3.1 Pareto analysis

The Pareto analysis was executed using defect data gathered from the quality engineering department, with the findings illustrated in Figure 4.

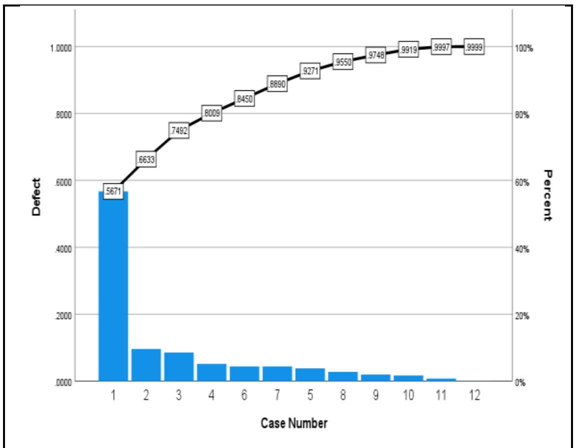

Fig 4. Pareto Analysis

The results depicted in Figure 4 demonstrate that these four defects account for 80% of the total defect impact, which ultimately leads to the classification of the product as scrap.

This analysis identified four predominant defects within the manufacturing process:

Irregular Lengths, Roll Marks, High Yield Stress, and Overfill (abbreviated as IRL, ROM, HYS, and OVF).

3.3.2 Cause and Effects Diagram

The cause and effects diagram shown in Figure 5 shows the significant and insignificant actions during the machining process. Many possible reasons for an impact or problem are found here. From this diagram, the machine was determined to be creating problems, especially with cooling system.

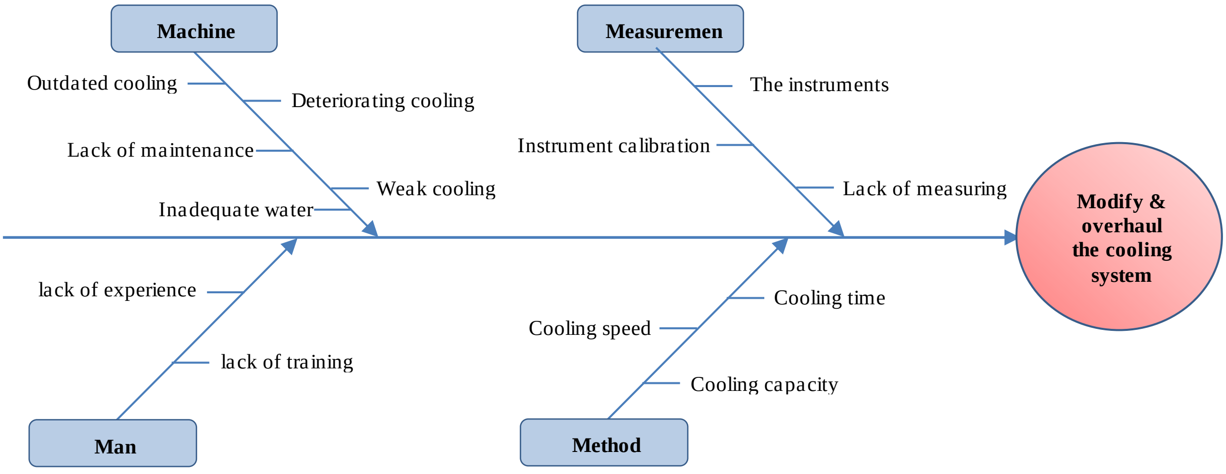

Fig 5. Cause and effects diagram

3.4 Improve

The yield stress analysis indicates that the process means, as well as the lower and upper control limits, are within the specified range. However, four samples exhibiting yield stress values of 617, 618, 621, and 628 N/mm² displayed a pattern that deviates slightly from the overall population trend. This discrepancy can be attributed to a malfunction in the cooling system. In the tensile strength analysis, the process mean exceeded the specification mean, indicating a shift in the process. Additionally, two samples, with tensile strength values of 722 and 778 N/mm², were found to be outside the upper specification limit. This issue arose from the quenching process. The Pareto analyses identified that among the 12 defects related to process quality, four defects—IRL, ROM, HYS, and OVF—have the most significant impact on production quality. These defects are primarily responsible for the observed decline in quality. Their effects, along with other defect causes, are detailed in Table 5.

To ensure the efficient and effective implementation of the Six Sigma methodology, selecting the optimal optimization solution is crucial. Therefore, the optimal solution was to modify and overhaul the cooling system, which would improve the process.

Table 5. The percentage for defect causes and the return product

Defect No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Defect	IRL	ROM	HYS	OVF	LYS	SCA	UNS	SEM	TWP	OLP	UNF	BAP
Wt.*	3337.15	566.357	505.596	304.276	224.297	259.31	259.153	164.235	116.315	100.875	45.776	1.407
% **	4.86	0.82	0.74	0.44	0.326	0.377	0.377	0.239	0.169	0.147	0.067	0.002
Percentage	80%				20%							

* Wt. refers to the defected weight to each cause.

** % = wt./Total production.

The data presented in Table 5 indicates that four specific defect causes account for 80% of the overall waste. Therefore, addressing these causes is expected to significantly decrease the total production waste from 8.6% to just 1.7%.

3.5 Control

The team was informed of the results, and the production and maintenance departments were instructed to operate the production process according to the proposed standards, implement necessary equipment repairs, and perform preventative maintenance.

During the operational step, the team monitors the equipment (especially the cooling system), while the production and quality team monitors the production process to ensure smooth production and product quality.

The quality team then performs a standardized test (Z-test) on samples to verify whether the average process is below the upper limit of specification (USL) for the product. The test was conducted with a 95% confidence level.

4. RESULTS AND DISCUSSION

Control charts reveal that the yield stress of four samples exceeded the specified limits, suggesting that the cooling system in the production line requires repair and maintenance. Additionally, the average tensile strength of the entire process deviated from the specification mean, with two samples falling outside the specification limits due to issues in the quenching process. A Pareto Analysis identified that 12 defect causes collectively contribute to 80% of the total waste production, while the remaining eight causes account for only 20%. Thus, by eliminating the four primary defect causes (IRL, ROM, HYS, and OVF), the production waste percentage was reduced from 8.6% to 1.7%, resulting in a 6.9% improvement in overall production quality.

5. SCIENTIFIC CONTRIBUTION

This study applies the Six Sigma DMAIC process to improve the quality and efficiency of Thermo-Mechanically Treated (TMT) rebar manufacturing in a steel rolling mill. It identifies critical-to-quality (CTQ) features, like yield strength. Using statistical tools, it finds that four major defects cause most production waste. By fixing issues with the cooling system and quenching process, waste is reduced from 8.6% to 1.7%.

6. FUTURE WORK

Future research may combine advanced data-driven methods with Six Sigma for better process optimization in steel manufacturing. Machine learning models, like Artificial Neural Networks, could predict mechanical properties based on cooling rate and temperature. Optimization algorithms, such as Genetic Algorithms, might improve rolling process conditions. Real-time monitoring with Industrial Internet of Things could enhance production control.

7. CONCLUSION

This research focused on identifying defect causes in the rebar manufacturing process, with several samples tested for yield stress and tensile strength. Data were collected and analysed using the SPSS program to generate control charts and assess process capability. The analysis revealed that certain samples did not meet specifications. Furthermore, a six-month analysis of the rebar manufacturing line at LISCO in 2024 utilized Pareto analysis as a statistical method to identify the most significant process influences. The results indicated that four out of the twelve defect causes had the most substantial effect on process quality, and their elimination would enhance overall process quality by 6.9%.

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