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Improving Productivity in Electrowelded Pipe Production Lines through the Development of a Maintenance Plan Based on Autonomous Maintenance

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ABSTRACT

This research aimed to increase the efficiency of electrowelded pipe production by developing a maintenance plan based on autonomous maintenance. This approach allows machine operators to perform industrial maintenance tasks, rather than relying solely on maintenance technicians. As a result of implementing the 5S methodology, conducting a time study, and establishing a comprehensive maintenance plan, plant productivity increased from 77% to 152%. The model proved effective in increasing productivity by raising overall equipment effectiveness (OEE) from 37.43% to 82.74%.

Keywords: autonomous maintenance, lean manufacturing, productivity, OEE (overall equipment effectiveness), CTQ (critical to quality).

INTRODUCTION

According to the World Bank's edition of the World Economic Outlook, the global economy is experiencing a significant slowdown due to new threats posed by COVID-19 variants, alongside rising debt, inflation, and income inequality. These factors could jeopardize the recovery of developing and emerging countries. As global fiscal and monetary support decreases, global growth is projected to decline significantly, dropping from 5.5% in 2021 to 4.1% in 2022, and further down to 3.2% in 2023 (Banco Mundial, 2022).

This year, steel demand is expected to increase by only 0.4%, reaching 1,840 million tons, below the 2.7% increase forecasted in 2021. This slowdown is primarily due to the impact of the Ukraine crisis and rising prices. The conflict is expected to affect the steel industry by increasing raw material and energy costs, as a result of disruptions in the global supply chain (Forbes, 2022, p. 25).

The construction sector has experienced a remarkable increase of 34.7% in recent years, making it the most sustainable economic activity. It is closely followed by the manufacturing sector, which has grown by 17.7%, and the mining and hydrocarbons sector, with a growth rate of 7.4%.

The company under study is located in the province of Chimbote and specializes in the production and sale of steel. In response to current challenges, the company has been compelled to improve its processes and minimize defects to boost productivity.

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Consequently, the objective of this article is to propose and implement a maintenance plan based on autonomous maintenance, supported by the tools of total productive maintenance (TPM). This plan is designed to improve the quality, standardization, and time efficiency of the company's production process. It is expected that this model will not only achieve its objectives within the examined company but can also be applied to other companies in the industrial sector that face similar challenges.

This research aims to demonstrate that implementing autonomous maintenance in the manufacture of electrowelded pipes in a steel plant can significantly increase productivity. The proposed paradigm is suitable for application in similar contexts, as evidenced by the considerable productivity improvements observed after the introduction of the continuous improvement model. This paper is intended to serve as a resource in the research field for both researchers, guiding further studies based on continuous process improvement, and for companies in the industrial sector seeking a lean manufacturing model to enhance their processes.

The significance and originality of this research study stem from the development of a model based on selected tools to tackle the main challenges in the steel sector, including worker training, machine maintenance, disorderliness, lack of cleanliness, and prolonged cycle time, all of which impact productivity.

This research study contributes to the growth of the sector by proposing a maintenance plan based on autonomous maintenance, providing a new approach to continuous improvement within the steel industry and the research sector.

Autonomous maintenance is essential for effectively managing the operational processes of companies. In his study, Jima (2015) employed various tools, including a prioritization matrix, questionnaires, FMEA tables, interviews, and preset time systems, to develop a comprehensive maintenance system for the company Centro de la Madera. The study involved four participants: three plant employees and one administrative staff member. They were surveyed and interviewed to assess the current state of machine maintenance and each employee's safety plans. Consequently, descriptive field, pre-experimental, correlational, and longitudinal descriptive study designs were used as research methods. The result of this effort was the implementation of a comprehensive industrial safety and maintenance system.

According to Martínez, various approaches, including kanban, kaizen, autonomous maintenance, just-in-time (JIT), benchmarking, total quality control, and continuous improvement, are supported by a quasi-experimental, applied, descriptive, correlational, and cross-sectional quantitative design. Companies engaged in the production of goods that aimed to maintain their machinery, facilities, and equipment in excellent working order proposed to apply the principles of total productive maintenance (TPM) and foster a change in mindset among their personnel to achieve desired results. The workforce is a key factor in transforming processes through training and incentives. The findings indicated that this approach was effective only 30% of the time, particularly when staff members adapted their work environments and worked as individuals and teams. They experienced constructive and cooperative development, and some employees even successfully applied these concepts at home (Martínez, 2009).

Productivity

Optimal equipment productivity requires a combination of operational and maintenance strategies, as no equipment can be truly productive without adequately trained personnel in both production and maintenance. It is common for organizations to have a department in charge of maintaining ideal operating conditions, which seeks collaboration and support from other departments, especially those directly involved in production and maintenance. Ideally, operators should be able to perform simple and quick tasks to keep the equipment operational rather than specific maintenance. Achieving productivity is challenging for any company without a clear, well-defined, and shared strategy, as well as a concrete structure and an appropriate distribution of responsibilities aligned with that structure (Carro & Gonzáles, 2024).

Autonomous Maintenance

The efficient use of equipment has been crucial in reducing costs and enhancing the competitiveness of companies. Maintenance performed by employees, often referred to as "autonomous maintenance", improves equipment efficiency and prevents its degradation (Cáceres, 2019).

It is a fact that the lack of interest among operators to perform new activities will not change overnight. Changing attitudes is a challenging process that requires time, and it is hard for them to abandon their usual work habits; usually, operators focus fulltime on production while maintenance personnel handle repair responsibilities (Castelo, 2017).

> *El mantenimiento autónomo busca alcanzar los seis objetivos descritos a continuación. Emplear la máquina/equipo como instrumento para el aprendizaje y adquisición de conocimientos. Desarrollar nuevas habilidades para el análisis de problemas y creación de un nuevo pensamiento sobre el trabajo, mediante una operación correcta y permanente que evite el deterioro. Mejorar el funcionamiento de la máquina con el aporte creativo del operador. Construir y mantener la máquina en condiciones óptimas. Mejorar la seguridad en el trabajo. Mejorar la moral en el ambiente de trabajo* [Autonomous maintenance aims to achieve six key objectives: 1) to use machines and equipment as tools for learning and knowledge acquisition, 2) to develop new skills for problem analysis and encourage innovative thinking about work through consistent and proper operation to prevent deterioration, 3) to enhance machine operation with creative input from operators, 4) to build and maintain equipment in optimal condition, 5) to improve workplace safety, and 6) to boost morale in the work environment]. (Montilla, 2019, p. 185)

Lean Manufacturing

> *Lean manufacturing es un nuevo modelo de organización y gestión del sistema de fabricación que persigue la mejor calidad, el menor lead time y el menor coste mediante la eliminación continua del despilfarro.… La implantación de las metodologías y herramientas del lean manufacturing es muy sensible a la actitud y participación de las personas. Es imprescindible que la dirección lidere, impulse y apoye, con rigor y constancia, el lean manufacturing* [Lean is a new model for organizing and managing manufacturing systems, focusing on achieving the best quality, the shortest lead times, and the lowest costs through the continuous elimination of waste… The implementation of lean manufacturing methodologies and tools is highly dependent on the attitudes and engagement of the workforce. Management must lead, drive, and support these initiatives with thoroughness and determination]. (Madariaga, 2023, pp. 25-26)

The ultimate goal of lean manufacturing is to improve quality, reduce costs, and shorten the time between customer orders and product shipments.

5S

The 5S methodology focuses on systematically managing the components of a workplace through five steps that require perseverance and effort. It aims to organize work routines to reduce waste and maintain tidy and clean work areas.

Profitability and Competitiveness

La rentabilidad es el beneficio renta en términos relativos o porcentuales respecto a otra magnitud económica como el capital total invertido o los fondos propios [Profitability refers to the profit earned relative to another economic measure, such as total invested capital or equity] (Cáceres, 2019, p. 8).

The market ultimately serves as the final judge; it dictates how the industrial sector must design, produce, and sell products. Companies must create more appealing offerings than similar products offered by competitors.

CTQ

The parameters that are critical to meeting the customer quality requirements are known as CTQ, which stands for “critical to quality”. This process involves prioritizing the characteristics that contribute to the desired outcomes and eliminating those that are not essential to meet the customer’s needs.

The characteristics that satisfy a key customer requirement are defined as the CTQ for any product, process, or service. As noted, CTQ directly conveys the voice of the customer, providing a comprehensive understanding of their needs.

METHODOLOGY

SidePerú is the leading steel company in Peru that specializes in the manufacturing and sale of steel products. Since its establishment in 1956, it has produced and distributed high-quality steel goods. Its steel complex is located in Chimbote, covering an area of 600 hectares, and has a production capacity exceeding 600 000 tons of finished steel products annually. The complex consists of multiple areas, including reduction, steelmaking, flat and long product rolling, coated flat product rolling, tubular products, rails, and numerous auxiliary facilities. Additionally, it features a quay designed to accommodate ships with a capacity of up to 50 000 tons.

The simple random finite population sampling formula was used across the entire company to determine the sample size. This method helped to identify which specific section to analyze, selecting the one with the number of employees closest to the sample number. As a result, the pipe section was selected, as it employs the largest number of workers.

The pipe section is divided into two categories of machinery: cold machines (M2, TMC, M2.5) and hot machines (YODER FERRUM, SHULTER FERRUM, W35). There are 62 operators, 6 setup workers, 3 supervisors, and 3 quality inspectors, resulting in a total of 74 employees working in three shifts at the plant.

RESULTS

Statistical Hypotheses

The implementation of autonomous maintenance in the electrowelded pipe manufacturing process at the steel manufacturing plant improves productivity. The feasibility of this assumption will be tested at a significance level of α = 0.05.

- H_0 = The implementation of autonomous maintenance in the electrowelded pipe manufacturing process at the steel manufacturing plant does not improve productivity.
- H_1 = The implementation of autonomous maintenance in the electrowelded pipe manufacturing process at the steel manufacturing plant improves productivity.

A CTQ matrix was developed to assess the quality of the tubular products produced by the steel manufacturing company. The analysis revealed that none of the gaps exceeded 5%, indicating that product quality was not the issue. However, the highest value (4.50) was found in manufacturing, prompting the analysis to focus on this area. Table 1 below presents the CTQ matrix.

A brainstorming exercise was carried out to analyze the possible causes (X) that might affect the process. This analysis served as a basis for identifying the main variables that contribute to a significant amount of waste (Y) in the process. To aid in this analysis, the Ishikawa cause-and-effect diagram was used, focusing on the productivity of electrowelded pipes, as illustrated in Figure 1.

Table 1. *CTQ Matrix.*

CTQ	Importance		Plan	Enable	Source	Make	Delivery	Return	Satisfaction	Dissatisfaction	Gap
	Nro.	%	Planning	Indicators	Resources	Manufacturing	Distribution	Returns			
Updated Offers	8	20%	3	0	0	9	3	0	80%	20%	4.00
Credit Facility	7	18%	9	0	0	0	3	0	76%	24%	4.20
Stock Replenishment for Sale	10	25%	3	1	0	9	0	0	90%	10%	2.50
Variety of Tubular Products	9	23%	0	0	0	9	3	0	83%	17%	3.83
Friendly Sales Staff	6	15%	0	0	9	0	3	0	72%	28%	4.20
	40		2.18	0.00	1.35	3.83	2.25	0.00			

Source: Prepared by the author.

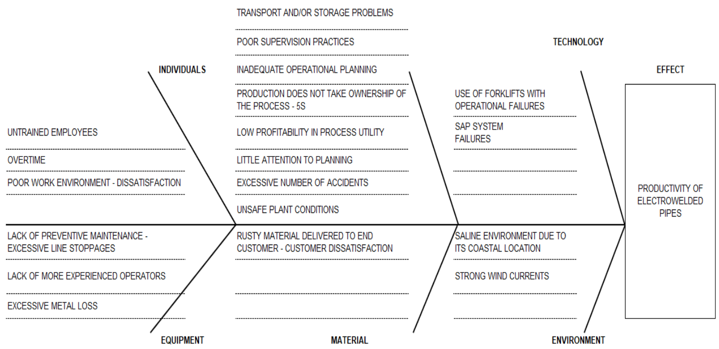

Figure 1. Cause-and-effect diagram.
Source. Prepared by the author.

Table 2. *Determination of Possible Root Causes.*

Detail	Failure Mode	Possible Root Cause	Frequency	Severity	Controls	Ratio	
Untrained employees	Repeated production line stoppages due to lack of quick solutions	Untrained employees	3	3	4	**36**	X_1
Increased overtime for plant personnel	Fatigue experienced by operators and line maintainers	Overtime	3	2	3	18	
Lack of commitment from employees	Poor communication between operators and line maintainers	Poor working environment leading to dissatisfaction	4	3	3	**36**	X_2
Repeated production line stoppages	Equipment reliability issues	Lack of preventive maintenance leading to excessive line stoppages	4	4	3	**48**	X_3
Excessive turnover rates among line employees	Insufficient knowledge of line equipment	Lack of more experienced operators	3	2	3	18	
Repeated production line stoppages	Excessive scrap in the transit yard	Excessive metal loss	4	4	4	**64**	X_4
Poor quality of the final product	Internal customer complaints	Transportation and/or storage problems	2	2	2	8	X_5
Disorganized procedures	Inadequate supervision	Poor supervision practices	2	2	2	8	
Lack of routine planning	Products not meeting operational criteria	Inadequate operational planning	4	4	3	**48**	
Dirty plant environment	Tools and materials scattered throughout the plant	Production does not take ownership of the process - 5S	3	4	4	**48**	X_6
Repeated production line stoppages	Products not meeting operational criteria	Low profitability in process utility	4	4	3	**48**	X_7
Instability in the manufacturing system	Production based solely on demand	Little attention to planning	4	3	3	**36**	X_8
Unstable plant conditions	Occurrence of plant accidents	Excessive number of accidents	3	3	4	**36**	X_9
Disorder in the plant	Products not meeting operational criteria	Unsafe plant conditions	4	4	3	**48**	X_{10}
Oxidation of products in storage	Oxidation of tubular products	Rusty material delivered to end customer - customer dissatisfaction	4	4	4	**64**	X_{11}
Equipment stopped due to lack of raw materials	Forklift failure	Use of forklifts with operational failures	2	2	3	12	
SAP system downtime	Stopped production lines	SAP system failures	3	3	3	27	
Oxidation of product while in storage	Oxidation of tubular products	Saline environment due to its coastal location	4	4	4	**64**	X_{12}
Oxidation of product while in storage	Oxidation of tubular products	Strong wind currents	3	3	3	27	

Source: Prepared by the author.

To determine which variables significantly impacted the generation of scrap during the process, the Delphi method, an expert judgment approach, was used to ascertain the possible root causes, as shown in Table 2.

Data related to these 12 variables was collected over 18 months, from July 2018 to December 2019 (see Table 3). Additionally, productivity data for the same period was also gathered.

A correlation test was performed using Minitab 17, with a confidence level of 95%, involving the 12 variables. The test revealed that only variables X_1, X_2, X_3, X_4, X_5, and X_6 exhibited a high correlation with waste generation (Y). Specifically, the Pearson correlation coefficient for these variables is either greater than 0.5 or less than −0.5 and their *p*-values are less than 0.05, as can be seen in Table 4.

As illustrated, the six variables strongly correlated to waste generation (Y) in the initial productivity diagnosis were X_1, X_2, X_3, X_4, X_5, and X_6.

The regression was performed on these variables, excluding those that do not contribute significantly

Table 3. *Data Collection of 12 Variables over 18 Months (July 2018 - December 2019).*

Detail	Month	Productivity (Y)	Trained personnel (X_1)	% Approval of work environment (X_2)	% Deviation from scheduled shut-downs for preventive maintenance (X_3)	% Metallic loss (X_4)	% Customer complaints (X_5)	Observations reported (X_6)	% Variation of planned vs. actual pro-duction costs (X_7)	% Scheduled tons completed on time (X_8)	% Accidents with time loss (X_9)	% Unsafe conditions reported (X_{10})	% Material with oxidation (X_{11})	% Tons placed under observation (X_{12})
Before Implementation	Jul-18	0.77	27.4%	16.4%	23.3%	1.1%	1.1%	31.3%	121.3%	96.4%	13.7%	15.4%	1.1%	2.6%
	Aug-18	0.77	33.3%	22.2%	20.0%	1.0%	0.9%	40.0%	109.3%	85.2%	4.1%	57.1%	1.3%	5.4%
	Sep-18	0.70	31.5%	21.9%	22.4%	0.8%	0.8%	41.9%	107.1%	108.0%	9.6%	23.1%	0.5%	3.1%
	Oct-18	0.76	30.6%	20.8%	23.5%	0.9%	1.0%	28.6%	111.3%	81.5%	5.5%	57.1%	0.4%	2.4%
	Nov-18	0.78	26.0%	15.1%	16.7%	1.0%	1.0%	27.3%	103.5%	71.4%	1.4%	41.7%	1.4%	7.9%
	Dec-18	0.79	26.4%	16.7%	12.5%	1.2%	1.0%	26.7%	101.2%	86.2%	6.8%	30.8%	1.6%	2.3%
	Jan-19	0.82	27.4%	17.8%	14.7%	1.0%	0.8%	32.3%	110.0%	86.7%	8.2%	57.1%	1.0%	0.8%
	Feb-19	1.02	20.8%	11.1%	16.4%	1.0%	0.8%	26.7%	112.5%	87.5%	2.8%	18.2%	0.3%	2.1%
	Mar-19	1.08	30.1%	21.9%	8.6%	0.5%	0.6%	37.0%	102.6%	97.0%	11.0%	30.0%	2.1%	3.5%
	Apr-19	1.01	29.4%	20.6%	9.0%	0.5%	0.6%	35.7%	105.1%	90.6%	4.4%	77.8%	0.6%	2.4%
	May-19	1.06	35.7%	27.1%	8.3%	0.5%	0.5%	52.2%	109.0%	96.9%	5.7%	20.0%	2.5%	2.1%
	Jun-19	1.09	30.6%	22.2%	9.2%	0.6%	0.5%	40.0%	110.4%	88.2%	12.5%	75.0%	0.2%	5.7%
	Jul-19	0.99	37.8%	31.1%	6.0%	0.5%	0.4%	51.9%	110.4%	92.9%	4.1%	55.6%	1.1%	2.1%
	Aug-19	1.09	33.8%	27.0%	8.0%	0.6%	0.5%	50.0%	116.9%	71.0%	2.7%	18.2%	0.3%	0.5%
	Sep-19	1.24	35.3%	30.9%	4.4%	0.5%	0.4%	40.0%	103.9%	96.8%	10.3%	62.5%	0.6%	2.2%
	Oct-19	1.19	31.4%	28.6%	7.0%	0.6%	0.5%	38.5%	110.4%	88.9%	12.9%	66.7%	0.3%	2.9%
	Nov-19	1.24	26.8%	25.4%	5.9%	0.6%	0.5%	37.0%	103.9%	98.5%	4.3%	20.0%	0.8%	2.3%
	Dec-19	1.25	32.9%	24.3%	4.0%	0.5%	0.4%	33.3%	106.8%	90.9%	7.1%	42.9%	0.2%	1.4%

Source: Prepared by the author.

due to high *p*-values. The results yielded an R-squared (R_2) and adjusted R-squared (R_{2adj}) of less than 10%, and the *p*-value of the equation close to 0.05. Figure 2 displays the regression analysis of these variables.

Although the obtained values are optimal, they can be enhanced further by removing X_5 because it has the highest *p*-value. The regression analysis of variables without X_5 is presented in Figure 3.

The following equation was obtained:

$$Y = 0.6137 + 0.113\,X_1 + 0.566\,X_2 - 0.2278\,X_3 - 2.33\,X_4 - 0.0746\,X_6$$

As observed, the variables that need to be addressed to improve productivity in the plant are related to workforce management and equipment knowledge. Therefore, involving employees in daily tasks is essential to improve asset availability, reduce costs, and increase the productive efficiency of the equipment. Although there are various methodologies to improve maintenance management, the decision was made to implement autonomous maintenance as a strategy for continuous improvement.

Hypothesis Testing

After obtaining the results and defining the methodology, the decision was made to implement the management system and monitor the results over the next 18 months. Table 5 presents the data collected for the relevant variables from January 2020 to June 2021, following the implementation of autonomous maintenance

After evaluating the equality of variances (see Tables 6 and 7), it is observed that the average productivity rates before and after implementation differ.

As illustrated in Figure 4, the t-statistic (−9.04) falls within the rejection region, leading to the rejection of the null hypothesis.

Sample data

Variance 1 - 0.035949

Variance 2 - 0.0115399

N_1 - 18

N_2 - 18

Sig. level (α) - 0.05

F_1 critical value - 0.3740

F_2 critical value - 2.6733

Test statistic

$F_{cal} = s1^2/s2^2$

1.- Hypothesis statement

$H_0 = \sigma 1^2 = \sigma 2^2$

2.- Significance level

$\alpha = 0.05$

3.- Test statistic 3.115

5.- Decision - H_0 is rejected

6.- Conclusion

At a significance level of 5%, the variability in the data before and after the implementation of autonomous maintenance is different.

Table 4. *Correlation of Variables.*

Variable	Pearson	*p-value*
X_1	0.8590	0.0000
X_2	0.9640	0.0000
X_3	−0.5830	0.0110
X_4	−0.7100	0.0010
X_5	−0.7330	0.0010
X_6	0.7200	0.0010
X_7	−0.2030	0.4200
X_8	0.1450	0.5660
X_9	0.0630	0.8050
X_{10}	0.2870	0.2480
X_{11}	−0.0660	0.7950
X_{12}	−0.1500	0.5540

Source: Prepared by the author.

Regression Analysis: y versus x1, x2, x3, x4, x5, x6

```
Analysis of Variance

Source      DF    Adj SS    Adj MS  F-Value  P-Value
Regression   6  0.036828  0.006138    43.64    0.000
  x1         1  0.000039  0.000039     0.27    0.611
  x2         1  0.001827  0.001827    12.99    0.004
  x3         1  0.000554  0.000554     3.94    0.073
  x4         1  0.000102  0.000102     0.73    0.412
  x5         1  0.000006  0.000006     0.05    0.835
  x6         1  0.000104  0.000104     0.74    0.408
Error       11  0.001547  0.000141
Total       17  0.038375

Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0118596  95.97%     93.77%      86.50%

Coefficients

Term         Coef  SE Coef  T-Value  P-Value    VIF
Constant   0.6094   0.0423    14.39    0.000
x1          0.099    0.188     0.52    0.611   7.41
x2          0.579    0.161     3.60    0.004   9.51
x3         -0.250    0.126    -1.99    0.073   8.53
x4          -2.85     3.33    -0.85    0.412   7.45
x5           1.33     6.22     0.21    0.835  27.29
x6        -0.0661   0.0768    -0.86    0.408   4.71
```

Figure 2. Regression analysis of variables.
Source: Prepared by the author.

Regression Analysis: y versus x1, x2, x3, x4, x6

```
Analysis of Variance

Source      DF    Adj SS    Adj MS  F-Value  P-Value
Regression   5  0.036821  0.007364    56.88    0.000
  x1         1  0.000058  0.000058     0.44    0.518
  x2         1  0.002031  0.002031    15.69    0.002
  x3         1  0.001340  0.001340    10.35    0.007
  x4         1  0.000143  0.000143     1.11    0.314
  x6         1  0.000182  0.000182     1.40    0.259
Error       12  0.001554  0.000129
Total       17  0.038375

Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0113783  95.95%     94.26%      90.11%

Coefficients

Term         Coef  SE Coef  T-Value  P-Value   VIF
Constant   0.6137   0.0356    17.23    0.000
x1          0.113    0.169     0.67    0.518  6.50
x2          0.566    0.143     3.96    0.002  8.18
x3        -0.2278   0.0708    -3.22    0.007  2.94
x4          -2.33     2.22    -1.05    0.314  3.58
x6        -0.0746   0.0630    -1.18    0.259  3.44
```

Figure 3. Regression analysis of variables without X_5.
Source: Prepared by the author.

Table 5. *Data Collection of Variables over 18 Months (January 2020 - June 2021) After Implementing Autonomous Maintenance.*

Detail	Month	Productivity (Y)	Trained personnel (X_1)	% Approval of the work environment (X_2)	% Deviation from scheduled shut-downs for preventive maintenance (X_3)	% Metal loss (X_4)	% Customer complaints (X_5)	Observations reported (X_6)	% Variation of planned vs. actual production costs (X_7)	% Scheduled tons completed on time (X_8)	% Accidents with time loss (X_9)	% Unsafe conditions reported (X_{10})	% Material with oxidation (X_{11})	% Tons placed under observation (X_{12})
After Implementation	Jan-20	1.31	29.2%	22.2%	3.3%	0.5%	0.3%	45.5%	105.4%	98.6%	1.4%	80.0%	0.1%	1.3%
	Feb-20	1.21	25.7%	18.9%	2.9%	0.5%	0.4%	47.6%	101.4%	98.4%	1.4%	40.0%	0.1%	1.9%
	Mar-20	1.23	29.4%	25.0%	2.0%	0.5%	0.2%	60.0%	101.4%	98.5%	0.0%	50.0%	0.1%	1.6%
	Apr-20	1.33	33.8%	27.9%	2.2%	0.5%	0.2%	66.7%	102.8%	98.6%	1.5%	60.0%	0.1%	1.1%
	May-20	1.39	35.3%	30.9%	2.1%	0.4%	0.1%	92.3%	102.8%	98.6%	0.0%	100.0%	0.1%	1.3%
	Jun-20	1.40	35.7%	35.7%	0.8%	0.5%	0.1%	91.7%	102.9%	98.6%	0.0%	66.7%	0.1%	0.9%
	Jul-20	1.44	31.4%	31.4%	0.3%	0.4%	0.2%	90.0%	102.9%	98.7%	1.4%	100.0%	0.1%	0.6%
	Aug-20	1.48	31.9%	31.9%	0.0%	0.4%	0.1%	87.5%	102.9%	98.7%	0.0%	66.7%	0.1%	1.0%
	Sep-20	1.52	31.1%	29.7%	0.0%	0.4%	0.2%	100.0%	102.9%	98.8%	0.0%	100.0%	0.1%	0.4%
	Oct-20	1.52	38.6%	40.0%	0.5%	0.4%	0.1%	100.0%	102.9%	98.8%	0.0%	100.0%	0.1%	0.2%
	Nov-20	1.52	41.4%	45.7%	0.0%	0.4%	0.1%	100.0%	102.9%	98.8%	0.0%	100.0%	0.0%	0.2%
	Dec-20	1.52	38.6%	42.9%	0.0%	0.4%	0.0%	100.0%	101.5%	98.8%	0.0%	100.0%	0.0%	0.2%
	Jan-21	1.52	44.3%	50.0%	0.0%	0.4%	0.0%	100.0%	102.9%	98.8%	0.0%	100.0%	0.0%	0.2%
	Feb-21	1.52	45.7%	54.3%	0.4%	0.3%	0.0%	100.0%	102.9%	98.8%	0.0%	100.0%	0.0%	0.2%
	Mar-21	1.52	47.1%	57.1%	0.0%	0.4%	0.0%	100.0%	102.9%	98.8%	0.0%	100.0%	0.0%	0.2%
	Apr-21	1.52	50.0%	58.6%	0.0%	0.3%	0.0%	100.0%	101.5%	98.8%	0.0%	100.0%	0.0%	0.0%
	May-21	1.52	54.3%	61.4%	0.0%	0.3%	0.0%	100.0%	100.0%	98.8%	0.0%	100.0%	0.0%	0.2%
	Jun-21	1.52	57.1%	64.3%	0.0%	0.3%	0.0%	100.0%	100.0%	98.8%	0.0%	100.0%	0.0%	0.0%

Source: Prepared by the author.

Table 6. *Equality of Variances (%).*

Before Implementation	After Implementation
0.77	1.31
0.77	1.21
0.70	1.23
0.76	1.33
0.78	1.39
0.79	1.40
0.82	1.44
1.02	1.48
1.08	1.52
1.01	1.52
1.06	1.52
1.09	1.52
0.99	1.52
1.09	1.52
1.24	1.52
1.19	1.52
1.24	1.52
1.25	1.52

Source: Prepared by the author.

Table 7. *Equality of Variances (Decimal Value).*

Detail	Before Implementation	After Implementation
Mean	0.981452599	1.445961934
Variance	0.03594997	0.011539979
Observations	18	18
Pooled variance	0.023744974	
Hypothesized mean difference	0	
Df	34	
t Stat	−9.043360584	
P(T<=t) one tail	7.17E-11	
t critical one-tail	1.690924255	
P(T<=t) two-tail	1.43E-10	
t critical two-tail	2.032244509	

Source: Prepared by the author.

Figure 4. Acceptance region of H_0.
Source: Prepared by the author.

If the p-value is less than the significance level, the null hypothesis is rejected (1.43E-10 < 0.05).

Thus, the alternative hypothesis (H_1) is accepted, the implementation of autonomous maintenance in the electrowelded pipe manufacturing process at the steel manufacturing plant improves productivity.

$H_0 = U1^2 = U2^2$

$H_1 = U1^2 \neq U2^2$

The autonomous maintenance program is initiated using data from the historical records of the pipe mill.

DISCUSSION

All experts reached a consensus on the validation of the autonomous maintenance model. The analysis revealed an acceptable t-statistic value of −9.04 and a *p*-value significantly lower than the significance level (1.43E-10 < 0.05). This supports the null hypothesis and validates the proposed hypothesis. Therefore, this model enhances productivity in companies within the industrial sector. This statement is based on the implementation of lean manufacturing principles and CTQ.

These findings are consistent with those of Anticona and Quiroz (2017), who reported that implementing a progressive maintenance approach in Procter & Gamble’s diaper production plant improved efficiency, reducing the average vertical start-up from 7.1 to 4.0 and maintenance from 45% to 29%. Additionally, Valencia (2016) demonstrated that the use of maintenance management tools at Hilados Cheviot led to increased efficiency and production times, ultimately boosting production by 30%. Finally, the findings are consistent with those of Estrada (2017), who found that the adoption of maintenance management tools effectively reduces vehicle breakdowns and enhances productivity.

CONCLUSIONS

Productivity improved significantly, from 2800 MT (1.24 MT/hour) to 4000 MT (1.79 MT/hour) per month; thus, plant productivity increased from 77% to 152%.

Production staff gained greater knowledge of production equipment and process management.

A substantial portion of the existing waste in the industrial plant was eliminated, which resulted in time savings during process changes, reduced oil consumption, and minimized metal losses.

Competitive capabilities were developed through the industrial processes, empowering employees to take ownership of their production and maintenance roles.

The working environment in the pipe plant was optimized and improved.

Costs were reduced, making the company more competitive and profitable in the market.

A better working environment characterized by clean, orderly, and standardized facilities was achieved.

Unscheduled shutdowns were reduced for a variety of reasons, including improvements in communication and operational efficiency.

The general objective of enhancing productivity was successfully achieved using the two-sample t-test or Mann-Whitney *U* statistical test.

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