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Proposal for the implementation of a TMS 4.0 (IoT), TPM and Standardized Work system to minimize the rejection rate during the distribution of frozen products of a 3PL logistics operator

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Abstract — The frozen food logistics sector faces high rejection rates in 3PL operations due to low equipment availability, the absence of real-time temperature monitoring, and a lack of standardized operating practices. This study employs a quasi-experimental empirical methodology that integrates Total Productive Maintenance (TPM), IoT sensors for continuous temperature monitoring, and the development of standardized work procedures. The results show an annual reduction in rejected orders from 3,142 to 49, an increase in OTIF from 84% to 99.76%, an increase in MTBF to 952 h, and a decrease in MTTR to 0.92 h. The main contribution of the work lies in empirically demonstrating the technical and economic viability of an integrated improvement model for the cold chain in 3PL operators, supported by an NPV of S/ 169,868, an IRR of 36% and a B/C ratio of 7.58.

Keywords — cold chain, TPM, TMS, IoT, industry 4.0, standardized work, logistics

I. Introduction

Previous studies report that frozen product logistics is a critical component of the modern supply chain, as inefficient temperature management directly affects product quality and generates significant economic losses. Evidence shows that approximately 12% of perishable food is lost annually worldwide due to cold chain failures, while in Latin America these losses reach 526 million tons, with an economic impact exceeding US$94 billion [1], [2]. In Peru, this problem is exacerbated by structural limitations of the logistics system, particularly the age of the refrigerated fleet and the low adoption of real-time monitoring technologies, given that more than 90% of vehicles are over ten years old and only 23% have digital temperature control [3], [4]. These conditions compromise thermal traceability and logistical performance, reflected in an average OTIF level of 84% and a rejection rate of 5.12% in the analyzed 3PL logistics operator, mainly associated with operational failures, unsystematic maintenance, and a lack of standardized procedures. To address this gap, this study proposes a TMS 4.0 system integrated with IoT sensors, Total Productive Maintenance (TPM), and Standardized Work (WS), validated through a quasi-experimental empirical approach and a controlled pilot in frozen transport units, providing applied evidence on the integration of Industry 4.0 technologies and Lean methodologies in cold chain management [5], [6].

II. Literature review

The literature on cold chains and logistics of perishable products agrees that loss of thermal control is one of the main causes of waste and rejection of goods, with significant economic and social impacts at the global and regional levels. International reports and recent studies quantify these losses and recommend integrated approaches that combine technology, management, and operational practices to mitigate them. [2][15]

A. Background

In developing countries, deficiencies in infrastructure and thermal control lead to losses of up to 40% of food production [2]. While experimental studies demonstrate that thermal variations reduce product shelf life [3], these studies do not address their interaction with logistics management systems or operational practices, which limits their applicability in contexts characterized by prolonged land transport and high operational variability, such as Peru [4].

From a digitalization perspective, evidence shows low adoption of IoT technologies and a high dependence on manual processes, factors that increase costs and reduce traceability [5][7]. However, the literature reveals a scarcity of studies that integrate advanced TMS platforms with operational standardization mechanisms specifically geared towards cold chain control.

At a regional level, although the use of IoT sensors has been shown to reduce thermal breakdown events [8], [24], [25], these results are mainly obtained in controlled scenarios and do not consider structural constraints such as the age of the refrigerated fleet, which is prevalent in Peru [26]. Similarly, predictive maintenance and staff training show benefits when analyzed in isolation [27][30], but lack joint validation in 3PL logistics operators under real operating conditions.

III. Proposed model

B. Model description

This paper proposes a systemic model that integrates four levers of Industry 4.0: TMS 4.0 (central orchestration platform), IoT sensors (real time thermal/operational monitoring), TPM (reliability and technical availability), and Standardized Work (operational discipline and variability control). The proposal is based on empirical evidence and recent literature [5][15] and is validated through a quasi-experimental design (As-Is vs. To-Be).

C. Model structure

The model is implemented in four sequential phases (see Fig. 1) aimed at addressing the root causes of frozen product rejection through an iterative cycle of continuous improvement: (1) initial analysis, focused on identifying critical points and establishing the baseline (As Is); (2) planning, where objectives, key performance indicators (KPIs) and operational responsibilities are defined; (3) implementation, which integrates IoT sensors, Total Productive Maintenance (TPM) and Standardized Work (WS) and FIFO protocols; and (4) evaluation and feedback, in which the To-Be results are compared with the baseline to validate improvements and make adjustments.

The model's architecture articulates the operational problems identified as system inputs and transforms them into quantifiable results through integrated and sustainable management. The analysis phase identifies thermal breakdowns and maintenance failures with a direct impact on rejections; the planning phase translates these causes into operational goals and KPIs (OTIF, MTTR, MTBF, and FIFO compliance); the implementation phase executes the defined technological and operational solutions, including their integration with TMS 4.0 and staff training; and the evaluation phase consolidates continuous improvement by correcting deviations and updating operational protocols. (see Fig. 1)

D. Analysis of causes and proposed solutions

The initial diagnosis identified four main causes affecting cold chain performance, reflected in a rejection rate of 5.12% and an average OTIF (On-Time In-Full) rate of 84%. Each cause is addressed through a specific technological or operational solution, supported by the integration of TMS 4.0 and IoT sensors, TPM, and Standardized Work (WS). The root causes and mitigation strategies implemented are detailed below. Figure 1 illustrates the general structure of the proposed integrated model and its sequential phases.

1) *Cause 1:* Inefficient cold chain monitoring during transport: Recurring temperature deviations were detected along routes, resulting in loss of traceability and delays in responding to failures, generating a 5.12% rejection rate and 11.5% of routes outside the target range. The average response time to alerts was 35 minutes, and temperature range compliance was 88.5%. Real-time monitoring with IoT sensors and TMS 4.0 is proposed, with targets of <2% out-of-range routes, <10 minutes response time, and ≥98% range compliance. As observed in Figure 2, significant temperature deviations occur during transport, exceeding the acceptable range.

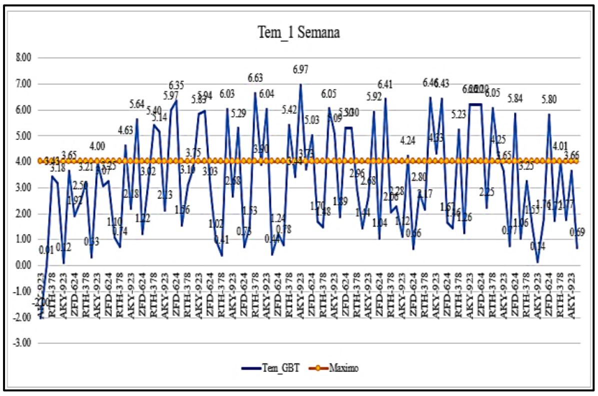


Fig. 2. Temperature control chart recorded at the end of delivery, showing thermal variations above the permitted range

2) *Cause 2:* Trucks without preventive maintenance: The average MTBF was 157.7 h, the MTTR was 5.9 h, and the monthly cost of corrective maintenance reached S/ 4,800, demonstrating reactive management and a lack of structured inspection. The implementation of TPM aims to increase the MTBF to 952 h, reduce the MTTR to 0.92 h, and decrease costs to S/ 2,500, improving the technical availability of the fleet .

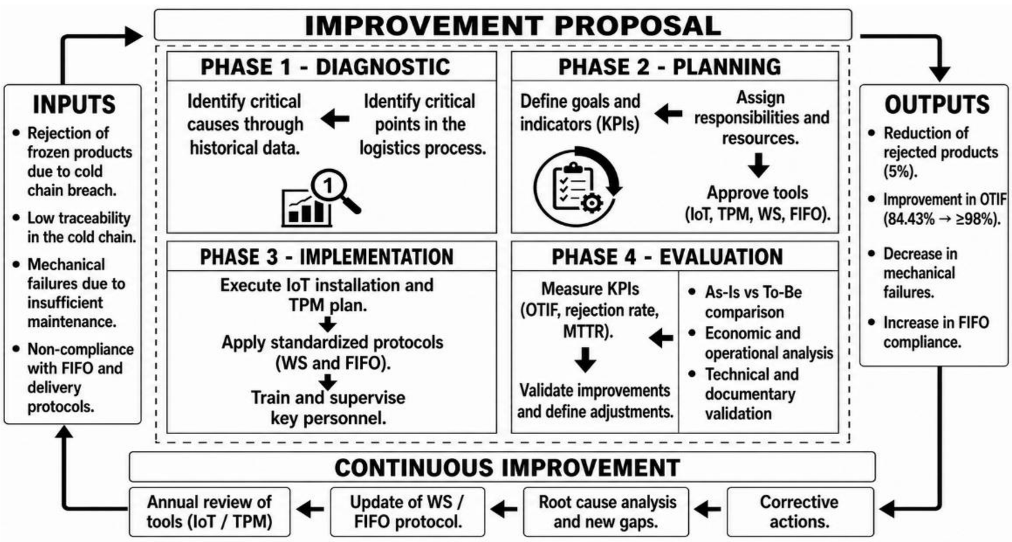


Fig 1. General scheme of the proposed model integrating inputs and outputs within an improvement proposal.

As can be seen in Figure 3, the frequency of reported failures per truck unit reflects the absence of preventive maintenance.

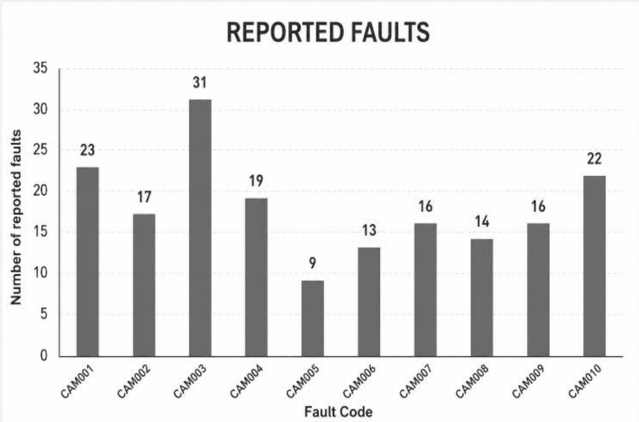


Fig. 3. Failures reported per truck unit during the diagnostic period, showing the high frequency of incidents in the freezing systems and the absence of structured preventive maintenance.

3) Cause 3: Low compliance with the food delivery protocol: 87.93% compliance with the Worksheet was observed, with an average door opening time of 14 minutes 30 seconds and 3.8% rejections due to mishandling. Standardizing processes through Worksheets and training staff will increase compliance to ≥95% and reduce door opening time to ≤6 minutes, minimizing human error and improving traceability. As illustrated in Figure 4, the current delivery process lacks standardization, leading to operational variability.

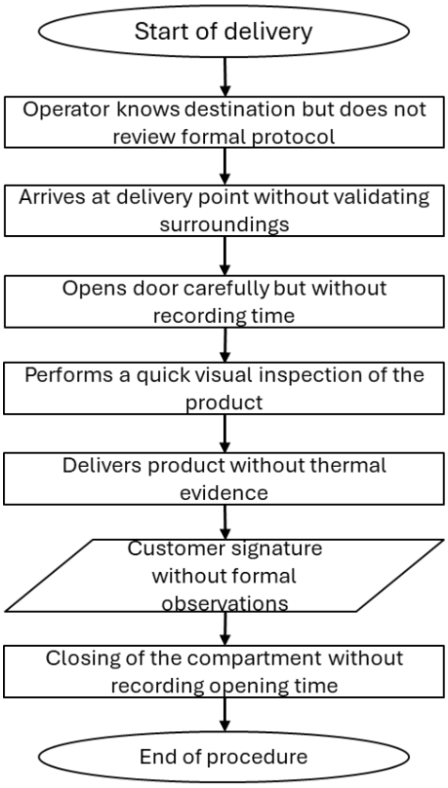
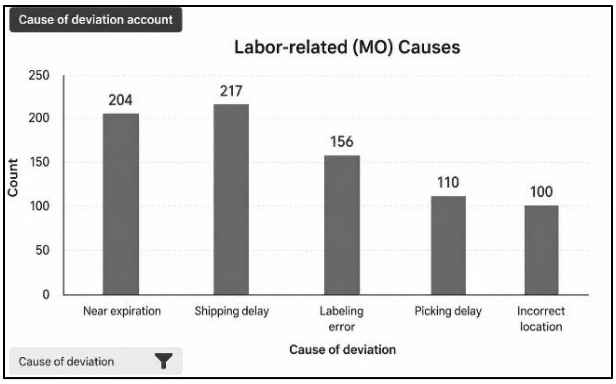


Fig. 4. Representation of the current operational flow under the standardized work scheme (WS) used during product delivery.

4) Cause 4: Poor adherence to FIFO methodology in the warehouse: Only 77.59% of products followed the correct sequence, resulting in 2.7% expired stock and monthly losses of S/ 3,500. Implementing visual controls and WS/FIFO will increase proper rotation to 97%, reduce products nearing their expiration date, and optimize inventory management. As

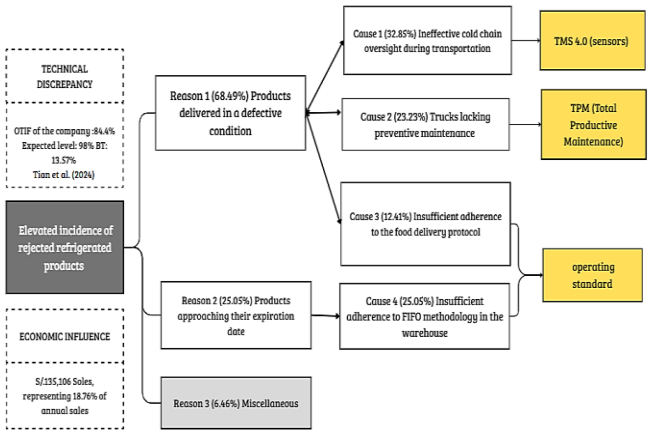


shown in Figure 5, multiple errors occur in the execution of the FIFO method during dispatch operations.

Fig. 5. Number of failures in the execution of the FIFO method during the dispatch process

The diagnosis revealed non compliance with the FIFO method in the dispatch of frozen products, leading to an accumulation of older batches and losses due to expiration. Currently, only 77.59% of shipments adhere to the correct sequence, resulting in 2.7% of products in stock being expired and average monthly losses of S/ 3,500; this situation will be corrected through the implementation of visual controls and a Working Standard, increasing proper rotation to 97%.

As shown in Figure 6, the problem tree is presented



below, where the main reasons and their associated causes are organized.

Fig. 6. Problem tree diagram showing the main root causes and their associated sub-causes affecting cold chain performance and rejection rates in the 3PL logistics operator.

E. *Application of solutions*

A systemic model is proposed that integrates four levers of Industry 4.0: TMS 4.0 (central orchestration platform), IoT sensors (thermal monitoring/door opening/real-time operation), TPM (technical reliability and availability) and Standardized Work WS (operational discipline and variability control).

The proposal is supported by empirical evidence and recent literature [5][15] and is validated through quasi-experimental design (As-Is vs. To-Be).

5) Solution to cause 1: An integrated IoT monitoring system was implemented in the transport units, consisting of temperature sensors (N=3 per truck) and door opening sensors (N=1 per truck), strategically installed inside and outside each vehicle. As illustrated in Figure 7, the proposed IoT-based monitoring system allows for real-time control of transport conditions. These devices perform continuous sampling every 30 minutes, recording real-time thermal conditions and compartment opening or closing events during the journey.

Fig. 7. Architecture of the proposed IoT monitoring system, integrated with TMS 4.0 for real-time data acquisition and control.

The captured information is automatically transmitted to a cloud platform via 4G-LTE connectivity, where more than 2,500 records per unit are stored and processed daily. The data is integrated into the TMS 4.0 (Transportation Management System), which centralizes the visualization and operational control of the fleet through real-time dashboards. This integration enables georeferenced tracking and dynamic control of critical variables from a single interface, accessible to supervisors and technical personnel.

Additionally, a GPS tracker with an accuracy of ±5 meters was incorporated, providing complete traceability of routes and delivery times (Fig. 9). The system generates automatic alerts for temperature deviations outside the established operating range (±2 °C) or unauthorized door openings, immediately notifying those responsible through mobile devices synchronized with the TMS 4.0.

As a result, significant improvements in temperature reports are evident; Fig. 8 compares the As-Is state and the To-Be scenario, showing greater thermal stability and monitoring capacity.

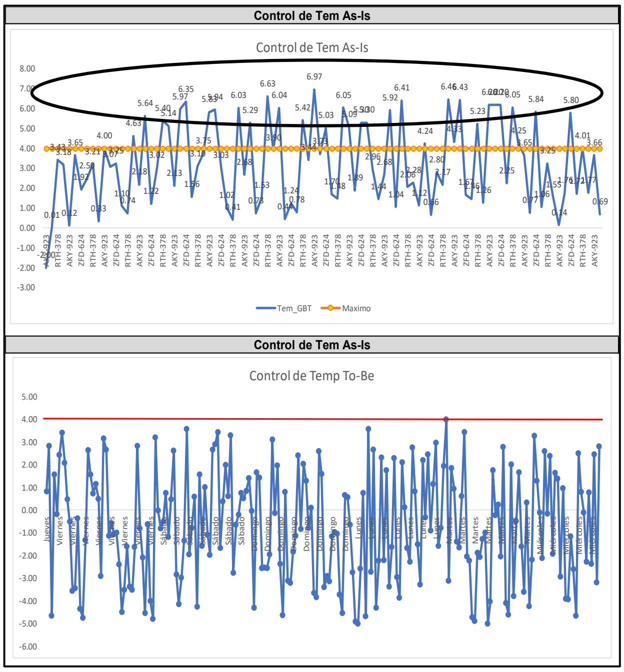


Fig. 8. Comparison of temperature behavior between As-Is and To-Be scenarios, showing improved thermal control and reduced variability.

As can be seen in Figure 9, the integration of GPS tracking provides full traceability of transport units, enhancing route monitoring and control.

Fig. 9. GPS-based traceability of transport units integrated with the TMS platform for real-time monitoring.

6) Solution to cause 2: The lack of preventive maintenance was causing recurring failures in the refrigeration systems and prolonged downtime. To correct this, the Total Productive Maintenance (TPM) methodology was applied, based on the pillars of Preventive Maintenance and Autonomous Maintenance.

In the first stage, a monthly maintenance plan was developed for each unit, defining inspections and replacement of critical components of the refrigeration system in accordance with ISO 14224:2016.

Checklists were implemented to record interventions and facilitate failure analysis. Simultaneously, drivers were trained to perform daily inspections and detect early anomalies, strengthening a culture of prevention.

7) Solution to cause 3: The analysis revealed variability in deliveries due to the absence of formal procedures and standardized records. To correct this, Standardized Work (WS) was implemented, a Lean tool that seeks to standardize critical tasks and ensure product safety during distribution.

The WS established a seven-step operational sequence, from order verification to final customer registration, integrating visual checklists and physical forms. This standard was designed in accordance with ISO 9001:2015 and the health standard DS No. 011-2012-SA, ensuring document control and traceability. As illustrated in Figure 10, the standardized workflow defines a structured sequence of activities to ensure consistency and compliance during delivery operations.

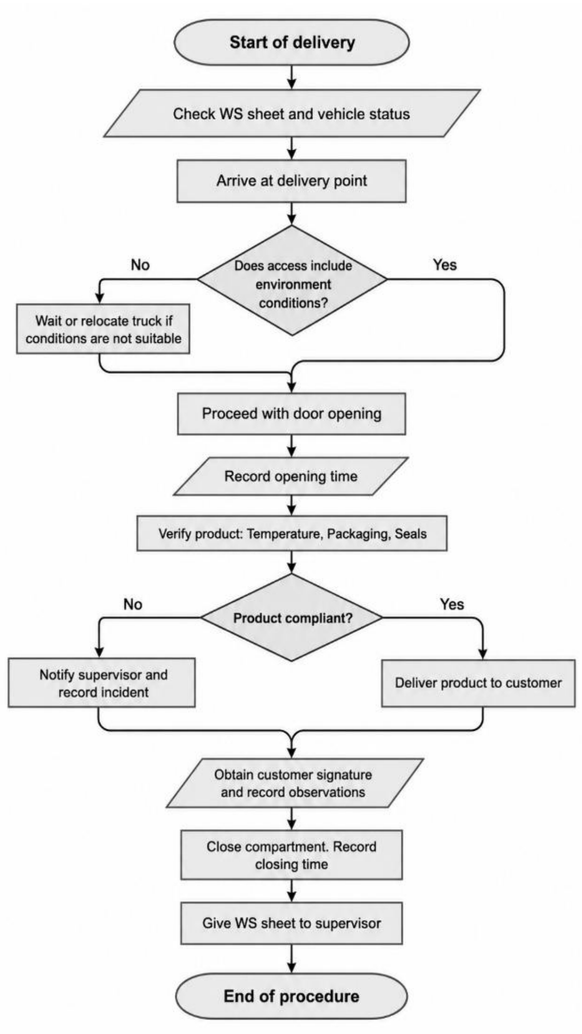


Fig. 10. Proposed standardized workflow (WS) applied to the delivery process, including control points and verification steps

8) Solution to cause 4: Failure to comply with the First In, First Out (FIFO) method resulted in the shipment of products with near expiration dates. It should be noted that the company under study does have the methodology in place, but the operational side does not adhere to it. To mitigate this cause, a visual rotation standard was developed based on the WS approach was developed, as shown in Figure 11, incorporating color-coded signage, control cards, and priority zones according to expiration dates.

The procedure was complemented with monthly training sessions for warehouse staff and weekly audits led by the logistics supervisor, who verified the correct arrangement of batches and compliance with the FIFO sequence.

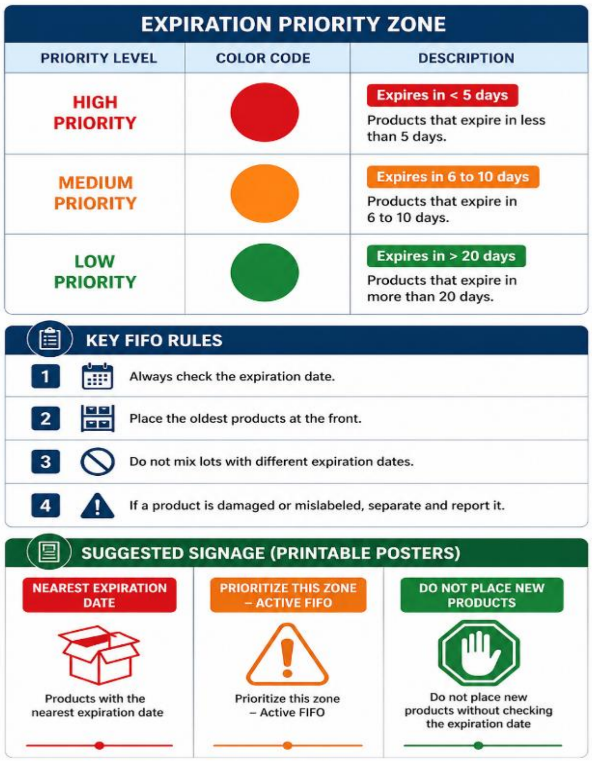


Fig. 11. Control sheets used for recording operating parameters and verifying compliance with FIFO

IV. Validation

The validation of the proposed model was carried out with the objective of verifying its effectiveness under real operating conditions, evaluating the impact of the technological and methodological solutions implemented on the key indicators of the cold chain.

This stage allowed comparing the results obtained during the pilot with the initial values (As-Is), verifying the improvement in thermal traceability, the technical availability of the units, the operational efficiency and the reduction of rejections. Confidence intervals were also calculated to support the statistical robustness of the results.

F. Selection of the validation method

To verify the effectiveness of the proposed model, a controlled operational pilot validation method was selected. This method also incorporates statistical analysis and expert judgment validation, ensuring the reliability of the results.

G. Development of the validation methodology

The validation methodology was organized in successive stages designed to verify the model's performance under real operating conditions. The process was applied to a pilot consisting of three refrigerated transport units, selected according to criteria of representativeness, frequency of operation, maintenance status, type of cargo handled, and assigned routes in order to ensure consistency in the results.

As shown in Figure 12, the validation process follows a structured methodology applied during the pilot implementation under real operating conditions.

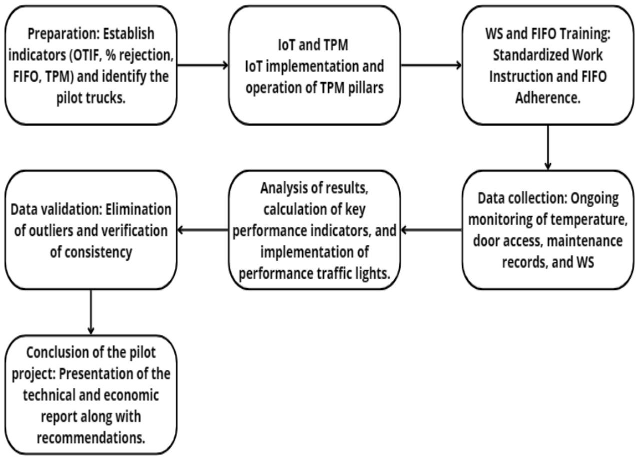


Fig 12. Fig. 12. Validation process applied during the pilot study, including data collection, analysis, and performance evaluation stages.

During the twelve weeks of intervention, a sufficient volume of data was generated to perform statistical analyses with a confidence level of 95% and a power greater than 80%. To evaluate and interpret the impact of the model, comparative metrics and a traffic light system composed of three ranges were used:

(1) Red: Low or substandard performance.
(2) Yellow: intermediate results, in the process of improvement.
(3) Green: optimal compliance according to the established objectives.

The definitions, formulas, and purpose of the indicators used are detailed below.

H. Research indicators

9) Thermal range compliance (OTFR): In the case of perishable foods, organizations such as the WHO (WHO, 2015) and the FAO (Food and Agriculture Organization, 2019) establish that frozen products must be kept at ≤-18°C to preserve safety and prevent deterioration.

$$OTFR = \frac{Records\ within\ the\ \leq -18°C\ range}{Total\ records} \qquad (1)$$

This allowed us to validate the performance of the IoT sensors during the pilot, determining the capacity of the IoT and TMS system to detect thermal deviations, improve traceability and prevent rejections due to temperature non-compliance.

10) Mean Time To Repair (MTTR): In order to find exact measures of repair time in the trucks under study, we used the MTTR indicator, which is a widely used indicator in maintenance and reliability systems.

$$MTTR = \frac{\sum Repair\ time}{Number\ of\ failures} \qquad (2)$$

11) Mean Time Between Failures (MTBF): In order to obtain accurate measurements of the failure time in the trucks under study, we used the MTBF indicator. MTBF is a key indicator in reliability engineering, defined by IEC 60050 and IEEE 1413, used to measure The reliability of a system or equipment. The higher the MTBF, the lower the failure frequency.

$$MTBF = \frac{Total\ operating\ time}{Number\ of\ failures} \qquad (3)$$

12) Delivery Protocol Compliance Index (DPI): We will measure standardized delivery procedures, which are based on Good Distribution Practices (GDP) guidelines and Codex Alimentarius regulations for handling and transport.

$$DPI = \frac{Correct\ deliveries}{Total\ deliveries} x\ 100 \qquad (4)$$

13) FIFO Compliance in Order Preparation and Delivery: To evaluate and optimize food inventory turnover in the warehouse, the OTIF indicator was used, given that the company already implements the FIFO methodology. This study included an analysis of operational FIFO compliance, focusing on potential non-compliance during order preparation and delivery that could affect product integrity and freshness.

$$FIFO = \frac{Correct\ FIFO\ orders}{Total\ orders} x\ 100 \qquad (5)$$

I. Results

Cold chain breaks were reduced from 5.12% to 0.08% thanks to IoT- enabled thermal monitoring and TMS 4.0. Preventive maintenance with TPM increased MTBF from 157.7 to 952 hours and reduced MTTR from 5.9 to 0.92 hours, improving fleet availability. Standardized work procedures raised protocol compliance from 87.93% to 92.41%, decreasing human error, while the correct application of FIFO increased proper stock rotation from 77.59% to 97%, reducing near-expiration products by more than 90%. As shown in Table I, a comprehensive summary of As-Is versus To-Be results is presented below.

Table I presents a comparative summary of the As-Is and To-Be operational results across the four identified causes.

TABLE I
As-Is vs To-Be Results

RESULTS		
Cause 1: Inefficient cold chain monitoring during transport		
Present Value (As Is)	Target Value (To Be)	Present Value (To Be)
5.12%	≥ 1%	0.08%
Cause 2: Trucks without preventive maintenance		
Present Value (As- Is)	Target Value (To -Be)	Present Value (To -Be)
5.9 (MTTR)	≤ 1 h	0.92
157.67 (MTBF)	≥ 800 h	952.78
Cause 3: Poor compliance with the food delivery protocol		
Present Value (As- Is)	Target Value (To -Be)	Present Value (To -Be)
87.93%	≥ 95%	92.41%
Cause 4: Poor compliance with FIFO methodology in the warehouse		
Present Value (As- Is)	Target Value (To -Be)	Present Value (To -Be)
78%	≥ 90%	97%

Taken together, these results validated the effectiveness of the comprehensive model, showing a sustained improvement in all key indicators.

As shown in Table II, the economic losses generated by product rejection before the improvement are detailed below. Reason 1 accounts for the largest proportion, followed by Reasons 2 and 3. Each reason is broken down by specific causes, allowing identification of its direct contribution to the total cost. Table II details the economic losses due to product rejection before the implementation of the proposed model.

TABLE II
LOSSES DUE TO PRODUCT REJECTION BEFORE

REASON 1	**Weight of Reason**	**Amount (S/)**
	68.49%	S/ 91,229.13
Weight Cause 1	32.85%	S/ 43,749.29
Weight Cause 2	23.23%	S/ 30,946.69
Weight Cause 3	12.41%	S/. 16,533.16

REASON 2	**Weight of Reason**	**Amount (S/)**
	25.05%	S/ 33,841.00
Weight Cause 4	25.05%	S/ 33,841.00

REASON 3	**Weight of Reason**	S/ 10,035.87
	6.46%	

As shown in Table III, the losses due to rejection after the improvement reflect a significant reduction in all reasons. Reason 1 decreased drastically, as did Reasons 2 and 3. The distribution by cause confirms the effectiveness of the implemented actions. Table III shows the distribution of economic losses after the implementation, highlighting the reduction achieved.

TABLE III
LOSSES DUE TO PRODUCT REJECTION AFTER

REASON 1	**Weight of Reason**	**Amount (S/)**
	1.16%	S/ 1,570.81
Weight Cause 1	0.54%	S/ 731.00
Weight Cause 2	0.18%	S/ 237.81
Weight Cause 3	0.45%	S/ 602.00

REASON 2	**Weight of Reason**	**Amount (S/)**
	0.38%	S/ 516
Weight Cause 4	0.38%	S/ 516
REASON 3	**Weight of Reason**	**Amount (S/)**
	0.34%	S/ 0.00

As shown in Table IV, the performance of the OTIF indicator reflects the improvement from As-Is to To-Be conditions.

TABLE IV
OTIF SUMMARY

INDICATOR	**As- Is**	**To Be**
Units delivered outside of OTIF	3,142	49
Economic impact (S/)	S/135,106.00	S/ 2,086.81
OTIF FINAL	84%	99.76%

J. Economic impact assessment

With the implemented model, the operation is transformed from reactive and costly to preventive, digitized and controlled, improving the efficiency and traceability of the cold chain.

In quantitative terms, the rejection rate due to cold chain breaks decreased from 5.12% to 0.08%, representing an annual savings of approximately S/ 43,700 in product losses alone. Additionally, rejections due to products nearing their expiration date decreased from 767 to 46 orders, generating savings of S/ 31,000.

From a financial point of view, the investment of S/ 22,421 generated an NPV of S/ 169,868, an IRR of 36% and a B/C ratio of 7.58, confirming the viability and sustainability of the model. The complete before-and-after loss comparison by cause is presented in Table V.

TABLE V
LOSSES DUE TO PRODUCT REJECTION

Cause	**BEFORE (S/)**	**CURRENT (S/)**
Cause 1	S/ 43,749.29	S/ 731
Cause 2	S/ 30,946.69	S/ 237.81
Cause 3	S/ 16,533.16	S/ 602
Cause 4	S/ 33,841.00	S/ 516
Total	S/ 135,106.00	**S/ 2,086.81**

V. DISCUSSION

From a managerial perspective, the findings support investment in digital traceability, preventive maintenance governance, and workforce standardization as complementary not isolated capabilities for cold chain excellence. Future research should validate long-term performance, multi-site deployment, seasonality effects, and predictive analytics extensions for anomaly detection and maintenance forecasting.

The quasi experimental design maintained route structure, fleet type, product category, and service window constant between As-Is and To-Be conditions. Potential confounding factors such as seasonal demand variation, weather, operator learning effects, and prior maintenance condition were monitored as study limitations. Although the pilot covered three trucks in one Peruvian 3PL operator, the model shows practical scalability to larger fleets through modular IoT deployment and centralized TMS orchestration.

A hypothesis-testing framework was applied under H0: the integrated model does not significantly improve operational performance, versus H1: the integrated model significantly improves performance. Comparative weekly observations over 12 weeks were analyzed at a 95% confidence level, reporting statistically significant differences ($p < 0.05$) in rejection rate, MTBF, MTTR, and OTIF. Variability remained controlled, supporting process stability during the pilot.

Additionally, the study has inherent constraints, including a reduced sample size (three trucks), a short evaluation period (12 weeks), and implementation within a single logistics operator, which may limit generalizability.

From a practical standpoint, the model demonstrates scalability potential through modular IoT deployment and centralized TMS orchestration. However, scaling to larger fleets would require additional considerations such as data management capacity, staff training, and maintenance planning.

Future research should validate long-term performance, multi-site deployment, and seasonality effects, as well as explore predictive analytics approaches, including machine learning models for anomaly detection and predictive maintenance, enabling scalable deployment across larger fleets and diverse geographic contexts.

VI. CONCLUSIONS

This paper presents the design, implementation, and validation of a comprehensive model for managing the cold chain logistics in a 3PL company, based on the integration of TMS 4.0 methodology, IoT sensors, Total Productive Maintenance (TPM), and Standardized Work. Experimental results showed that the proposed system reduced the number of rejected orders to 49 per year, compared to the initial scenario, and reduced the total economic impact from S/ 135,106 to S/ 2,086.81, representing a reduction of over 98.4%. Specifically, the model demonstrated a significant improvement in the OTIF indicator, reaching a value of 99.76%, reflecting greater reliability and stability of the logistics service.

The comparative analysis also confirmed a consistent improvement in operational indicators, achieving a reduction in MTTR of 5.90 h to 0.92 h and an increase in MTBF to 952.78 h, in contrast to the values obtained before implementation. This quantitative evidence reinforces the operational robustness and controllability of the proposed model.

Overall, the study confirms that integrating Industry 4.0 technologies with maintenance and standardization methodologies is an effective strategy for managing temperature variations and operational uncertainties in the cold chain. Therefore, the proposed system represents a reliable, scalable, and sustainable alternative for 3PL logistics operations that require a high level of traceability, efficiency, and service quality.

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