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Optimization of the Operations of a Paint Production Plant Applying 5S, Poka Yoke 4.0, and TPM

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Abstract* - Manufacturing SMEs show that unplanned production line stoppages, technical failures, and workplace disorder reduce operational reliability and limit productivity, highlighting the need to apply methodologies that stabilize operations and reduce errors. Operational variability, mechanical failures, and lack of standardization were addressed through a Lean approach integrating 5S to organize and standardize the work area, TPM to increase mean time between failures, and a sensor-based Poka Yoke system designed to prevent input shortages during the injection process. The results were validated through a hybrid model, with on-site implementation of 5S, a laboratory pilot for the digital Poka Yoke system, and an Arena simulation for TPM and the integrated model, respectively. The optimization showed an increase in productivity from 45.75 to 59.77 units per man-hour, mean time between failures increased by 24.87%, unproductive time was reduced by 70.55%, and the 5S index improved by 28%. These findings demonstrate that integrating Lean methodologies with accessible solutions constitutes a viable strategy to increase productivity, reduce variability, and enhance operational reliability in resource-constrained SMEs.

Keywords—Lean Manufacturing; 5S; TPM; Poka Yoke 4.0; Productivity

I. INTRODUCTION.

Processes in the chemical sector that combine manual and automated operations require order, control, and stability to ensure the efficiency of the production flow. The literature shows that the lack of standardization increases unproductive time and rework [1], [2], that the absence of prevention mechanisms facilitates errors [3], and that deficiencies in maintenance increase the recurrence of failures and reduce equipment availability [4], [5]. These conditions increase operational variability and directly affect productive performance.

In the case study, a manufacturing–chemical company dedicated to the production of tempera paints through a semi-automated line produces tempera paints through three stages: container distribution, injection, and final packaging. The diagnosis revealed high unproductive times, mechanical failures, and errors derived from the omission of verification of input availability, which increased cycle variability and reduced productivity in units per man-hour. Operator dependency, the lack of technical documentation, and the continuous nature of the process cause small deviations to generate significant losses.

These observations motivated the intervention of the factors limiting performance. The literature indicates that sustained order reduces unproductive time [1], that error prevention decreases deviations [3], and that structured maintenance reduces failures and unplanned stoppages [4]. Therefore, the use of tools oriented toward order, prevention, and equipment reliability constitutes a viable alternative to improve the efficiency and stability of the line.

The article presents the theoretical foundations supporting the proposal, the applied methodology, and the results obtained. Finally, the implications for processes with similar characteristics are discussed.

II. STATE OF THE ART

A. Application of 5S in industrial and manufacturing production processes

The 5S methodology is based on sorting, order, cleaning, standardization, and discipline, with the objective of optimizing the workstation and eliminating unnecessary activities in manufacturing environments [6]. Its application allows the work area to be structured visually and functionally, reducing unproductive time associated with disorder and the search for materials. The implementation of 5S improves operational efficiency through space reorganization, the definition of locations, and the elimination of non–value-added elements [7]. Likewise, the use of visual management tools reinforces standardization and reduces interruptions in operational activities [8].

In industrial plants, this methodology contributes to reducing downtime and improving the continuity of the workflow [9]. The standardization of workstations and operational discipline strengthen process stability, reducing losses and improving the overall performance of the production system [10].

B. Application of Poka Yoke 4.0 in Manufacturing Processes

Poka-Yoke systems integrated with Internet of Things (IoT) technologies enable the detection of deviations through sensors that continuously monitor process conditions and interrupt operation when parameters exceed established limits. Digital communication, real-time data recording, and automated control strengthen quality assurance by preventing the progression of the flow when material, position, or process values do not meet defined tolerances [11], [12]. This approach extends traditional Poka-Yoke toward cyber-physical configurations with advanced sensing, electronic traceability, and intelligent blocking, reducing technical failures, dimensional deviations, and rework in high-precision manufacturing environments [13].

Likewise, Poka-Yoke 4.0 systems based on digital operator guidance employ visual interfaces and automated verification to ensure the correct selection, sequence, and quantity of components. Systems such as Pick-to-Light and step-by-step confirmation reduce human variability and assembly errors through continuous supervision, achieving significant reductions in defects and unproductive time in assembly operations and repetitive manual work [13], [14].

C. Application of Total Productive Maintenance in Manufacturing Processes

Total Productive Maintenance (TPM) is a key methodology for reducing technical failures, minimizing unplanned stoppages, and improving operational availability in continuous production processes. Its application, through autonomous maintenance, basic inspections, and personnel training, increases process stability and reduces the recurrence of failures, strengthening the overall performance of the production system [15]. Likewise, the elimination of micro-stoppages and the implementation of cleaning routines and systematic monitoring contribute to significantly improving operational continuity and machinery reliability [16]. In processes sensitive to interruptions, a low level of TPM implementation increases failure frequency and compromises the technical sustainability of the production flow [17]. Additionally, the standardization of routines and the use of visual control reinforce technical efficiency and process reliability [18].

The impact of TPM is enhanced when it is integrated within a broader Lean approach. Its articulation with tools such as 5S and SMED makes it possible to reduce unplanned stoppages, improve quality, and stabilize operational flow, especially in environments with high operational variability, recurrent mechanical failures, and long setup times [19].

III. METHODOLOGY / CONTRIBUTION

Figure 1 presents the proposed model, in which three components based on the Lean Manufacturing methodology are defined, oriented toward the fulfillment of the research objectives previously developed. The first component, 5S, consists of reducing unproductive time in the packaging area through order, sorting, cleaning, standardization, and continuous improvement. As the second component, Poka Yoke aims to reduce filling noncompliance through a sensor that enables real-time visualization of barrel volume (IoT). Finally, as the third component, TPM seeks to reduce line stoppages by applying autonomous and preventive maintenance to the machines presenting issues.

However, the selection of the tools is supported by an analysis of the specialized literature. From this review, it is observed that the analyzed studies apply Lean tools in an isolated manner or through partial combinations, without jointly integrating 5S, Poka Yoke, and TPM to address the same operational problem. Likewise, most applications are developed in manufacturing sectors other than the paint industry and evaluate the results of each tool independently. The systematic literature review identifies that there are few studies that integrate these three tools in companies within the manufacturing–chemical sector, which evidences a thematic gap associated with both the industrial context and the integration approach. In this sense, the present study proposes to address this gap through the joint application of 5S, Poka Yoke, and TPM in a productive process of the paint sector.

The systematic literature review identifies that existing research often applies Lean tools in a fragmented manner, overlooking the operational interdependencies in chemical-manufacturing environments. This study addresses a methodological gap by proposing a synergistic framework that integrates 5S, TPM, and Poka Yoke 4.0 as a cohesive system. Unlike isolated applications, this integrated approach focuses on the synchronization between environmental stability, equipment reliability, and real-time digital monitoring. Furthermore, by incorporating an IoT-based sensor for filling control, the model serves as a digital bridge between traditional Lean practices and Smart Manufacturing principles, providing a scalable solution for resource-constrained SMEs. This contribution is further supported by the comparative analysis in Appendix 1, which identifies the lack of integrated 5S-TPM-Poka Yoke models in the chemical-manufacturing literature, reinforcing the relevance of the proposed synergistic approach.

This thematic gap is supported through a comparative analysis presented in Appendix 1, where four studies relevant to the present research are examined. In this appendix, it is evidenced that the relationship between 5S, Poka Yoke, and TPM is partial or nonexistent in the analyzed cases, as well as their limited application in the manufacturing–chemical sector. This comparison allows a structured visualization of the differences in the methodological approach and reinforces the relevance of the integrated model proposed in this study.

A. Proposed Model

The model will be implemented in the object of study mentioned, in which low process productivity has been identified as the main problem.

The integration of Lean tools such as 5S, Poka-Yoke, and TPM constitutes a compatible approach to improve operational stability and reduce waste, as they share principles of order, control, and prevention. 5S and Poka-Yoke are oriented toward environmental standardization and error elimination, and their articulation with TPM strengthens process reliability and operational stability [20]. Likewise, the joint application of 5S and TPM promotes routines of order, cleaning, and systematic inspection that reduce stoppages and improve production continuity in lines where equipment availability is critical [21].

The relationship between 5S and TPM further contributes to reducing operational variability, improving early fault detection, and consolidating autonomous maintenance [22]. Under this approach, the proposed model integrates 5S for area standardization, Poka-Yoke for the prevention of operational errors, and TPM to ensure equipment performance, forming a coherent system that increases order, reliability, and quality of the production process.

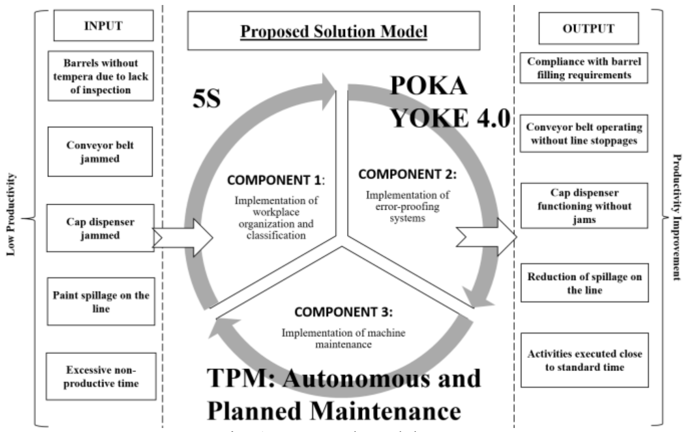

Fig. 1. Proposed Model

B. Model components

Component 1. The process began with a diagnosis by applying the 5S criteria to evaluate the current state of the area through a checklist. In *Seiri* (Sort), all elements that did not belong to the production process were removed. In *Seiton* (Set in order), signage and labels were implemented to streamline the identification of inputs. With *Seiso* (Shine), a specific protocol was established to prevent the accumulation of residues. In *Seiketsu* (Standardize), color-coding and labeling rules were applied to sustainably maintain the first three S. Finally, in *Shitsuke* (Discipline), the results were reviewed and aspects for improvement were defined to consolidate a culture of order and cleanliness in the process.

Component 2. The process begins with the identification of the error in the production process, related to the omission of prior verification of input levels before the start of the injection operation. Based on this diagnosis, a preventive Poka Yoke device is selected, composed of an ESP32 microcontroller and an HC SR04 ultrasonic sensor, intended for filling level control. Appendix 2 presents the Arduino code associated with the HC-SR04 ultrasonic sensor, highlighting its main features and underlying logic, with an average measurement error of 0.073 cm. In addition, the logical design of the system is developed through programming in the Arduino language, and the device is assembled with the corresponding electronic components. Likewise, tests are carried out in a controlled environment under different filling conditions to evaluate system operation, although the potential effects of paint vapors and prolonged exposure on the sensors are not considered. Furthermore, the data transmitted in real time via IoT by the sensor module are analyzed in order to evaluate the performance of the device.

Component 3. The process begins with the technical diagnosis of the machines, identifying the root causes of operational failures. Once these causes are determined, a TPM team is formed to develop maintenance plans for the involved equipment. In addition, autonomous maintenance is proposed through one point lessons, oriented toward standardized routines performed by operators before the start of each shift. To ensure sustainability, operators complete a maintenance log to record each intervention. This log is reviewed every two weeks by the supervisor to monitor compliance with the standardized routines. Likewise, the planned maintenance plan is developed considering three time intervals weekly, monthly, and semiannual, defined according to failure criticality and component wear frequency. Additionally, performance indicators such as MTBF are evaluated, which allow system monitoring and support continuous improvement actions.

The objective of these components is to reduce unproductive time in the packaging area and unplanned line stoppages. Fig. 2 shows the implementation process of the proposed model. It should be noted that both the diagnosis and the validation of the tools were considered separately from the three components.

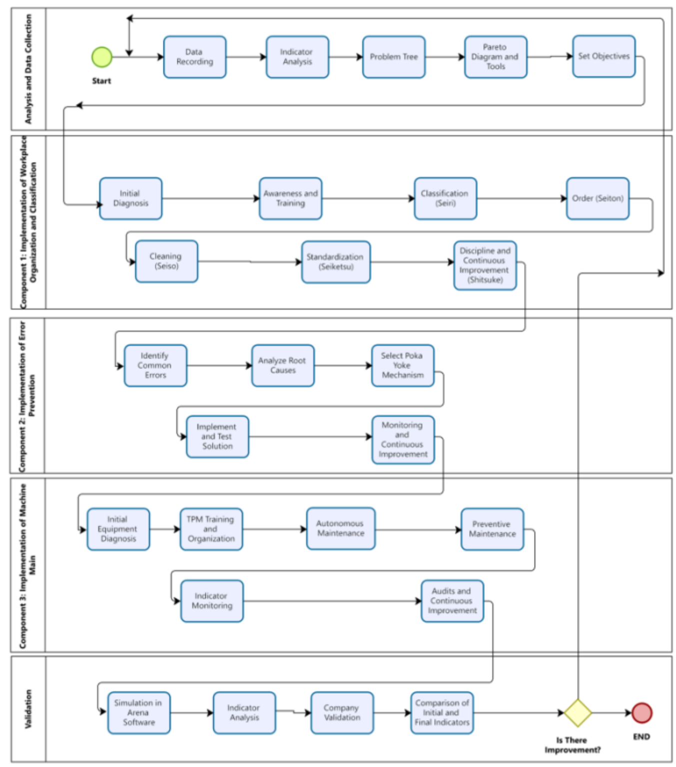

Fig. 2. Proposed Model Process.

C. Indicators

The selected indicators make it possible to effectively characterize the problem, the causes, and their respective root causes.

1) Productivity

Productivity improves when Lean eliminates non value added activities and optimizes flow [23].

$$Productivity = \frac{Packages}{Man{-}Hours} \tag{1}$$

2) Line stoppages (MTBF)

Line stoppages decrease when TPM reduces failures and increases equipment availability [24].

$$MTBF = \frac{\textbf{Total operating minutes}}{\textbf{Number of recorded failures}} \quad (2)$$

3) Unproductive time

Unproductive time decreases when 5S organizes and standardizes the area, reducing searches and operational delays [25].

$$Unproductive\ Time\ = T_{Avail} - T_{Prod} \quad (3)$$

where T_{Avail} is the total available time and T_{Prod} is the actual productive time.

4) 5S Index

Higher 5S compliance ensures order and stable operation with fewer errors [26].

$$5S\ index\ = \frac{Number\ of\ Compliant\ Items}{Total\ Items} \quad (4)$$

5) Filling noncompliance

Activity noncompliance is reduced through Poka Yoke, which prevents deviations in the operation [27].

$$Noncompliance\ Rate\ = \frac{Noncompliance\ Hours}{Total\ Operating\ Hours} \quad (5)$$

D. AS IS and TO BE values

Thus, based on the literature and the identified indicators, the AS IS and TO BE scenarios are defined with the expected and referenced improvement.

TABLE I. AS-IS and TO-BE Values

KPI	As-Is Value	To-Be Value	Expected Improvement (%)	References (Literature)
Productivity	45.47	60.62	33,33%	Based on [3]
MTBF	9.70	12.61	30%	It was obtained from the average of the root causes.
Filling Noncompliance	Sí	No	100%	Based on [3]
MTBF 1	47.91	58.34	21.77%	Based on [28]
MTBF 2	41.43	50.44	21.77%	
MTBF 3	17.22	20.96	21.77%	
Unproductive Time	1.46	0,58	60%	Based on [29]
5S Index	36%	51%	15%	Based on [30]

IV. VALIDATION

The validation was carried out through two pilot tests applied to 5S and Poka Yoke, and an ARENA simulation for the TPM component. Subsequently, a master simulation was executed integrating the results of all previous tests, allowing the joint performance of the tools to be validated in the context of the manufacturing–chemical company.

A. Current Situation

The results of the initial diagnosis evidence a significant technical gap in the productivity of the SET X7 line, which reaches only 43% of its theoretical potential. This loss of efficiency is mainly attributed to line stoppages (85.50%) and unproductive time (14.50%), associated with mechanical failures, operational disorder, and variability in task execution. Among the root causes of line stoppages, filling noncompliance due to lack of control is identified (38.10%), jamming of the cap feeder caused by inadequate lubrication and the presence of plastic residues (10.99%), tempera spillage during capping due to misadjustments and wear (25.65%), and cap ejection due to poor synchronization and residue accumulation on the conveyor belt (10.76%). Regarding unproductive time, the predominant cause corresponds to excessive time in the packaging activity, originating from disorder and lack of classification (14.50%). These inefficiencies generate a direct economic impact of S/. 18,428.87 per semiannual production order and a projected annual cost of S/. 36,857.73, associated with inefficient use of labor and unnecessary electrical energy consumption, as shown in Fig. 3.

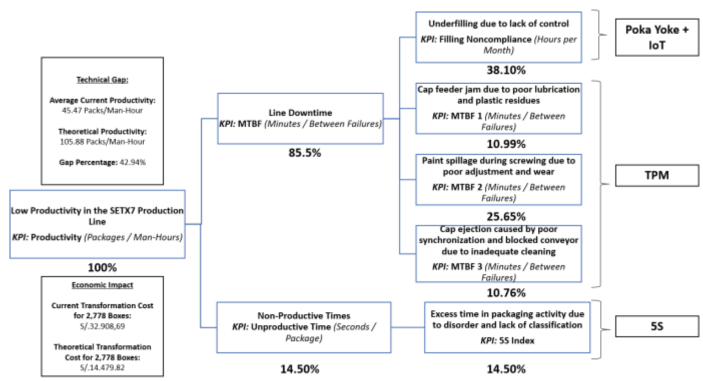

Figure 3. Problem Tree

B. Application of the Proposed Solution

1) 5S Pilot + Simulation

The work environment of the packaging area was reorganized, as shown in Figure 4 and Figure 5, which present the before and after conditions, respectively. In addition, a simulation was conducted to ensure the statistical significance of the scenarios and to validate the impact generated.

Figure 4. Before 5S Implementation

Figure 5. After 5S Implementation

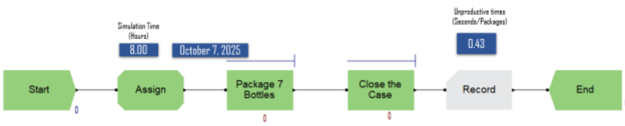

Figure 6. 5S Arena Model

2) Poka Yoke Pilot

It was possible to correctly transmit the tempera content inside a barrel during 3 iterations of 11 tests with different volumes, sending the data to the online dashboard (Arduino Cloud) via IoT with a reduced margin of error.

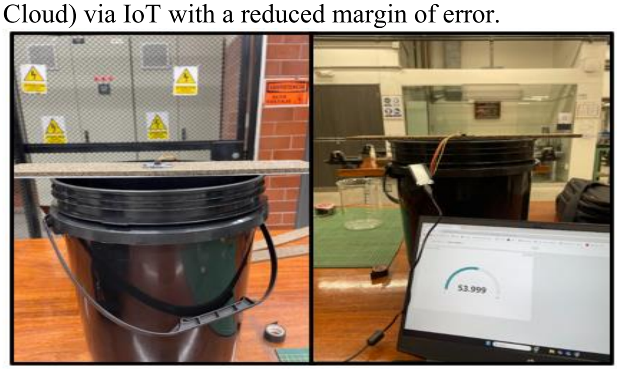

Figure 7. Poka Yoke Pilot

3) TPM Simulation

The input was constructed using all observations recorded during the initial diagnosis, including processing times, line stoppages, and failure frequency, while the improvement scenario was estimated using the reduction percentages reported in the literature from previous studies.

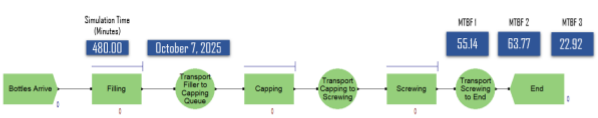

Figure 8. TPM Arena Model

4) Master Simulation

The master or overall simulation used all outputs obtained from the previous validations to determine the overall improvement of the entire SET X7 production line process.

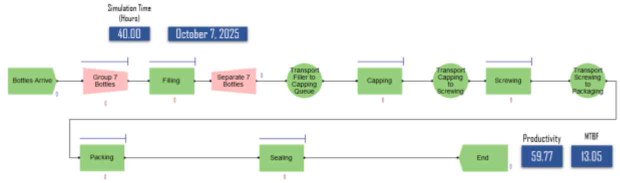

Figure 9. Complete Arena Model

C. Results Obtained

The results obtained from each application are presented considering the previously defined indicators. Likewise, overlap intervals between scenarios are established for the tools that were evaluated through simulation, which allows their stability and consistency to be compared. In the case of the pilot tests, this interpretation does not apply due to their experimental nature. In addition, no overlap analysis was performed for the productivity indicator, since its inputs were obtained directly from the outputs generated by the other simulations and pilot tests, which had been previously validated and did not require additional verification of consistency between scenarios.

TABLE II. Initial and Final Results

KPI	As-Is Value	To-Be Value	Initial Scenario Interval	Final Scenario Interval
Productivity	45.75	59.77	-	-
MTBF	9.70	13.05	169.30 - 181.65	116.66 - 126.36
Filling Noncompliance	14.98	0	-	-
MTBF 1	47.91	63.77	169.30 - 181.65	116.66 - 126.36
MTBF 2	41.43	55.14	169.30 - 181.65	116.66 - 126.36
MTBF 3	17.22	22.92	169.30 - 181.65	116.66 - 126.36
Unproductive Time	1.46	0.43	6.439 - 6.441	5.429 - 5.431
5S Index	36%	64%	-	-

The economic evaluation confirms the feasibility of the model with a cost of capital (COK) of 5.45%. The project recovers its investment in 1.08 years, reaches an internal rate of return (IRR) of 40.33%, and presents a net present value (NPV) of S/ 22,414.57. In addition, its benefit–cost ratio (B/C) of 2.34 shows that it generates more than double the benefits for each sol invested.

V. Discussion

The application of the model made it possible to increase productivity by 30.64%, as defined in (1), as a result of the combined contribution of 5S, TPM, and Poka Yoke. In Cause 1, MTBF, as shown in (2), an improvement of 25.64% was achieved, highlighting the complete elimination of filling noncompliance, where the noncompliance rate, as defined in

(5), was reduced from 14.53% to 0%, and improvements of 24.87% in critical mechanical failures. In Cause 2, unproductive time, calculated in (3), was reduced by 70.55%, while the 5S index, given in (4), increased by 28%, evidencing the effect of standardization on manual tasks.

Relative to the projected values, productivity showed a variation of minus 2.69%, while previous studies report higher increases in similar interventions [3]. In Cause 1, the variation was minus 4.36%, lower than the improvements documented in TPM applications [28]. In contrast, Cause 2 reached plus 10.55%, aligned with studies reporting significant reductions through 5S [29]. Arena simulations confirmed the absence of overlap between confidence intervals, supporting the statistical validity of the observed differences.

The study presents three limitations. First, TPM was evaluated through simulation due to the time required for its real implementation. Second, the Poka Yoke system could only be tested in a laboratory setting due to plant constraints. Third, the diagnosis was based on 28 hours of observation, a limited period to capture process variability. For future research, it is suggested to extend the observation period, test the Poka Yoke system under real operating conditions with its final design, and promote TPM through planned maintenance in order to reduce MTBF variability and strengthen process stability.

The study presents three limitations. First, TPM was evaluated through simulation due to the time required for its real implementation. Second, the Poka Yoke system could only be tested in a laboratory setting due to plant constraints. Consequently, the long-term impact of chemical residues or vapors from the painting plant on the ultrasonic sensor's precision remains to be evaluated, as these environmental factors could induce signal interference or hardware degradation, potentially compromising the system's reliability in a continuous production cycle. Nevertheless, the laboratory results provide a functional proof of concept, establishing a technical baseline for future on-site calibration. Third, the diagnosis was based on 28 hours of observation, a limited period to capture process variability. For future research, it is suggested to extend the observation period, test the Poka Yoke system under real operating conditions with its final design, and promote TPM through planned maintenance in order to reduce MTBF variability and strengthen process stability.

VI. CONCLUSIONS

The implementation of the Lean Manufacturing approach made it possible to optimize productivity on the line, achieving an improvement of 30.64%. This confirms that the integrated model fulfilled its objective and significantly enhanced the operational performance of the system.

The joint application of 5S, TPM, and Poka Yoke clearly strengthened operational indicators. 5S compliance improved substantially, unproductive time decreased markedly by 70.5%, and MTBF showed a consistent increase, reducing the occurrence of critical failures. In addition, the Poka Yoke system completely eliminated filling noncompliance.

The proposal was validated through 5S and TPM simulations, a Poka Yoke pilot test, and an overall simulation that integrated the three tools. The validation confirmed its effectiveness against root causes, evidencing improvements in organization, failures, and process stability. Overall, it is demonstrated that the combination of 5S, TPM, and Poka Yoke is a viable and replicable strategy for optimizing similar manufacturing systems.

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Appendix 1
Comparative table of the components of the Proposal Model vs Literature Review

	Overall equipment effectiveness (OEE) through total productive maintenance (TPM) practices: a case study in chemical industry		Lean-TPM Production Model for Efficiency and Quality Enhancement in the Brewing Industry: Insights from a Peruvian Case Study		Implementing Poka-Yoke in Manufacturing: A Case Study of Tesla Rotor Production		Implementación de estandarización de trabajo, Poka Yoke y 5S para reducir las piezas defectuosas en una empresa del sector joyero		Optimization of the operations of a paint production plant applying 5S, Poka Yoke 4.0 and TPM	
	Agung, F. Y., & Siahaan, A. (2020)		Cerna-Arribasplata, J. A., Rivas-Atauchi, A. M., & Tupia-De-La-Cruz, E. L. (2025)		Goel, G. (2024)		Tippe Sanchez, Nadia Micaela Quispe Tubias, Jhoanna Geraldine (2025)		Alonso Antonio, Lopez-Luna, Santiago, Rejas-Rouillon, Rafael, Chavez-Ugaz & Juan Carlos, Quiroz-Flores	
Component 1: Implementation of Order and Classification in the Work Area (5S)	*Literary Review*	✓	*Literary Review*	✓	*Literary Review*		*Literary Review*	✓	*Literary Review*	✓
	Engineering Tool	✓	*Engineering Tool*	✓	*Engineering Tool*		*Engineering Tool*	✓	*Engineering Tool*	✓
	Case Study	✓	*Case Study*	✓	*Case Study*		*Case Study*		*Case Study*	✓
	Metric		*Metric*	✓	*Metric*		*Metric*	✓	*Metric*	✓
Component 2: Implementation of Error Prevention (POKA YOKE)	*Literary Review*		*Literary Review*		*Literary Review*	✓	*Literary Review*	✓	*Literary Review*	✓
	Engineering Tool		*Engineering Tool*		*Engineering Tool*	✓	*Engineering Tool*	✓	*Engineering Tool*	✓
	Case Study		*Case Study*		*Case Study*	✓	*Case Study*		*Case Study*	✓
	Metric		*Metric*		*Metric*	✓	*Metric*	✓	*Metric*	✓
Component 3: Implementation of Machine Maintenance (TPM)	*Literary Review*	✓	*Literary Review*	✓	*Literary Review*		*Literary Review*		*Literary Review*	✓
	Engineering Tool	✓	*Engineering Tool*	✓	*Engineering Tool*		*Engineering Tool*		*Engineering Tool*	✓
	Case Study	✓	*Case Study*	✓	*Case Study*		*Case Study*		*Case Study*	✓
	Metric	✓	*Metric*	✓	*Metric*		*Metric*		*Metric*	✓
	Total	**7**	**Total**	**8**	**Total**	**4**	**Total**	**6**	**Total**	**12**

Appendix 2

Arduino code for the HC-SR04 ultrasonic sensor

```
#include "thingProperties.h"
#include <NewPing.h>
#include <math.h>

// Pines del sensor ultrasónico
#define TRIG_PIN 12
#define ECHO_PIN 13
#define MAX_DIST 100  // cm (suficiente para sensor + offset)

// Inicialización del sensor
NewPing sonar(TRIG_PIN, ECHO_PIN, MAX_DIST);

// -------------------- Parámetros reales --------------------
const float altura_balde = 30.0;       // cm (altura útil)
const float diametro_balde = 30.0;     // cm
const float radio_balde = diametro_balde / 2.0;
const float offset_sensor = 7.0;       // cm sobre el borde

// Volumen nominal (20 L) y corrección
const float volumen_nominal_litros = 20.0;
const float volumen_teorico_cm3 = M_PI * radio_balde * radio_balde * altura_balde;
const float factor_correccion = (volumen_nominal_litros * 1000.0) / volumen_teorico_cm3;

void setup() {
  Serial.begin(115200);
  delay(1500);
  Serial.println("Sistema Poka Yoke iniciado con ajuste a 20 L exactos.");

  // Inicialización de IoT Cloud
  initProperties();
  ArduinoCloud.begin(ArduinoIoTPreferredConnection);

  setDebugMessageLevel(2);
  ArduinoCloud.printDebugInfo();
}

void loop() {
  ArduinoCloud.update();  // Mantener conexión con la nube

  float d_cm = sonar.ping_cm(); // Lectura desde el sensor

  if (d_cm == 0 || d_cm > (altura_balde + offset_sensor + 5)) {
    Serial.println("⚠ Medición fuera de rango o inválida.\n");
    delay(1000);
    return;
  }

  // Ajuste por offset del sensor
  float altura_agua_cm = altura_balde - (d_cm - offset_sensor);
  if (altura_agua_cm < 0) altura_agua_cm = 0;
  if (altura_agua_cm > altura_balde) altura_agua_cm = altura_balde;

  // Cálculo del volumen ajustado
  float volumen_actual_cm3 = M_PI * radio_balde * radio_balde * altura_agua_cm;
  volumen_actual_cm3 *= factor_correccion;

  // Conversión a litros
  float volumen_actual_litros = volumen_actual_cm3 / 1000.0;

  // Porcentaje sobre 20 L nominales
  float porcentaje = (volumen_actual_litros / volumen_nominal_litros) * 100.0;
  if (porcentaje > 100) porcentaje = 100;

  // Mostrar datos en Serial
  Serial.printf("Distancia medida: %.1f cm\n", d_cm);
  Serial.printf("Altura líquida: %.1f cm\n", altura_agua_cm);
  Serial.printf("Volumen: %.2f L (ajustado a 20 L)\n", volumen_actual_litros);
  Serial.printf("Porcentaje de llenado: %.1f %%\n\n", porcentaje);

  // Enviar dato a Arduino IoT Cloud
  INDICADOR = porcentaje;

  delay(2000);
}
```