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Implementation of lean manufacturing methods to improve rolling mill productivity

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Abstract
Currently, steel producers face challenges in enhancing the efficiency of their rolling mills to boost goods productivity. The productivity of any company significantly influences its profitability. Enhancing equipment availability can lead to increased productivity. By minimizing breakdowns, the availability of equipment can be maximized, thus elevating productivity. Consequently, this study aims to reduce downtime in the rolling mill and improve equipment availability. The primary objective is to enhance the productivity of the rolling mill by implementing lean manufacturing methods, specifically single minute exchange of die (SMED) and total productive maintenance (TPM). Following the implementation of SMED and TPM, the availability and productivity of the rolling mill improved by approximately 11.37% and 5%, respectively. Moreover, the average overall equipment efficiency (OEE) witnessed a significant improvement of about 30.30%, rising from 56.42% to 73.52%. This enhanced OEE can be attributed to the reduction in section changeover time and a decrease in breakdowns.

Keywords
Rolling mill, Single minute exchange of die, Total productive maintenance, Equipment availability, Productivity, Overall equipment efficiency.

1.Introduction
In recent years, the steel industry has been under pressure due to high operating costs and product quality issues. Due to globalization and technological development, high productivity, good quality and low cost are important factors for business organizations to survive in the competitive market [1, 2]. According to the World Steel Association, by 2050, the steel demand is expected to increase by 1.5 times to meet the needs of a growing population. Therefore, it is a big challenge for steel manufacturers to meet customer demand with low-cost and good-quality products [3, 4]. Lean manufacturing (LM) is an advanced methodology to improve the performance of the company. It is widely adopted in various manufacturing sectors such as automobiles, textiles, and steel [5–10] to improve the performance. Researchers and technicians have studied and reported that the implementation of LM plays an important role in improving production with low cost [11–17].

LM, also known as the lean production system, originated at the Japanese company Toyota, which was separated from global competition for decades. Lean is a set of tools and methodologies that aim to reduce waste in the production system and improve productivity [18].

It is not a new technology, but it is still widely used by manufacturing industries across the world. The most commonly used lean methods in steel manufacturing industries to improve productivity are single minute exchange of die (SMED), value stream mapping, seiri, seiton, seiso, seiketsu, and shitsuke (5S), Kaizen, total productive maintenance (TPM) and many others [19–23].

Among these methods, TPM and SMED methods are widely used in manufacturing industries. TPM is a maintenance program that involves a newly defined concept for maintenance plants and equipment. TPM originated in the Japanese car industry in the 1970s [23]. TPM is an inclusive approach to increase operational efficiency. Its main objective is to reduce

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breakdowns and defects as much as possible by the employees involved in the process. TPM is a methodology that reduces failures and machine downtime. It is a comprehensive strategy for equipment maintenance that attempts to achieve maximum production efficiency by eliminating malfunctions, minimizing downtime, minimizing defects, and preventing accidents. Maintenance has traditionally been viewed as a non-productive support function, as it does not directly generate revenue. Yet, for an industry to manufacture goods that meet customer expectations in terms of quality and quantity and to ensure timely delivery, its plant or equipment must operate efficiently and accurately. There are eight pillars that form the foundation of TPM, each playing an important role in achieving its goals. These pillars include autonomous maintenance, focused maintenance, planned maintenance, quality maintenance, education and training, safety, health and environment, office TPM and development management [11]. The TPM methodology brings together both production and maintenance with a combination of practice, teamwork, and continuous improvement [24]. It is designed to maximize overall equipment efficiency (OEE) by improving productivity and reducing maintenance costs. OEE is determined by multiplying equipment availability, process efficiency, and rate of production of quality products. Benchmarking key performance indicators such as OEE can help an organization achieve its goals. The ultimate goals of TPM include zero breakdowns, zero defects, zero machine stoppages, zero accidents, and zero pollution. By measuring and comparing these metrics, organizations can strive for continuous improvement and operational excellence [25].

However, SMED focuses on a reduction in changeover time by converting internal activities to external activities in single-digit minutes (less than 10 minutes) [26]. This helps reduce waste and improve flexibility in manufacturing processes. By carefully planning and coordinating processes and methods, non-productive time or wastage can be reduced. Although each setup cannot be reduced to single-digit minutes, any reduction in setup time is an increase. Setup time refers to the period required to move a machine from the last part of one production lot to the initial good part of the next production lot. The idea was first introduced by Shingo, one of the founders of the Toyota production system, in the 1960s. Since then, it has been implemented in other countries, including West Germany and Switzerland in 1974 and Europe and the US in 1976 [12]. Shingo [27] divides the setup operation into two parts: internal and external setup. The internal setup can only be performed when the machine is turned off. However, external setup is performed when the machine is running. These operations can be performed before or after the machine is shut down. For example, prepare the equipment for setup operations before the machine is turned off. An external activity can be performed when the machine is running. SMED can be applied in any factory and on any machine. The SMED methodology helps to meet customer demand with less waste. If the machine is a bottleneck, then setup time will be more important. The reduction in set-up time may lead to the production of more products at the same time. The main objective of this study is to increase the productivity and OEE of the rolling mill division in a steel plant located in central India by employing TPM and SMED methodologies. This study will provide invaluable insights and benefits to steel plant rolling mill. Adoption of LM techniques will effectively address the growing need to increase productivity in the ever-evolving global steel sector.

The present study is structured in six sections introduction, literature review, methods, results, discussion, and conclusions respectively.

2.Literature review

Many researchers applied TPM and SMED methods to improve productivity. Aadithya et al. [25] implemented TPM and SMED methods in an equipment manufacturing company. Their objective was to identify the factors that hinder the production process and found that the company facing significant challenges, such as insufficient stock in feed and long equipment turnaround times. These issues directly impacted machine availability, leading to a significant decline in OEE. However, OEE was improved by 6.06% through the implementation of TPM and SMED. Arun et al. [28] TPM was successfully implemented in textile manufacturing industry to enhance the performance of the industry. It was found that the workers were not aware of the machine, resulting in increased breakdowns of the machines. Additionally, the company's maintenance policy was improper. However, after the implementation of TPM, the performance of the industry improved significantly. OEE has increased from 61.14% to 65.68% due to more effective maintenance policy adopted by the Company. Dogra et al. [29] improve the performance of cold rolling mill through the implementation of TPM methodology. Breakdowns and failures were reduced after TPM implementation. Sethia et al. [30] implemented TPM in a rolling mill to improve the performance of the plant and reported that performance was improved by 91.03%. Ovedje et al. [31] studied OEE on the performance of machines and equipment by TPM at premium steel and mines limited in Nigeria. The cost of maintenance was reduced and the OEE of the plant increased from 39.76% to 51.22% after the implementation of TPM. Prabowo and Sulistyowati [32] implemented TPM in Indonesian sugar mills and reported that mill performance was improved and maintenance costs were reduced. Due to the occurrence of many failures during the sugarcane milling process, the implementation of proper maintenance procedures has reduced these failures to a great extent. As a result, the reduction in failures also reduced maintenance costs. Andersson et al. [33] implemented TPM in a corporate office to identify how TPM could be implemented within the support process and identify impacts from an employee and business perspective. After the implementation of TPM, it was noted that the occurrence of omission or forgetting of areas of responsibility decreased, leading to increased participation. Additionally, it was highlighted that TPM not only enhances business objectives like cost and quality but also facilitates waste reduction. TPM is the only tool that can stand between failure and success for a company. Au-Yong et al. [34] implemented TPM in the operations and maintenance team of a green office building and reported that employee participation in operations and maintenance activities increased by 64.7%. TPM is the only tool that can stand between failure and success for a company. Its application is accepted in various fields like manufacturing, building construction, civil maintenance, shipping, and many more [35]. Ramos et al. [36] applied TPM to mitigate the challenges posed by fierce competition, minimize expenses, and optimize their supply chain operations. After successful implementation of TPM, machine breakdowns reduced and costs also reduced.

Similarly, SMED also plays an important role in improving the performance of the industry. Mendhe and Rathi [6] SMED method was effectively used to significantly reduce the setup time of the band saw cutting machine. Their primary goal was to reduce setup time by 50%. But through the implementation of SMED technology, setup time was reduced by 75%. Kumar and Abuthakeer [37] used the SMED methodology in forging presses in the automobile industry to improve productivity. Productivity was increased by a reduction in setup time for forging presses. SMED change overtime was reduced from 40 minutes to 12 minutes, i.e., a reduction of 28 minutes. Afonso et al. [19] developed an ergonomic SMED model to improve the productivity of an automotive steel spring plant and reported that productivity was improved and setup time reduced by 55% with an ergonomic SMED model. The ergonomic SMED model is comprised of six steps, focusing on the setup operations of a moulding machine and including rapid upper limb assessment, rapid entire body assessment, job strain index, key indicator methods, and Shoaf's model methods. Sinha and Kumar [38] implemented the SMED methodology in a steel melting shop for section change in slab caster. Slab production was improved by reducing set-up time in the section change process of the caster with the same level of resources. The set-up time of the section change process was reduced by SMED. Das et al. [39] SMED methodology was used to improve the productivity of air conditioning coil manufacturing in Blue Star Limited. The productivity of air conditioning coil manufacturing improved by 76%, which means that the manufacturing rate of coils was improved from 121 coils to 214 coils per shift after the implementation of SMED. Rosa et al. [40] implemented SMED with visual management and 5S lean techniques in the assembly line of the automotive sector and reported that assembly line time was reduced by 58.3%. Brito et al. [41] applied the SMED method and ergonomics techniques in the turning production of a steel factory to reduce setup times and improve ergonomic conditions. Setup time was reduced by 50% following the implementation of SMED. Lozano et al. [42] also applied the SMED methodology in the food industry and measured the mean time between failure (MTBF), mean time to repair (MTTR), and OEE, and found the performance of the industry was improved. MTBF and MTTR depend on the number of breakdowns and the standardization of maintenance procedures. Braglia et al. [43] presented that SMED improves equipment performance by eliminating set-up losses during the equipment changeover time.

Guzel and Asiabi [44] applied SMED and 5S technologies in metal cutting machining. Their goal was to reduce the changeover time of the machines. They report that turnaround time improved by 50% and setup time improved by 60% after the implementation of the SMED methodology. Sayem et al. [45] used SMED methodology to identify and address excess turnaround time in the furniture industry in Bangladesh that was negatively impacting production cycle time. Their findings showed that tool and die change times decreased from 34.24 minutes to 11.91 minutes, resulting in a significant increase in productivity of 65.28%. Morales and Silva [46] implemented SMED in the interconnection axle manufacturing cell to reduce set-up time. After the implementation of SMED, set-up time was reduced; resulting in OEE was increased from 77 to 85%. Furthermore, productivity also increased by 10%. Junior et al. [47] used SMED methodology in an oil and gas company to increase its performance and reported that after the implementation of SMED, there was a significant improvement of 91.6% in setup time, decreasing from 1 hour 44 minutes 56 seconds (6,296 seconds) to 8 minutes 52 seconds (532 seconds). Additionally, a significant increase of 44.6% in overall equipment effectiveness OEE was observed and setup activities were standardized, ensuring consistency and efficiency. Furthermore, the setup time for each manufactured work piece was measured and compared to target achievement and it was also reported that this innovative framework demonstrates the potential to offer competitive strategies in different sectors of the industry. A summary of application of SMED and TPM in various industries is shown in *Table 1*. However, there is a lack of information available in the literature on the applications of SMED and TPM in increasing rolling mill productivity in steel plants.

Table 1 Summary of application of SMED and TPM

Authors	Applied method	Observation
Tampubolon and Purba [2]	Lean methods	Review article
Nallusamy and Saravanan [5]	SMED applied in automobile industry	Changeover time reduced by 18%
Mendhe and Rathi [6]	SMED applied in steel industry	Productivity improved by 15%
Moreira et al. [7]	Lean tools applied in steel industry	OEE improved by 4%
Rehman et al. [9]	TPM applied in textile industry	Production improved by 9.6%
Barot et al. [10]	Lean methods applied in heat exchange manufacturing industry	Productivity improved by 50-70%
Mishra et al. [11]	TPM applied in Indian Manufacturing industry	Review article
Saputra et al. [12]	SMED applied in automobile	Productivity improved by 16%
Mulugeta [13]	Lean tools applied in textile industry	Productivity improved by 16.66%
Shah and Patel [14]	SMED and TPM applied steel industries	Review article
Deshpande [15]	SMED applied steel industries	Review article
Mofolasayo et al. [17]	Lean tools applied in SMEs industry	Review article
Maldonado-Guzmán et al. [18]	Lean methods applied in automobile industry	Review article
Afonso et al. [19]	SMED applied in automobile	Setup time was reduced by 55%
Suryaprakash et al. [23]	TPM and SMED applied in equipment manufacturing industry	OEE was improved by 6.06%

3.Methods

The experimental work was carried out in the rolling mill division of an integrated steel plant located in central India to improve productivity by implementing the SMED and TPM methodologies, which are proven methodologies of LM. The work is divided into three phases. First, literature was reviewed on the applications of SMED and TPM in different industries. The literature review is based on textbooks, articles, journal papers, and case studies from various industries covering current research. In the second phase, daily basis data was collected and analyzed for three months: July, August, and September 2022, as shown in *Table 2.*

Table 2 List of delay time per month before the implementation of TPM

Month(2022)	Planned delay (h/m)	Mechanical (h/m)	Operation (h/m)	R & G shop (h/m)	Electrical (h/m)
July	18.38	16.88	12.00	5.20	4.59
Aug	17.28	16.80	14.32	5.00	3.84
Sep	17.56	15.76	13.52	4.90	4.00
Average	17.74	16.48	13.28	5.03	4.14

During data collection, a file was maintained, details of planned delays (section change, pass change, guide change, roll change), mechanical delays, operational delays, rolling & guide (R&G) shop delays, and electrical delays were recorded, and snapshots and videos were also shot. The current maintenance procedure was also recorded. This was a direct observation. The collected data was analyzed by a Pareto chart. The delay time of these breakdowns was recorded in hour per month (h/m). The purpose of the Pareto chart was to improve the 80/20 performance of the rolling mill. This means that if we put in 20% effort, we can achieve 80% improvement. The Pareto chart was prepared using *Table 3*. The Pareto chart shows that planned, mechanical, and operational delays contributed 80% of total delays, as shown in *Figure 1*. However, 20% of the delays are due to the R & G shop and electrical department.

Table 3 Average production delay time in April to September 2022 before implementation of TPM

Cause of delay	Average production delay (h/m)	Cumulative	Cumulative (%)
Planned delay	17.74	17.74	31
Mechanical	16.48	34.22	60
Operation	13.28	47.50	84
Electrical	5.03	52.53	93
R & G shop	4.14	56.67	100

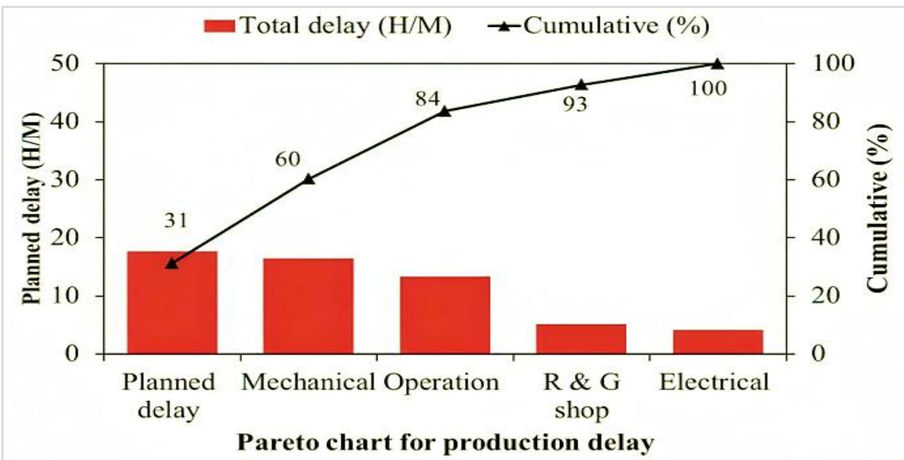


Figure 1 Pareto chart for production delays in a rolling mill

In the third phase, in the month of October, SMED was implemented as a planned delay (section change) activity to reduce the setup time of section changes. A pillar of TPM education and training was also implemented during the section change. However, other pillars–autonomous maintenance, focused maintenance, and planned maintenance of TPM – were applied to rolling mill breakdowns.

Before the implementation of SMED, researchers noted the timing of each activity with the help of a stopwatch, and a short video was made in the rolling mill. Time was recorded as hour, minute, and second (H:M:S) and identified which activities were taking longer to complete. SMED was implemented using brainstorming techniques to eliminate waste or reduce the time of an activity and some activities changed from internal to external.

TPM was implemented in planned delay, operation, mechanical, R&G shop, and electrical delay. The main objective of TPM was to reduce the downtime of the rolling mill in the months of October to December 2022. The results are compared with three months of data collection and three months of modification. The rolling mill produces thermal mechanical treated (TMT) bars of various sizes (8-32 mm). However, the present study was done for 25 and 32 mm TMT bars production. Billets are rolled in 25 and 32 mm for eight days per month. The flow diagram of the rolling process is shown in *Figure 2.*

Billets are hot-charged in the re-heating furnace for rolling. After that, they are rolled under rolling stands 1 to 16, and TMT bars are produced. The effect of TPM and SMED on MTTR, MTBF, equipment availability, productivity, and overall equipment performance was studied. Equipment availability, productivity, and OEE value of the rolling mill with and without SMED and TPM were analyzed. The value of OEE is compared with world-class steel values.

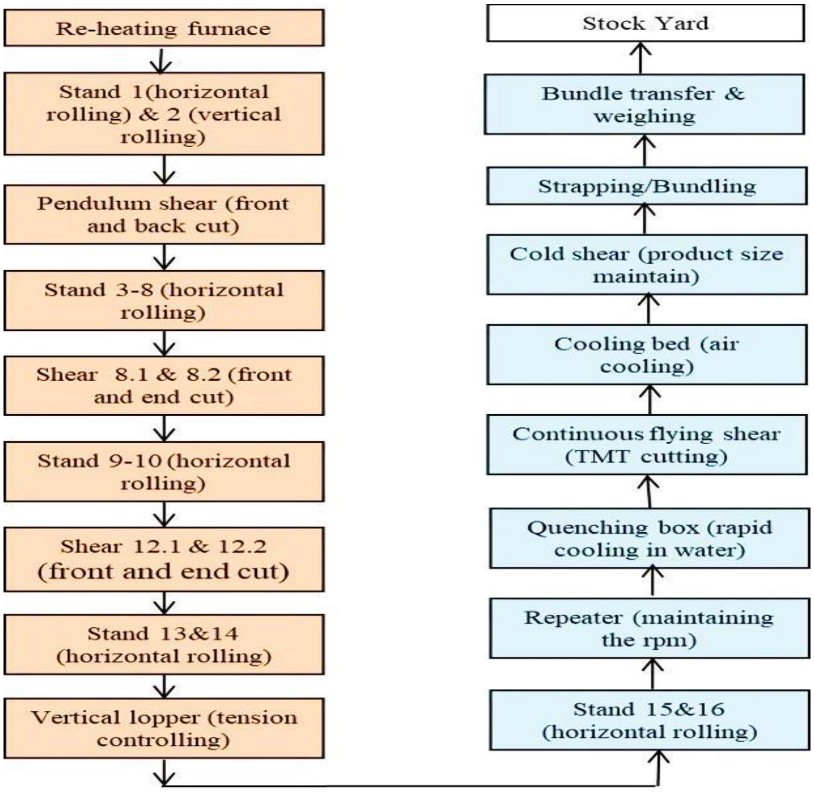


Figure 2 Flow diagram of rolling mill process

4.Results

4.1Implementation of SMED methodology

The SMED methodology is implemented during the section change process, and the completion time of the activities is recorded in *Table 4* and *Table 5*.

Table 4 SMED analysis sheet of section change of rolling mill process

S. No.	Activity	Internal/ External	Activity converted from internal to external	Section change time before SMED (H:M:S)	Section change time after SMED (H:M:S)	Department	Team	Team Size
1	To issue work permit, line clear permit and keep tool in working zone before starting the job	Internal	External	00:02:00	00:00:00	O/E/M	Mix team	
2	To depute manpower according to plan	Internal	External	00:02:00	00:00:00	O/E/M	Mix team	
3	To do entry guide and twister setting in new pass of stand 9	Internal	External	00:10:00	00:08:00	Operation	Team-2	4 Members
4	To do guide setting in new pass of stand 10	Internal	External	00:10:00	00:07:00	Operation	Team-2	
5	To do delivery pipe setting in new pass of stand 10	Internal	External	00:08:00	00:05:00	Operation	Team-2	
6	To remove stand 9 and 10	Internal		00:05:00	00:04:00	Operation	Team-1	4 Members
7	To do entry guide and twister setting in new pass of stand 13	Internal		00:10:00	00:08:00	Operation	Team-2	4 Members

S. No.	Activity	Internal/ External	Activity converted from internal to external	Section change time before SMED (H:M:S)	Section change time after SMED (H:M:S)	Department	Team	Team Size
8	To do guide setting in the new pass of stand 14	Internal		00:10:00	00:08:00	Operation	Team-2	
9	To do delivery pipe setting in the new pass of stand 14	Internal		00:08:00	00:07:00	Operation	Team-2	
10	To check stand 2,4 & 6 entry guides	Internal		00:10:00	00:07:00	Operation	Team-1	4 Members
11	To check stand 1,3 & 5 twister	Internal		00:10:00	00:08:00	Operation	Team-1	
12	To do the fitting of the stand 15 entry guide and twister	Internal		00:10:00	00:08:00	Operation	Team-3	3 Members
13	To do D-coupling and coupling of stand 16	Internal		00:20:00	00:17:00	Mechanical	Team-1	2 Members
14	To replace stand 16 housing	Internal		00:15:00	00:13:00	Operation	Team-3	
15	To remove snap shear (by passed)	Internal		00:15:00	00:11:00	Mechanical	Team-2	2 Members
16	To take/ bring pinch roll at stand 15 inline	Internal		00:15:00	00:11:00	Mechanical	Team-2	
17	To do alignments of slow speed shear both blades	Internal		01:05:00	0:50:00	Mechanical	Team-3	2 Members
18	To do all trough settings from stand 6 to stand 13 according to the center line	Internal		00:15:00	00:12:00	Operation	Team-1	2 Members
19	To do all trough settings from stand 15 to stand 16 according to the center line	Internal		00:10:00	00:08:00	Operation	Team-3	
20	Electrical system checking by the electrical team as per planning	Internal		00:45:00	00:30:00	Electrical	Team-1	3 members
21	To do long piece sampling for checking looping between stands	Internal		00:10:00	00:05:00	Operation	Mix Team with In-charge	
22	During sampling twisting is to be checked/adjusted as per the requirement	Internal		00:10:00	00:05:00	Operation	Mix Team with In-charge	
23	To monitor the first billet come from the furnace and stand on the pass to avoid slipping of billet	Internal	External	00:01:50	00:00:00	Operation	Mix Team with In-charge	
24	To check the temperature of the quenching of the TMT bar and it should be 520°C -550°C	Internal	External	00:01:50	00:00:00	Operation	Mix Team with In-charge	
25	To check the rolling sample of the first billet for section weight (range should be between 6.120 to 6.310 kg/mtr and core dia of the bar (31.4 to 31.6 mm)	Internal	External	00:20:00	00:10:00	Quality		
26	To check the mechanical property of the rolling sample of the first billet	Internal	External	00:20:00	00:05:00	Quality		

Table 5 Setup time of section change from 25-32 mm TMT bars

Team	**Work**	**Time taken by the team to section change before SMED (H:M:S)**	**Time taken by the team to section change after SMED (H:M:S)**	**Time saved after SMED (H:M:S)**	**Remark (justify how time have been reduced**
Team-1	Three teams of operation worked parallel	00:40:00	00:31:00	00:09:00	As mentioned above all the teams are working in parallel. However, Mechanical Team-3 was taking more time than the other team. But after the SMED method, the work of this team was reduced.
Team-2		00:56:00	00:43:00	00:13:00	
Team-3		00:35:00	00:29:00	00:06:00	
Team-1	Three teams of mechanical worked parallel	00:20:00	00:17:00	00:03:00	
Team-2		00:30:00	00:22:00	00:08:00	
Team-3		01:05:00	00:50:00	00:15:00	
Team-1	Work done by Electrical Team	00:45:00	00:30:00	00:15:00	More work was done in parallel
Sampling Time	Operation	00:20:00	00:10:00	00:10:00	Work done by planning
Quality testing time	Quality	00:20:00	00:05:00	00:15:00	Communication with the quality team was adequate.
Total time		**02:30:00**	**01:35:00**	**00:55:00**	

A total of seven teams worked together for section change, which included three teams of operation, three teams of mechanical, and one team of electrical. The total number of members in the whole team, including two managers, was thirty. Before the section change, prepared an action plan was prepared and discussed with all seven teams. Walkie-talkies were used by the group leader for communication. It was observed that many activities were taking more time, thereby delaying the production process. Although many of these activities could be performed while the mill was running, they were scheduled after the machine was shut down. This resulted in reduction in mill availability. The implementation of SMED resulted in the reduction or elimination of these types of activities from the production process. Mill run times were increased and changeover times were reduced through the implementation of SMED. It can be seen from *Table 4* that the total time taken to change the section before implementation was 150 minutes (2 hours 30 minutes), but after the implementation of the SMED, it was reduced to 95 minutes (1 hour 35 minutes). Setup time was reduced when activities were converted from internal to external. The section change is done after 6 or 7 shifts. These time constraints affect the production of the mill.

4.2Implementation of TPM methodology

TPM was implemented in the maintenance process. The main objective of TPM was to achieve zero breakdowns, zero failures, and zero accidents. The major reasons for the delay in production were pusher jams, poor lubrication in rolls, pass changes, guide changes, pinch roll changes, cold shear cutting, scale removal, a lack of operator training, and machine problems like improper setting, etc. All defects affect the production of the mill. The number of breakdowns and their delay times were recorded. After that, the TPM methodology was implemented step by step from October 2022 to December 2022. The four pillars of TPM were applied to reduce the breakdown. The TPM methodology is implemented using the following skills:

(1) Implementation of autonomous maintenance:

- Sources of breakdown were identified and eliminated.
- Improved the efficiency of equipment.
- Bringing together all maintenance teams for maintenance work.
- Responsibility of all team for equipment and technical issues
- Daily activities maintained during the production of the mill.

(2) Implementation of focused maintenance:

- Considered a benchmark value for all production delays.

a) Considered 1.5 hour/day delay time for the planned delay.
b) Considered 1.0 hour/day delay time for mechanical
c) Considered 0.5 hour/day delay time for operation

- The benchmark values were achieved through technical skills, and the running time of the mill was improved.

(3) Implementation of planned maintenance:

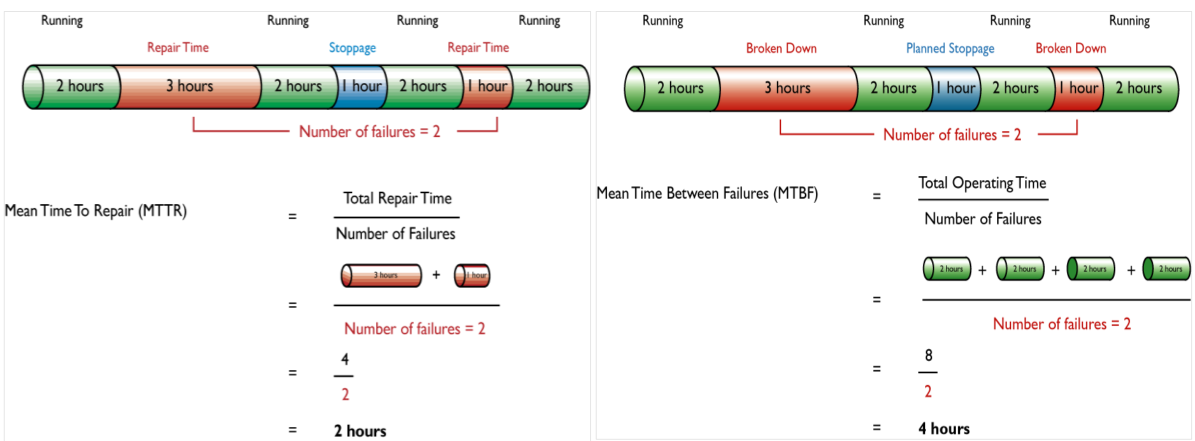
- Many activities that caused production delays were documented and problems were resolved.
- Changed the material of the roll and improved the life of roll.
- Change the material of the guide and improved the life of guide.

Due to this, the frequency of roll and guide failures decreased and equipment availability was increased.

(4) Education and training:

- Cross-training on technical skills was provided to operators and engineers.
- The performance of the rolling mill was also improved by the training program, and the availability of the mill was increased.

The analysis of MTTR and MTBF is carried out by a formula as shown in *Figure 3* and the value is shown in *Table 6*. Values are represented in minute per month (min/m). Through the MTTR model, we can understand that two failures occur at different times in a day. Suppose the first failure took 3 hours and the second failure took 1 hour. That means the total repair time is 4 hours, however failures are 2. According to the MTTR formula (MTTR = Total Repair Time/Number of Failures), MTTR = 4/2 equals 2. This means the MTTR is 2 hours. Similarly, for MTBF, suppose two failures of mechanical or electrical or operation or any other occur simultaneously and take 2-2 hours each to complete. But it will be considered a failure because it came at the same time. The model exposed that there are 2 failures, but they have taken 2+2+2+2 = 8 hours. Since MTBF = 8/2 equals 4 hours. It can be seen that after the implementation of TPM and SMED, the production delay time and MTTR have been reduced; However, MTBF increased as mill down time was reduced. Similarly, Pinto et al. [26] MTBF and MTTR values were calculated in an automobile company. Thereafter, OEE values were calculated based on the determined MTBF and MTTR values. The reliability of the equipment increases as the MTBF value increases. However, MTTR represents the exact period required to restore a device and bring it back to optimal functionality. Production delay time was reduced due to a reduction in changeover time and breakdowns, as shown in *Table 7*.



(A) (B)

Figure 3 A systematically illustrated model for (A) MTTR and (B) MTBF

Table 6 Performance indicators of rolling mill

Month(2022)	Production delay(h/m)	MTTR (min/m)	MTBF (min/m)
July	52.0	44.6	111
Aug.	56.0	44.8	106
Sep.	52.0	44.6	110
Oct.	40.0	36.9	126
Nov.	38.4	38.4	148
Dec.	37.6	41.0	166

Table 7 List of delay times per month after the implementation of TPM

Month(2022)	Planned delay (h/)	Mechanical (h/m)	Operation (h/m)	Electrical (h/m)	R & G shop (h/m))
Oct.	13.68	12.56	7.28	2.8	2.8
Nov.	13.52	11.84	7.68	2.8	2.8
Dec.	12.64	11.6	7.6	3.2	2.56
Average	13.28	12.00	7.52	2.93	2.72

The analyzed data of equipment availability, productivity, and OEE are presented in *Table 8*. The impact of TPM and SMED on equipment availability, productivity and OEE is calculated using the formulas Equation 1, Equation 2 and Equation 3 respectively [5, 30]:

Equipment availability = Total operating time / Total operating time + total repair time (1)

Productivity = total production / mill running time (2)

OEE= Availability × Performance × Quality (3)

The productivity of the rolling mill was improved after the implementation of TPM and SMED methodologies. The productivity was improved from ~46.82 to ~49.17 metric ton per hour (MT/h). However, equipment availability and OEE increased from ~70.90 to ~78.95%, and ~56.42 to ~73.52% respectively. The improvement in productivity, the equipment availability, and OEE was improved by ~5%, ~11.37% and ~30.30% respectively. However, World-Class steel availability and OEE are 90% and 85%, respectively [33]. The observed availability and OEE are not far from World-Class steel availability and OEE.

Table 8 The value of Equipment availability, Productivity and OEE are listed

Month(2022)	Equipment availability (%)	Productivity(MT/h)	OEE (%)
July	71.4	46.68	57.00
Aug	70.2	46.97	55.52
Sep	71.1	46.80	56.74
Oct	77.3	48.53	69.48
Nov	79.4	49.32	74.55
Dec	80.2	49.67	76.54

5.Discussion

SMED and TPM were successfully implemented in the months of October 2022 to December 2022, step by step, using a brainstorming technique.

5.1Implementation of SMED methodology

During data collection, various reasons were observed that were responsible for delays in production. Data collection revealed that more time was wasting during section changes (planned delays). Therefore, the SMED method was applied during the section change. Before the implementation of SMED, a planning chart for the implementation of SMED was prepared and discussed with the operations, mechanical, and electrical teams. During the section change, some activities were changed from internal to external and saved 55 minutes. Mendhe and Rathi [6] by applying SMED technology the setup time was reduced from 40 minutes to only 10 minutes which was very effective for the performance of the machines. It was also confirmed that SMED is a key LM technique used to effectively reduce machine setup time. It can be seen from *Tables 3* and *4* that after the implementation of the SMED methodology, the changeover time of various activities was reduced, which plays a dynamic role in the production of the rolling mill. This means SMED saved 55 minutes in two days, which is helpful in improving equipment availability and mill running time. On the other hand, if the availability of equipment improves, productivity will also improve. It is notable that SMED and quick turnaround programs have improved productivity by up to 70% [43]. Saputra et al. [12] also implemented SMED in Tokai Rika Indonesia, and addressed the issue of setup time in the transition model, reported that before the reform, setup time was 12.3% (59.2 min/shift), which significantly reduced to 3.8% (18.4 min/shift) after implementation. Consequently, the setup time experienced a substantial reduction of 68.9% (40.8 min/shift). However, productivity was measured based on the number of pieces produced per hour. The productivity level increased from 37 pieces per hour before the implementation of reforms to 43 pieces per hour post-reforms. This surpasses the company's objective of achieving 42 pieces per hour, leading to a noteworthy enhancement of 6 pieces per hour. In a similar vein, Sayem et al. [45] documented that minimizing changeover time has a positive impact on productivity. By reducing the setup time availability is enhanced, leading to an increase in production rate and ultimately improving productivity.

5.2Implementation of TPM methodology

From the Pareto chart it can be seen that we should pay attention to planned, mechanical and operational delays. Thereafter, TPM is applied to planned, mechanical and operational delays, although TPM is also applied to some R&G and electrical delay activities. From the data analysis, it was observed that maintenance was improper, operators lacked skills, and roll & guide life was not longer. The four pillars of the TPM methodology—autonomous maintenance, focused maintenance, planned maintenance, and education and training—were implemented. Regular activities were maintained, which increased the running time of the mill. TPM work was carried out as planned (pass change, guide change, roll change, etc.) with proper planning and discussed with the entire team, and breakdowns were minimized. It can be seen that the production delay time was reduced after the implementation of lean tools (*Table 8*). Hence, it is confirmed that breakdowns or failures affect the production of the mill. Improper maintenance and operation of machines may reduce their performance levels. As a result, the effectiveness and productivity of the machine decreased [48].

After the successful implementation of TPM and SMED, data was once again collected and analyzed. An education and training program also proved more efficient in reducing mill downtime. Zulfikar et al. [48] also, state that the education and training aspect of TPM is extremely important in increasing industrial productivity. Implementation of SMED and TPM methodologies has definitely improved machine availability and performance [25, 49–51]. Mofolasayo et al. [17] confirmed that lean methodology helps in increasing productivity by reducing waste. The core principle of lean is continuous improvement, driven by the belief that there is always room for progress. The advent of technologies in the manufacturing industry has immense potential to help manufacturing companies to make substantial progress in their development. The percentage of equipment availability and OEE compared with World-Class steel as shown *in Figure 4*. Sethia et al. [30], Sharma and Thakar [50], Avichena [51] also discussed World-Class steel OEE and availability in their research and reported that the value of OEE and availability of World-Class steel is 85% and 90% respectively.

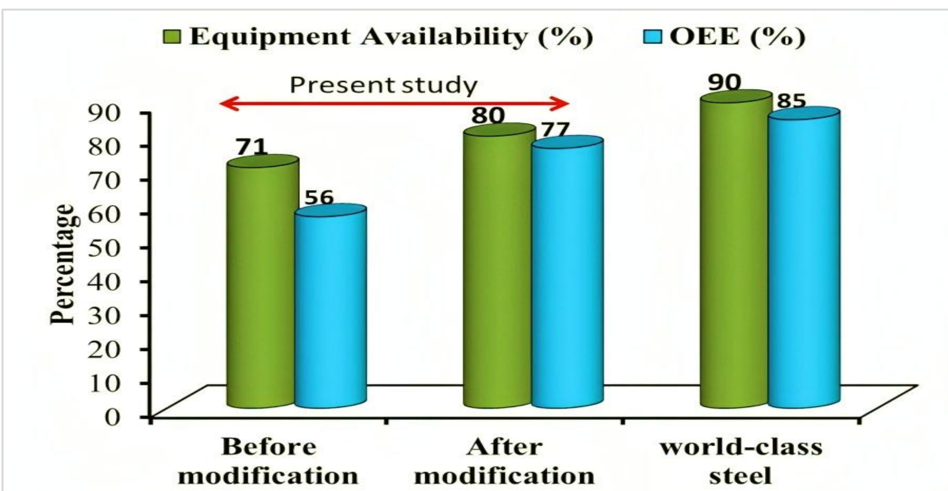


Figure 4 Comparison of world-class steel OEE and availability with present work

In their study, Tampubolon and Purba [2] highlighted the advantages of the LM method. The LM method is not only useful for the steel sector but also proves to be highly beneficial in other industries like textiles [9]. LM methodologies improve industry performance. Moreira et al. [52] have also reported an improvement in OEE based on the application of LM in the manufacturing industry. OEE is a key indicator that highlights the performance of industries [45–47]. Arun et al. [28] also reported that breakdowns play a vital role in equipment performance. Through their analysis, they have found that by reducing breakdowns, OEE can be increased. Additionally, it was recognized that breakdowns and failures lead to wasted work hours. The root cause of low OEE was identified as low availability of equipment, which was mitigated by implementing TPM. According to the findings of Zaheer et al. [53] and Vieira et al. [54], the adoption of LM methods has shown a reduction in the setup time of manufacturing machines. As a result, productivity increases. The improved OEE (30.30%) of the present work is compared with literature as represented in *Table 9.*

A complete list of abbreviations is summarised in *Appendix I.*

Table 9 The comparison of OEE after TPM and SMED implementation in different industries

Author	Methodology	Results
Mendhe and Rathi [6]	SMED implementation	OEE improved by 10%
Rehman et al. [9]	TPM implementation	OEE improved by 9.6%
Arun et al. [28]	TPM implementation	OEE improved by 7 %
Ovedje et al. [31]	TPM implementation	OEE improved by 22 %
Morales and Silva [46]	SMED implementation	OEE improved by 9.5%
Junior et al. [47]	SMED implementation	OEE improved by 44.6%
Zulfikar et al. [48]	TPM implementation	OEE improved by 10.53%
Vieira et al. [54]	SMED implementation	OEE improved by 10.8%
Present study	SMED and TPM implementation	OEE improved by 30.30%

6.Conclusion and future work

In this study, TPM and SMED methodologies were applied at a rolling steel plant within an integrated steel facility located in central India. The implementation of the SMED methodology resulted in a reduction of section change time from 150 minutes to 95 minutes. Following the application of both SMED and TPM methodologies, significant improvements were observed: equipment availability increased by 11.37%, productivity by approximately 5%, and OEE by 30.30%. The productivity of the rolling mill rose from 46.82 MT/h to 49.17 MT/h as a direct result of employing TPM and SMED methodologies. The OEE surged from 56.42% to 73.52%, approaching the 85% benchmark performance set by World Steel. The authors conclude that the adoption of Lean Manufacturing methodologies is highly beneficial for enhancing the production efficiency of rolling mills.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

Not applicable.

Author's contribution statement

Sardar Singh Rathi: Study conception, data collection, analysis, interpretation of results, draft manuscript. **Dr. Mithilesh Kumar Sahu and Dr. Sanjeev Kumar:** Manuscript editing, results verification and technical discussion. All authors reviewed the results and approved the final version of the manuscript

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Appendix I

S. No.	Abbreviation	Description
1	5S	Seiri, Seiton, Seiso, Seiketsu, and Shitsuke
2	h/m	Hour Per Month
3	H:M:S	Hour, Minute and Second
4	LM	Lean Manufacturing
5	MTBF	Mean Time Between Failure
6	MTTR	Mean Time to Repair
7	min/m	Minute Per Month
8	MT/h	Metric Ton Per Hour
9	OEE	Overall Equipment Efficiency
10	R & G	Rolling & Guide
11	SMED	Single Minute Exchange of Die
12	TPM	Total Productive Maintenance