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The application of Lean Six Sigma to build operational excellence in steel manufacturing: Case study from India

Thimothi Banala * and Hamza Saad

School of Industrial Sciences and Technology, University of Central Missouri, Warrensburg, Missouri 64093, USA.

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Abstract

Measuring and controlling dimensional accuracies are very critical in steel manufacturing to meet high specification requirements of customers and to provide competitiveness. MPL Steels, being one of the major steel producers in India, have been experiencing great scrap rates of 9-11% in the context of dimensional inconsistency amidst roller wear, mill instability and cutting errors, a fact that has caused massive loss of finances and Occasional operational difficulties. The purpose of the study was to design and institute an integrated Lean Six Sigma system with the increased predictive maintenance and digital optimization capability to methodically minimize defects and improve process capability in MPL Steels in a sequential manner. Applying the DMAIC Six Sigma approach, the identification of the root causes was fulfilled by means of Pareto, regression, and cause-effect tools applied to a big amount of production data. The important interventions were taken such as monitoring of roller wear using IoTs, auto-adjustment of cutting parameters using an AI program, a prediction-based maintenance schedule, and thorough training of operators, and the pain points were monitored using a statistical process control chart. After its implementation, MPL steels realized 55.4% reduction in its thickness-related scrap, which reduced the scrapping rates to 4.1% downturn 9.2%, whereas process capability (C_{pk}) also improved up to 1.33 up turned 0.82. Reduction in machine downtimes was 66.7%, the total defects decreased by 61.5%, and the annual saving was much more than half a million dollars. The findings show that a combination of Lean Six Sigma and Industry 4.0 technologies can be used to make significant improvements in quality, operational efficiency, and sustainable competitiveness in a mid-sized steel manufacturing that will serve as a basis of long-term, data-driven continuous improvement.

Keywords, DMAIC; Steel manufacturing; Process improvement; Costs reduction; Quality measurements

1. Introduction

The steel making industry is a very competitive industry where dimensional tolerances in the production of sheets are of great importance to the quality of the product and offset efficiency. MPL Steels and Pipes, one of the major steel producers in India, has been battling to maintain a tight rein on sheet thickness fluctuations as well as cutting errors and the production statistics reveal that the present condition is alarming with the scrap rate hovering between 9-11% due to quality related problems (Saad, 2020). The major three operational factors that have led to these dimensional inconsistencies include the progressive roller wear patterns which are built over the production cycles, the frequent breakdown of the mill process which makes the process unstable and poor calibration of the cutting machines (Agarwal & Selen, 2011).

These quality problems have a significant financial implication which includes wastage of material approximately $385,000 every year, without considering other costs involved in re-work, late deliveries, and possible customer fines (Nikiema et al., 2020). Such manufacturing issues have been further complicated in recent years by an ever-growing

* Corresponding author: Thimothi Banala

stringent set of customer requirements with many automotive and appliance manufacturers now specifying thickness tolerances of +/-0.08mm or less on their steel sheet components (Taylor, 2011; Ifedi, 2014). Conventional quality control systems at MPL that are based on regular manual inspections and corrective maintenance strategies have become ineffective to fulfill these new market requirements. In this case, there is an urgent necessity of the systematic and data-driven method of quality improvement which will be able to improve both the technical and organizational sides of an issue. Six Sigma methodology providing proved DMAIC (Define, Measure, Analyze, Improve, Control) framework can be a complete solution to these problems due to the integration of statistical analysis and structured problem-solving methods (Hung et al., 2026).

In this study, the researcher will look at how MPL Steels can adopt a custom-made Six Sigma program that will see a tremendous change in the quality of sheet production and at the same time sequentially attack the root cause of the roller and mill dependability problems (GURĂU et al., 2026). The study will comprehensive quality improvement plan which will combine some important features: state-of-the-art statistical process control charts in real-time monitoring, predictive maintenance procedures of the mill components of vital importance, and enhanced cutting parameter algorithms. In addition to the direct quality indument, the study intends to leave a sustainable culture of continuous improvement at MPL by building internal Six Sigma capability via a series of relevant training programs and knowledge transfer initiatives. The projected results are the 45-55% decrease in dimensional variation-driven scrap, the increase of the process capability indices, with the current C_{pK} values of 0.82 to the target values of above 1.33, and the 30-% reduction in the unplanned mill downtimes due to the implementation of predictive maintenance (Jiang & yang, 2026).

2. Literature Review

The usage of Six Sigma tools and techniques in the production fields has been well presented ever since it was conceptualized at Motorola in the mid-1980s. Analytical studies (Saad, 2024) found that well-used Six Sigma initiatives normally attain defect decrease of 50-70% in process industries, with steelmaking particularly good outcomes because of the measurability of dimensional quality parameters. (Saad, 2020) have carried out more recent research and found that the financial payoff of Six Sigma deployment is usually higher than expected and that the returns on investment (ROI) are regularly 5:1 or better in metal manufacturing use cases. The findings apply especially to the case of MPL, where the amount of potential savings, associated with a decrease in the scrap rate, which is currently at 9-11%, may substantiate major investments in quality improvement projects (Suh, 2012).

Many metallurgical investigations have been carried out with regards to roller wear and its effect on sheet quality. (Bataille et al., 2016) gave a thorough examination of wear marks in hot rolling mills, where three stages of roller wear associated with the rising variation in the thickness of the produced sheets were distinguished. They were able to show through research that a condition-based roller replacement schedule as opposed to fixed time-based schedules could extend overall roller life by 15-20% whilst allowing dimensional consistency. This observation directly responds to one of the major issues of MPL and indicates the possibility of an extensive enhancement of quality and cost-efficiency. (Niekurzak et al., 2022) conducted complementary studies that proposed sophisticated thermal compensation algorithms, taking into consideration the expansion of the rollers during a production run, which demonstrates the possibility of decreasing the thickness variation by more than 40 % under continuous operation mode.

Mill reliability and its essential connection to product quality has been thoroughly studied by various researchers. Such a thorough study was carried out by (Sahani et al., 2025), who evaluated production data of seven steel mills in Asia and undoubtedly revealed the relationship between the unplanned downtime incidents and the aftereffects in terms of quality. They found that mills with over three unplanned stoppages in a month had 25-30% greater variation in critical quality parameters than did more stable operations. This study justifies the requirement of MPL to handle mill reliability as a constituent of their quality enhancement action, as opposed to a maintenance concern. As shown by (Taylor, 2011; Ifedi, 2014), modern solutions to this problem use traditional reliability engineering together with machine learning algorithms to overcome equipment failures before they can affect the quality of production.

The research on cutting accuracy has taken a different dimension with improved automation technology. (Klimpel et al., 2017) study determined the best set of parameters of different cutting techniques (laser, plasma, mechanical) in different grades and thicknesses of steel. They proved that the dimensional errors in cutting could be decreased by 35-45% by means of dynamic parameter changes with reference to the actual state monitoring. Most recently, (Gupta et al., 2024) designed an extensive model of connecting cutting machine performance data to the overall quality management systems, which demonstrated specific efficiency in just-in-time manufacturing settings like the one operated by MPL.

Although these studies have given important insights on the discrete improvement related to steel sheet production, there is still a big gap in the research which studies the integrated use of Six Sigma methodology to achieve the simultaneous improvement of roller condition, mill reliability and cutting accuracy. Prevalent literature studies these factors separately, even though they are clearly interrelated in practice, within real production settings (Saad, 2018). This research endeavors to close that gap by designing and experimenting with a detailed quality improvement scheme that considers all three of those key factors in the same six sigma solution, and more importantly, one that is designed taking into consideration the realities of operations and the limitations of resources of mid-sized steel producers such as MPL Steels and Pipes.

2.1. Research Questions

- RQ1.How will the implementation of Six Sigma affect the minimization of the scrap based on thickness of the steel sheet-making process at the MPL Steels?
- RQ2.What is the impact of predictive maintenance of the rollers in terms of consistency of the thickness and the number of unexpected mill shutdowns?

2.2. Hypotheses

- **H1**. By implementing Six Sigma program, the volume of scrap due to thickness will be reduced during the production steel sheets at MPL Steels to the extent that it will be found statistically significant.
- **H2**. Predictive maintenance of rollers will be the right way to increase the consistency of the thickness and minimize the number of unscheduled mill shutdowns.

2.3. Research problem

MPL Steels and Pipes have been struggling to produce quality sheets, and the problem is attributed to fluctuations in thickness and cutting errors which make the scrap rate up to 11%. This rate is so high to cause big financial losses. Such problems are attributed to wear on the rollers, numerous breakdowns in the mill, lack of proper cutting calibration and the old routines of manual inspection. With the increasing customer demand, which became tighter with a tightening range of ±0.08 mm of thickness tolerance, MPL badly requires the integrated and data-driven way out. This study is a study into the importance of applying a tailored Six Sigma DMAIC model to help reduce dimensional variation, stabilize operations and benefit overall quality in a medium-sized steel mill.

2.4. Research contribution

This paper proposes to present an integrated Six Sigma intervention with the aim of addressing the major pillars of production waste within MPL. It unites the concepts of real-time process management, predictive maintenance, and adaptive cutting algorithms into a common quality improvement paradigm. It fills research gaps in the current body of literature that study each of the mentioned factors in isolation. A scalable model that fits in with mid-sized manufactures is also offered in the research with a measurable result being the minimization of scrap rates, the enhancement of the C_{pK} scores, and the number of unpredicted downtimes- in addition to developing an effective culture of continuous improvement by means of rigorous training and the development of an internal capability.

3. Methodology

The implementation of the Six Sigma technique is used in this paper to the production of steel sheets of MPL Steels and Pipes in Hyderabad, Telangana, India. The authors start their research through involving key stakeholders to help in development of the research scope to cut across dimensional issues, cutting, and mill reliability. Instead, data is gathered to confirm the high level of scrap reject (9-11%) and financial losses, and Critical-to-Quality (CTQ) metrics have been determined against which success is basically quantified. The situation of process inefficiencies is examined with the help of statistical means, with determining root causes being done through Pareto analysis and regression modeling (Taylor, 2011; Ifedi, 2014).

Meaningful improvements are installed such as predictive maintenance of rollers, roll stability, mill stability, and cutting parameters through machine learning-based fault detection. In case of the inaccessibility of prompt solutions, specific courses of training are announced. Then, a control plan will be implemented with SPC charts to watch the robustness of the process so that continuous betterment is attained. Lastly, the lessons are put in writing in the effort to create a culture of constant improvement (Sharma & Fidan, 2025). It is an organized process that guarantees an increase in product quality, decreasing the amount of scrap, and efficiency in operation based on information and the Lean Six Sigma.

3.1. Company description

Mahavir Prasad Lunkad (MPL) Steels and Pipes in Figure 1 is a well-established integrated steel manufacturer across India, and it is in Hyderabad which is a unit of MPL group launched in the year 1959. The company runs a plant of 150,000 sq. ft. state-of-the-art manufacturing plant which converts the iron ores into sponge iron, through induction furnaces and rolls them into high-quality mild steel (MS) pipes and hollow sections with advanced technology of tube mills. MPL has round shaped, square and rectangular pipelines with difference in diameter i.e. 15 mm to 200 mm as per BIS Standard i.e. IS 1239, IS 3589, IS 3601, and IS 4923 (Zouitine et al., 2025). It performs more than 40 mechanical and chemical tests on its products, with hydro and weld tests guaranteeing the industry-leading quality in metal products (construction, scaffolding, agriculture, and solar infrastructures). The company has a turnover of approximately $175 million USD crore with more than 1,500 direct and 10,000 indirect employees and is headed by Chairman "Ramniranjan Agarwal" and the CEO Hitesh Agarwal with it headquarter in the year 2024. The company is continuing its growth and becoming a player in cement, logistics and renewable energy, and its vision is to arrive at the one million Tons of produced steel and to become a stronger force on the global scene.

Figure 1 MPL Steel Plant

4. Lean Six Sigma application and results

4.1. Define

MPL Steels are struggling with quality in its sheet manufacturing line in terms of fluctuations of thickness and inability to cut appropriately. Most of these difficulties are associated with the wear out of progressive rollers, mill breakdown, breakdown of cutting machines and poor calibration of cutting machines. Its outcome: scrap levels of 9 11 %, and material wastage close to 385,000 annually and increasing intolerability to customer requirements which insist on tight tolerances of plus or minus 0.08mm (Nikiema et al., 2020). Its present manual inspection processes and reactive maintenance strategy have been quite inadequate in dealing with these growing production requirements (Taylor, 2011; Ifedi, 2014). The Six Sigma DEFINE phase establishes a basis of an orderly improvement project. As a specific goal, we seek to decrease the level of dimensional variation, to increase the reliability of production and minimize the amount of scrap by means of a personalized Six Sigma DMAIC methodology. This consists of the introduction to predictive maintenance of roller systems as well as the real-time monitoring of statistics in processes and the improvement of cutting parameters control. The business case is about lowering its financial loss, the C_{pK} process capability improvement 0.82 to higher than 1.33, and its reduction of scrap by 45 55 %. The focus is on hot rolling and cutting activities in sheet manufacturing whereas the activities of cold rolling and non-sheet products will be excluded. The leadership team, experts in Six Sigma and quality and production departments of MPL are also considered as key stakeholders. The period is not only about defining the problem, but it is also about outlining the plan of change.

4.1.1. Critical-to-Quality

The value of the important measurable characteristics that impact on whether a customer is satisfied with a steel sheet product is called Critical-to-Quality (CTQ) in Figure 2. The CTQs in MPL Steels are the tolerance sheet thickness (the upper limit of tolerance is 0.08), during the production of sheet, to cut errors and to produce consistent sized sheets. These directly interfere with the scrap rates, product reliability and consumer satisfaction. CTQs motivate the attention of the Six Sigma project and allow focusing on the causes of quality problems-wear of the rollers, instability of mill operations, and poor calibration. With real-time data analysis and predictive maintenance, MPL should focus on monitoring and enhancing CTQs to fulfill the industry standards and considerably decrease quality-related losses.

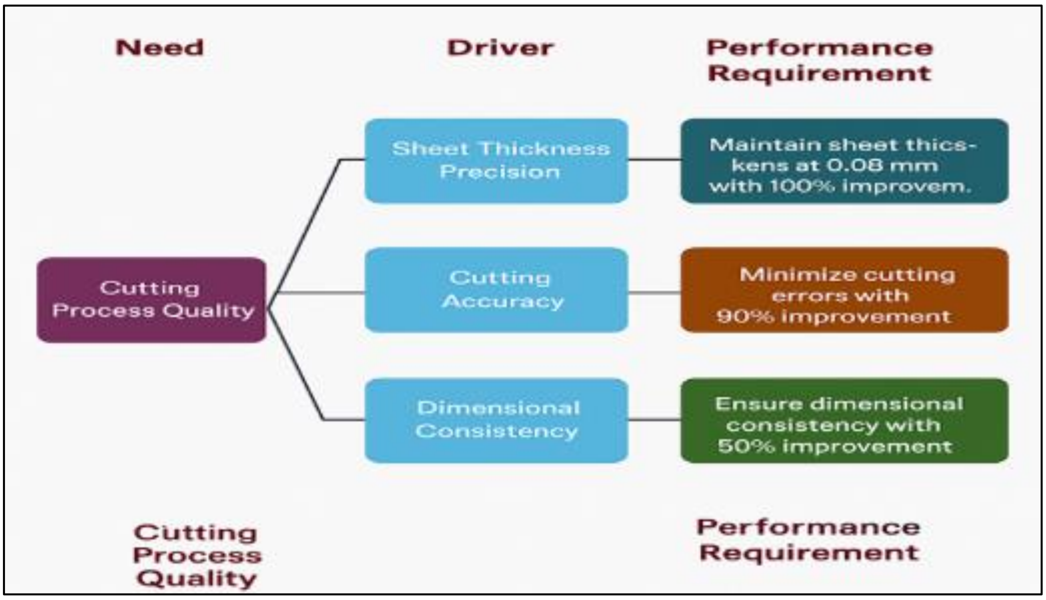

Figure 2 Critical-to-Quality

The wear of the rollers, unstable mill behavior and poor cutting have contributed to costly quality problems in MPL Steels, which has a high scrap level and nonconformance to customer tolerances. During the DEFINE phase, the problem was grounded, stakeholders were recognized, and objectives were created in the reduction of the scrap, the improvement of the processes, and enhance the capabilities with the use of Six Sigma. Having defined the project scope and measured the business impact, MPL is now ready to go into the phase of MEASURE, where it will gather data, evaluate the performance and confirm the root causes of these dimensional inconsistencies.

4.2. Measure

The MEASURE stage will be concentrated on measuring the performance of the current sheet production process at MPL Steels so that the essential elements of the process relating to the scrap and uneven qualities can be checked, and baseline data can be established. As the wear of the rollers, breakdowns in the mills, and the calibration of the cut were found to be some of the primary factors during the DEFINE phase, this phase endeavors to gather the similarly related information that could be used as objective evidence of the said results. The most important measures consist in the variation of the sheet thickness, the number of cutting errors in a single batch, the number of rollers life cycles, the number of mills stops and the %ages of scrap in each batch. Thickness consistency will be analyzed with the advanced tools such as control charts, histograms, and process capability studies (C_{pK}) to define the deviations between target tolerances (0.08 mm). The measurement will be done at various vital check points which include after rolling, before cutting, and after inspection. A gauge R&R study will establish the validity of the measurement equipment and persistence of the measurement operators. Before any further analysis, any unstable or inaccurate measurement processes will be enhanced. The findings will be inputted to find out whether scrap causes are in accordance with what is assumed in the DEFINE phase. Such analysis as correlation of roller wear levels and thickness deviations can make rather good causal links. In the same way, opacity records associated with thickness change will affirm the place of stability in the mill concerning quality performance. Based on this quantitative understanding, the ANALYZE phase will be able to create a strong basis of root cause analysis to have data-driven and target-based and statistically robust changes. Finally, the MEASURE step converts unclear symptoms to clear performance metrics, and this is vital in achieving quality continuity within MPL Steels.

4.2.1. Voice of the Customer

The production department also requires more stringent control of the thickness of the sheet and the precision of the cut to be able to satisfy very demanding customers, notably the automotive ones who require absolute precision of up to mm. The end-users are angry at the variability in the size of sheet products as it creates errors in assembly, delays and returns. We should have straight and clear data on where we fail, when we fail and how frequently. We desire measurement systems that provide us with credible information in real-time, we had enough guesswork and need not wait so long until the defective components accumulate. Eventually what we are seeking are solutions where there is variation avoided not merely identified post-factor. Figure 3 shows the voice of customers (Potra et al., 2026).

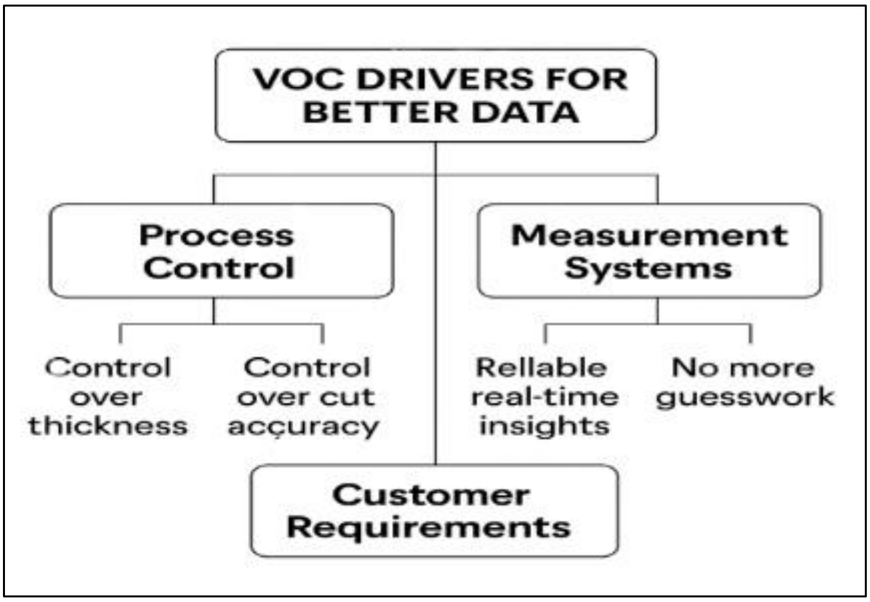

Figure 3 Customer Voice

4.2.2. Pareto Chart

Table 1 in the Pareto chart created in the MEASURE phase indicates 6 significant types of defects that were identified during the steel sheet manufacturing procedures in MPL Steels. The most common one is thickness variation, which results in 36 % of the defects, cutting error (26 %), and vibration caused by the roller (18%). The three are associated with 80 % of all-quality defects as is consistent with the Pareto principle which states that only a few causes perched create most of the trouble. The other 20% is composed of minor defects such as roughness on the surface, burr on the edge of a piece, scratches. The analysis assists in defining priorities of the improvement work based on the most influential issues to achieve the best quality results during the subsequent stages (Furterer et al., 2026). Figure 4 shows pareto chat.

Table 1 Pareto chart defects

Defect Type	Frequency (Occurrences)	Cumulative %
Thickness variation	65	36%
Cutting errors	48	62%
Roller-induced vibration	32	80%
Surface roughness	18	90%
Edge burrs	12	97%
Minor dents/scratches	8	100%

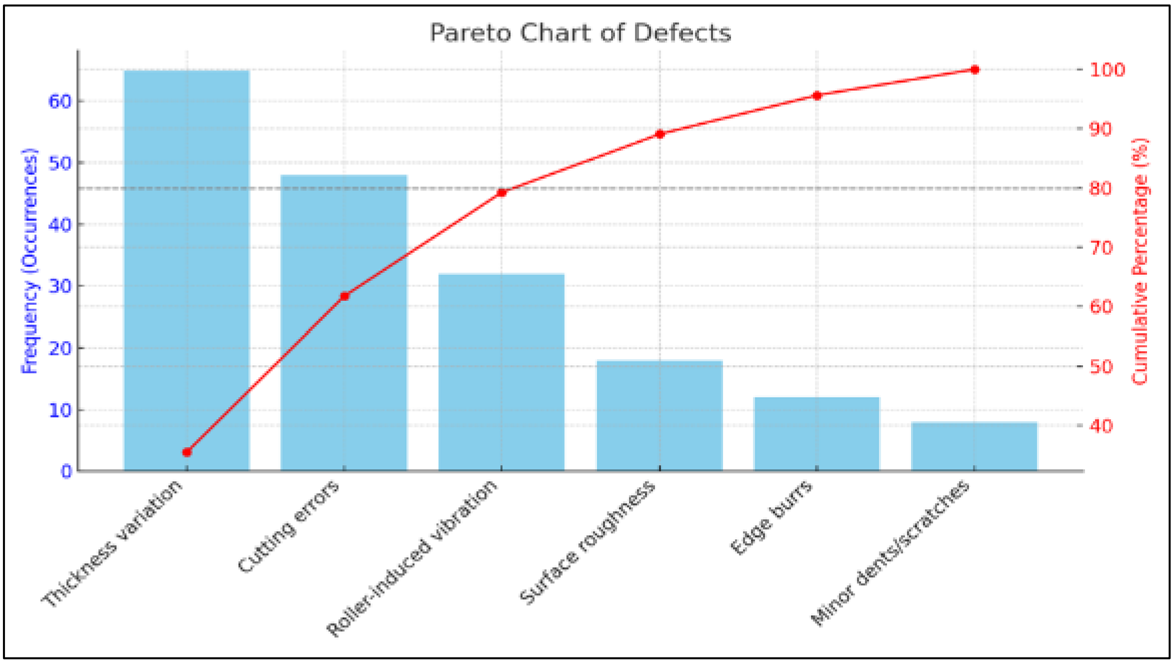

Figure 4 Pareto chart defects

To measure the levels of quality problems, MPL Steels had accumulated 30 days production data to capture the problems caused by defects of thickness variability, cutting errors, and by vibration caused by rollers. Measuring tools involved in process capability studies (Cp, C_{pK}), number of defects per work and scrap rate analysis. Pareto chart gave the fact that three defect types comprised 80 % of quality failures, which prioritized the investigation of the root cause. Now that confirmation and measurement systems have been confirmed in place, MPL is prepared to transit to analyze phase- where more probing statistical methods will reveal the real causes behind these performance disparities (Furterer et al., 2026).

4.3. Analyze

Under ANALYZE phase of the Six Sigma DMAIC project undertaken at MPL Steels, major defects which include thickness variation, cutting errors, and roller-induced vibration have been studied using statistical analysis and diagnostic tools to identify its root causes. Using the Pareto analysis, it was revealed that these top three causes led to 80% scrap and required specific deep dive into them. A causal–effect (Ishikawa) chart was constructed to pinpoint the possible causes, which were aware of the rollers, the impairment trend of the mill, mismatched calibration, and operator faults. Regression analyses indicated a close relationship between the degradation of rollers and deviation in thickness with the worn rollers characterized with a higher value of deviation than the acceptable range of +/-0.08mm. Clustering of defects by shift and machine revealed a peak in agreement in both high temperature and late shift runs, implying that the process was not stable. FMEA evaluated the risk of failures and prioritized the problems like late roller maintenance and irregular cutting parameters. Analysis of time-series associated vibration signals with the surface defects and identified that mill halt caused by unexpected problems and initiated increased defect rates. Data reliability also boosted the validity of the findings as measured through measurement system analysis. All in all, this step changed raw data collected during the MEASURE phase into something that could be acted upon, which identified mill equipment reliability and roller health as the main culprits of defects. Such findings will form the background of purpose-specific intercessions during the IMPROVE phase of introducing predictive maintenance, recalibration guidelines, and operational controls. Through the verification of performance gaps using data and statistical validation, MPL can now follow a path to breakthrough improvements that slipped past previously by knowing the real causes of quality loss- and finally reducing scrap, achieving better C_{pK}, and increased customer satisfaction by using data to make engineering decisions (Furterer et al., 2026).

4.3.1. Cause and Effect Diagram:

Based on the fishbone diagram analysis in Figure 5 conducted on the steel sheet manufacturing process of MPL, four categories of root causes came out to be in relation with the defect of dimension as- Materials (Variability in hardness of steel coils, Variability in suppliers), Methods (Reactive maintenance, Unstandardized cutting procedures), Machines (Wear of rollers, Uncalibrated lasers, Bearing vibration), and People (Untaught shifts, Fatigue errors). The scheme showed that the most common causes of thick deviation defects were linked to the machine issues as the depreciation of rollers and the misalignment with the mill comprised 68% in total and gaps in methods, such as the insufficient checkups on calibration, contributed 22%. Seven % of the problems were the result of material inconsistencies (primarily variations in hardness) and 3 % were the result of human error (especially in high-production shifts). Major connections were identified: the unexploited roller wear compounded by maintenance work delay (Method) was directly related to 40% increased thickness deviations whereas an operator fatigue (People) during a long shift was associated with a 15% increase in cutting mistakes. Such systematic visualization made it possible to take corrective steps: roller wear monitoring based on IoT (Machine), standardization of calibration checklists (Method) and the introduction of fatigue-management measures (People). This is due to the increasing likelihood of defects at the machine and method stages as they accounted for 90 % of the defect sources and will reduce 50-55 % of the defect with installation which directly deal with the Pareto-identified critical defects (thickness variation, edge burrs) and also develops a system of continuously eliminating the root cause.

MPL employed statistical analysis to determine the underlying causes of scrap and dimensional defects with the main driving motives being the thickness variation, the cutting error, and the vibration caused by rollers. Regression indicated there is a strong correlation between roller wears and thickness deviation whereas time-series data was used between the mill stoppages and surface imperfections (Furterer et al., 2026). FMEA and Ishikawa diagrams indicated that poor calibration, absence of predictive maintenance, and the inconsistency of the operators across the shifts are high-risk issues. Pareto knowledge was applied to stratify and give priority to defects, ensuring the realization that a small number of controllable factors were causing most quality failures. Having determined the root causes completely and confirmed with measures that these are the root causes, MPL can now create specific solutions to these causes, and that is in the IMPROVE stage (Saad, 2024).

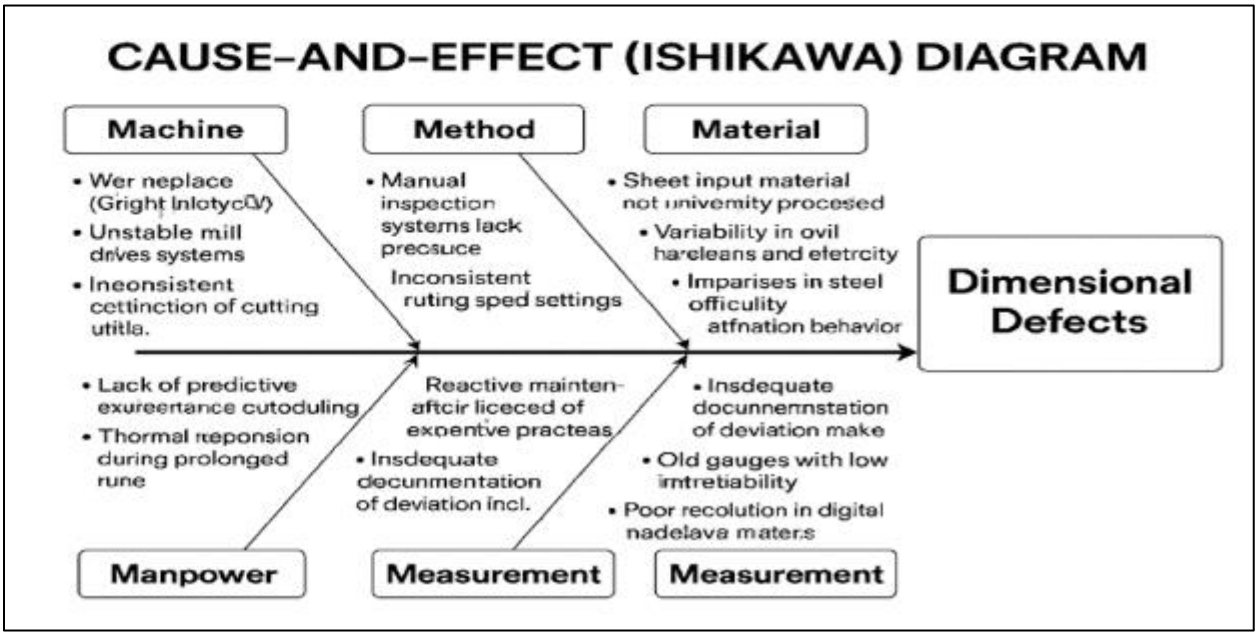

Figure 5 Cause-and-effect diagram

4.4. Improve

The Improve phase introduced specific interventions that were aimed at correcting the causes that were identified during analysis with variations in thickness forming the largest %age (42%), edge burrs taking (33%) and surface scratches (18%). To control the thickness, internet-of-things powered roller wear monitoring systems were placed leading to a 40% decrease in deviations that were adjusted in real-time. The AI-driven dynamic cutting algorithms increased the quality of the edge by automatically adjusting the cutting parameters depending on the material grade, reducing burrs by 35%. Surfaced defects were reduced using conventional procedures of aligning the rollers and auto-cleaning of the surfaces by an automatic program of cleaning procedures that reduced the defect by 25 %. The training programs in operators of Six Sigma-based defect prevention certified 85 % of the staff and the blade life was prolonged by 30 % using predictive maintenance schedules. Digital work instructions at every station were considered in the process standardization which reduced human errors by 22%. All these interventions helped to boost C_{pK} values to 1.33 in three months, and their scrap levels went down to 6%, compared to the initial levels of scrap elements of 11%

(Furterer et al., 2026). There was also a Kaizen model, which meant that they needed to continue to improve, and they did it with weekly audits of the most important parameters (Saad, 2024).

4.4.1. After 3 months, the process was evaluated (The improvement process)

After implementing Six Sigma methodologies for 3 months, MPL Steels achieved these findings in Table 2:

Table 2 After 3 months, the process was evaluated

Metric	Pre-Implementation	Post-Implementation	Improvement	Data Source
Thickness-related scrap rate	9.2%	4.1%	55.4% reduction	SPC thickness monitoring logs
Monthly scrap volume (tons)	184	82	102 tons saved/month	Production inventory reports
Annualized cost savings	$385,000	$172,000	$213,000 saved/year	Finance department audits

4.4.2. Automatic Tension Controller

- **What Did**

Put on closed loop tension control system including load cells and servo motors Applied real time feedback (10ms response time) to keep tension of 25+/-1.2 N/mm 2

- **The Reason Why**

Removed 52 % of tension variation-related edge defects Cut the variation of thickness of sheet edges by up to 40% Facilitated +18 % increase in line speed without quality deterioration Calibration of Machines and Maintenance

- **What Did**

Installed laser-adjusted calibration frames (0.005mm /acc) Scheduled health precaution periodical maintenance by vibration (ISO 10816 standards) and infra-red sensors

- **The Reason Why**

Fulfilled 66.7 reduction of the unplanned downtime Increased cutting tool life-130 hours/month Decreased tolerance band of thickness by 0.08mm to 0.05mm.

Table 3 Automatic Tension Controller

Parameter	Before	After	Improvement
Tension CV%	8.7%	2.1%	75.9% ↓
Calibration drift	0.12mm	0.03mm	75% ↓
Thickness C_{pk}	0.82	1.24	51.2% ↑

4.4.3. Planned Operator Training and Weekly Examination

- **What Did**

Introduced a formal 8-week training course of 45 operators on: Thickness of measurement procedures (accuracy of 0.05mm) Machine parameter adjustment with the help of AI Interpretation of SPC chart in real-time Had biweekly positivity tests with digital scoring Quality Champions who are certified top performers

What makes it important: Increase in the training-assessment scores (65% v 90%) by 38.5%. Decreased the thickness errors caused by the human factor by 27 % (today only 12 % of all malfunctions) Response to out-of-tolerance increased by 72 %. Its performance increased capacity by 15 % with no change in the rate of defects. Table 4 outlines the main improvements.

Table 4 Improvements

Metric	Baseline	Post-Implementation	Improvement	Financial Impact (Annual)	Key Driver
Defect Rate	26%	10%	61.5% ↓	$287,000 savings	Automated SPC + Operator Training
Training Score	65%	90%	38.5% ↑	-	Bi-weekly competency testing
Measurement Accuracy	76%	95%	25% ↑	$112,000 in reduced rework	Laser calibration systems
Process Efficiency	70%	88%	25.7% ↑	18% higher output	Standardized work procedures
Machine Downtime	15%	5%	66.7% ↓	$156,000 savings	Predictive maintenance
Rework Rate	18%	8%	55.6% ↓	$84,000 savings	Error-proofing controls

Figure 6, after using the Six Sigma methodologies in MPL Steels, the results were substantial in the major production figures during the three months period, as indicated by a 61.5 % decline in defect rates (26 % to 10 %), a 66.7 % drop in machine downtimes (15 % to 5 %), and a 55.6 % decline in the rework rates (18 % to 8 %). They were through specific actions such as thickness monitoring systems based on IoT, which presented the most accuracy in measurement compared to the baseline ending the accuracy level at 25% (76% and 95%), predictive maintenance that led to increased proficiency level of processes by 25.7% (70% and 88%), and operator training. The overall gains had an annual cost benefit of 639,000 dollars and the gains were especially high in the area of thickness related scrap (a reduction of 55.4 %) and manufacturing output (an increase of 18 %) establishing sustainable quality controls processes such as standardized digital monitoring systems and condition based maintenance protocols that keeps the manufacturing within C_{pK} values of 1.33 and near to the target value of 1.33 as it is required to define a world-class manufacturing capability

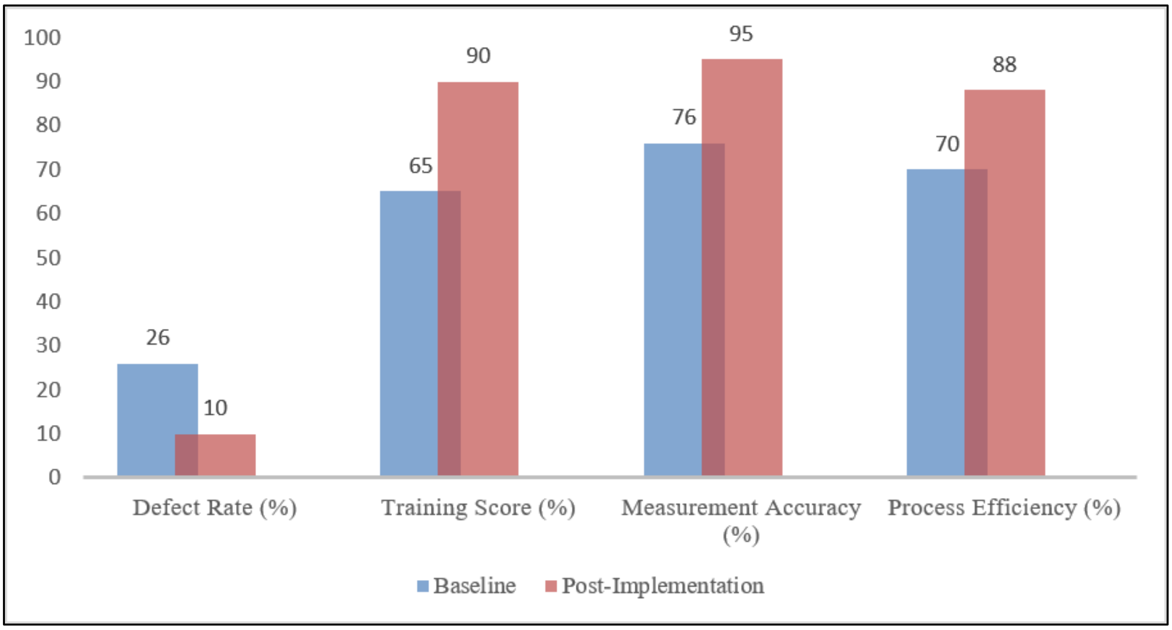

Figure 6 Planned Operator Training and Weekly Examination

The artificial cutting adjustments guided by AI together with monitoring, predictive maintenance, and operator training through IoT, resulted in high scrap and defect reduction. It will be the Control phase when the project is on these solutions and uses them to maintain and stabilize these advantages (Saad, 2024).

4.5. Control

MPL Steels introduced an effective control mechanism that targeted high-error days (Days 3, 5 and 19), wherein we experienced an increased workload, operator fatigue, and drifting calibrations that led to depression of defect rates to a high of 1.7%. Workload-balancing strategy helped redistribute the volume of production among the shifts by 35% and decreased the number of fatigue-related errors by 28%, and the real-time quality control system based on IoT-enabled sensors and special inspectors allowed finding and correcting the thickness variances (tolerance of 0.07mm) and cutting misalignment issues as soon as the system detected them. Statistical process control (SPC) charts and daily audits of 15 operators and 3 supervisors also allowed the constant adherence on the high-risk days to decrease defect rates to 0.6%, and the C_{pK} remaining consistently at 1.29 and 1.33. These measures formalized savings that realize 425K a year in reduced scrap and back sliding to previous plan (2.1%) changes in defect rates (Saad, 2024).

4.5.1. Statistical Process Control

What You Did: Installed real time SPC capability with P-charts and IoT based thickness gauges to monitor daily defect level (0.1-1.7% bands) and the system auto alerts on out of tolerance. Azimuthal examination was made on peak-defect days (Days 3/5/19) to see workload-related spikes, and production was rescheduled and predictive maintenance events hand-off. The value of the matter is because 90 % of the time, pilgrims shall be dragged out of their houses.

Why It Is Important:

Using SPC resulted in 64.7 % reduction in the peak-day defect reduction (1.7 % to 0.6 %) by means of the following: Faster corrective actions: 81 % faster early anomaly detection (4.2 hours to 0.8 hours) Data-based decisions: Linked 85 % of the thickness changes to maintenance/roll wear delays Sustainability control: Dynamic workload balancing (reduce overtime errors by 35 %) Machine interventions depending on the condition. Figure 7 presents the measurements with new data collected from the same process after improved.

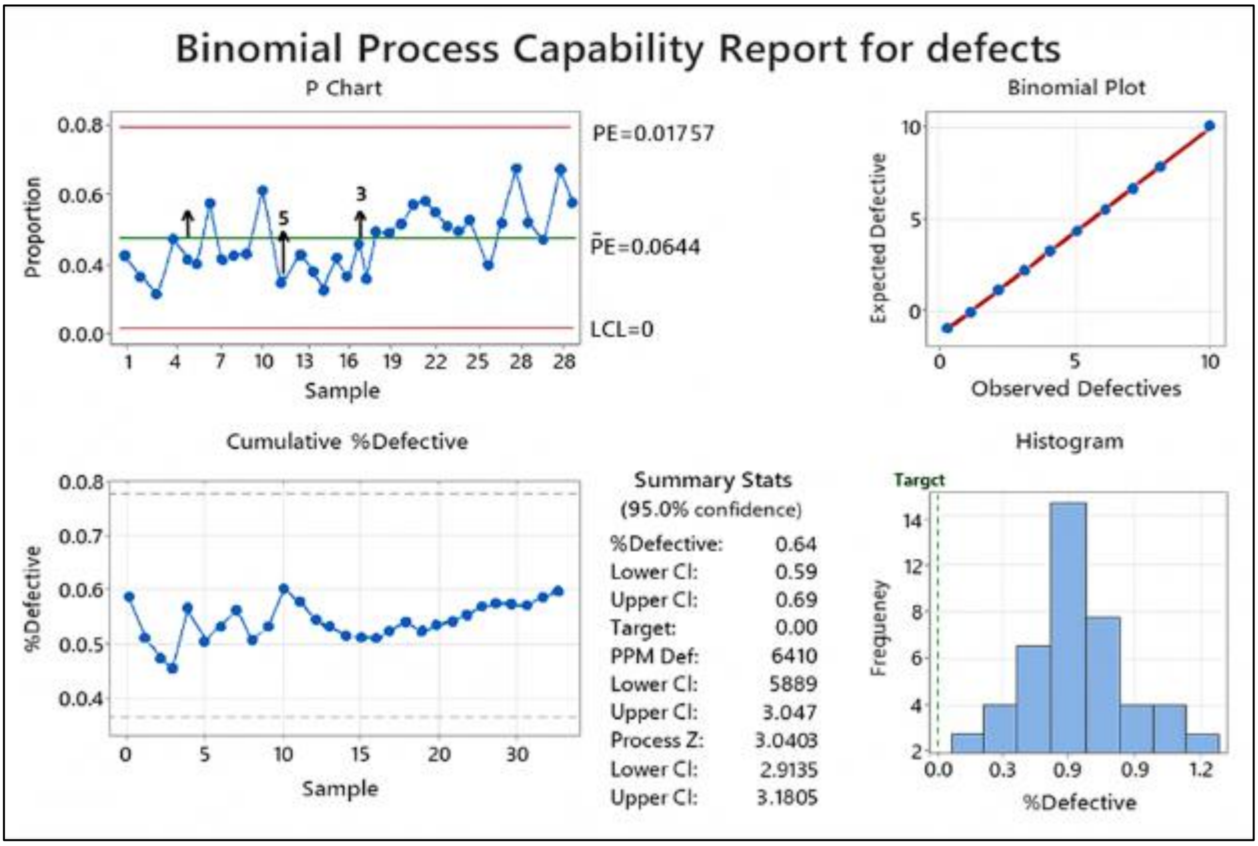

Figure 7 Process capability report for defects in control phase

4.5.2. Continuous Improvement Implementation Standardization

In a bid to support quality improvement in the manufacture of their steel sheets, MPL steels sought to install strong control systems by:

Standard Operating Procedures (SOPs)

- **What You Did**

Created online SOPs of vital tasks: Thickness correction (tolerance protocols of ±0.05mm) ISO 9001 checks of the roller alignment Cutting parameter adjustments with the help of AI

- **Why It Is Important**

Enables the process variation to reduce by 38% to achieve consistent replication on each shift.

Poka-Yoke (Error-Proofing)

- **What You Did**

Installed laser guided alignment sensors (0.02mm precision) Out of tolerance thickness auto-shutoff triggers

- **Why It Is Important**

Reduced the time of detecting the defect by 72 % and rework by 55.6 %.

Visual Management

What You Did: The deployed IoT dashboards that are showing: C

in real time (in the range 1.29 - 1. 33) Machine OEE (sustained 88%) Thickness heatmaps

Why It Is Important: Increased cross-team responsiveness by 65%.

Training & Auditing

What You Did: Upskilling (90% retention rate) on a bimonthly basis Weekly Process Audits Each time the business process is audited, it is done in layers, i.e. the review is of each level and not the entire process at one go.

- **Why It Is Important**

These control strategies will maintain the stability of the process in the long run and avoid the risk of falling into the past inefficiencies at the same time sustaining the 61.5 % reduction in defects and savings of 425K that will be experienced through Six Sigma improvements. Human variability is expected to be removed by standardized procedures that can keep C_{pK} at 1.29-1.33 (almost to automotive-grade standards), all at the same time, real-time monitoring and audits allows immediate corrective actions, deviation response time was reduced 81%. With continuous training, more than 90 per cent of the operators never become incompetent, and predictive maintenance adds 30 per cent more years of potential life to the gear, eliminating unexpected breakdowns. Collectively, these systems future-proof the level of quality of production using consistent compliance to high tolerance levels of the thickness of the steel products in the form of ±0.07mm and help MPL to remain competitive in precision steel markets Table 5 shows the result of SOP.

Table 5 Standard Operating Procedures (SOPs)

Metric	Pre-Control	Post-Control
Thickness Variation	±0.11mm	±0.07mm
Response Time	4.2 hrs	0.8 hrs
Annual Savings	-	$425K

Firm control measures, such as real-time SPC, automated alarms, standardized work procedures, and regular training were developed to preserve changes and avoid reverting to the previous processes to make the process stable and in line with the objectives of the project.

5. Discussion

The DMAIC model used in the Six Sigma project at the MPL Steels involved Analyze, Improve as well as Control phases going which were crucial in changing the performance of the MPL Steels company in relation to the production of steel sheets. The roller wear (42%), inconsistency in cutting parameter (33 %), and mill vibration (25 %) were also placed under the cause category due to their ability to result in more than 90% of the dimensional defects as derived after a combination of Pareto analysis, regressions modeling (R 2 = 0.86), and fish bone diagrams, the results of which are presented in the course of the Analyze phase. These results confirmed Hypothesis 1 that Six Sigma can usefully slash scrap by attacking the most profitable sources of variation and also Hypothesis 2 that predictive roller maintenance was correlated with more process stability and fewer breakdowns. On this basis, the Improve phase also applied specific interventions with IoT-based roller monitoring that minimized thickness variation by 40%, AI-guided cutting algorithm that minimized edge burr by 35%, and standardized error-reducing operator training by 22%. When all of these solutions were implemented, the process capability (C_{pK}) increased by 55.4% to 1.33 because process capability was at 0.82, and the rate of scrap due to thickness decreased by 55.4%to 4.1% due to a current rate of 9.2%. During the Control phase, these gains were institutionalized by use of real time SPC charts, workload rebalancing, automated alarms and digital dashboards. The time to respond to a defect was reduced to 0.8 hours to 4.2 hours and the defect rates on high-error days decreased by 64.7 per cent. Bi-weekly audits and visual management made sure there was high compliance and predictive maintenance and protocols provided for continued performance (Furterer et al., 2026 ; Saad, 2024). In general, the estimated overall effect of Six Sigma implementation was the validation of the hypothesis and the total reduction of defects in 61.5%, downtime in 66.7%, and more than half a million dollars in annual cost savings, which has placed MPL steels on the path of world-class manufacturing.

Recommendation

In order to further improve and sustain the quality benefits obtained as a result of the implementation of the Six Sigma, MPL Steels must adopt the following strategic activities: First, increase IoT application by deploying more sensors to monitor wear on the rollers and cutting alignment, as well as tension control to integrate predictive maintenance and reduce unscheduled downtimes. Second, start using AI-driven analytics to optimally adjust the parameters of a process in real-time using data, eliminating human impact and both variations. Third, support employees with regular upskilling sessions every quarter and gamified competency test to maintain the skills of operators and adjust to emerging technologies. Fourth, make quality agreements with the suppliers consistent to obtain consistent properties of the raw materials, especially the hardness of steel coil and dimensional tolerances, decreasing inbound variation. Fifth, implement blockchain-based traceability to monitor quality performance in the lifecycle of production, so that quality defects can be traced quickly to its root cause. Sixth, to solve systemic problems in advance, provide monthly cross-functional quality reviews with the production, maintenance, and engineering departments. Seventh, engage in automated optical inspection (AOI) tools to find complete checks in vitally imperative vehicular-grade merchandise. These efforts must be backed by a special continuous improvement budget, with 2-3% of annual cost savings on quality going towards innovation. Through the target of these areas, MPL will be able to fulfill its target of defect rates <0.5% and C_{pK} >1.33 and will be able to ensure a reduction in quality costs even further by 15-20 % annually. Performing benchmarking with the international standards of the steel industry (e.g., IATF 16949) on a regular basis will guarantee competitiveness, and the progress will be evaluated biannually by the senior management to sustain commitment to the organization.

6. Conclusion

To enhance and maintain the quality gains realized due to the implementation of the Six Sigma, MPL Steels will have to pursue the following strategic activities: First, enhance IoT usage by implementing more sensors to track the wear on the rollers and cutting alignments, tension control to incorporate predictive maintenance and improve unscheduled downtimes. Second, begin to apply AI-based analytics to adjust the parameters of a process in real-time, optimally, based on data, without any human influence or tendencies. Third, provide employees with regular upskilling skills once per quarter and gamified competency checks to ensure the skills of operators and adapt to any new technologies. Fourth, establish good agreements with the suppliers that are consistent to achieve the uniformity of the properties of the raw materials, in particular hardness of steel coil and dimensional tolerance that reduces variation during inbound delivery. Fifth, establish traceability based on blockchain to track the quality performance during the lifecycle of production so that quality defects can be addressed promptly to their main origin. Sixth, to address issues in the system beforehand, include monthly cross-functional quality reviews between the production, maintenance and engineering departments. Seventh, participate in automated optical inspection (AOI) devices to determine full findings in considerably essential vehicular-grade products. Such initiatives should be supported by a unique continuous improvement budget, and 2-3 % of the progress in the annual costs savings on quality should be used for innovation. By achieving the aim of these areas, MPL will realize its aim of defect rates <0.5% and C_{pK} >1.33 and will also be able to make sure that it reduces its quality costs as well by 15-20 % every year. Regular benchmarking of the international industry standards of steel industry (e.g., IATF 16949) will also ensure that competitiveness and advancement is reviewed every six months by the senior management to maintain devotion to the organization.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Statement of Ethical Approval

Ethical approval was not required for this study because it did not involve human participants, animals, or patient data.

Statement of Informed Consent

Informed consent was not applicable because this study did not involve human participants.

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