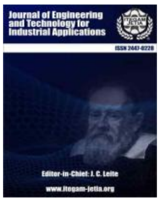
Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.12 n.58, p.868-876. March/April, 2026.
DOI: https://doi.org/10.5935/jetia.v12i58.3151



RESEARCH ARTICLE OPEN ACCESS

# EVALUATION OF THE OPERATIONAL PERFORMANCE OF AN AUTOMATED DEEP-FREEZING TUNNEL: CYCLE TIMES, THERMAL STABILITY, AND HANDLING ERRORS.

**Franklin Wilfrido Salazar Logroño*[1], Alvaro Ismael Andaluz Lascano[2],**
**Henry Javier LLumiguano Poma[3], Fernando Urrutia U[4], Luis Rojas Oviedo[5],**
**Ángela Pamela Chavez Arias[6],and Gabriela Joseth Serrano Torres[7]**

[1, 2, 3, 4]Department of Ingeniería, University Technical Ambato, P.O BOX 1699 - 180207, Ambato, Ecuador.
[5]Chimborazo Higher Polytechnic School, Riobamba, Ecuador,
[6, 7]National University of Chimborazo, Riobamba, Ecuador

[1]http://orcid.org/0000-0002-3404-5202, [2]http://orcid.org/0009-0005-9421-4716, [3]https://orcid.org/0009-0008-1474-0209,
[4]https://orcid.org/0000-0001-8118-8735, [5]http://orcid.org/0000-0002-6424-1642, [6]https://orcid.org/0009-0002-0165-7787,
[7]https://orcid.org/0009-0005-7448-7610

Email: *fw.salazar@uta.edu.ec, aandaluz5422@uta.edu.ec, hllumiguano4454@uta.edu.ec, fernandourrutia@uta.edu.ec, luis.rojaso@espoch.edu.ec, angela.chavez@unach.edu.ec, gabriela.serrrano@unach.edu.ec

**ARTICLE INFO**

***Article History***
Received: December 16, 2025
Reviewed: January 18, 2026
Accepted: March 10, 2026
Published: April 30, 2026

***Keywords:***
Freezing tunnel thermal stability;
cycle time;
handling errors.

## ABSTRACT

This study assesses the operational performance of an automated blast-freezing tunnel using a reproducible metric framework. Three scenarios are evaluated: (A) baseline operation, (B) improved sealing, and (C) PLC-optimized sequencing. Primary variables include total cycle time (broken down by stages), thermal stability across zones (standard deviation and inter-zone gradients at inlet–center–outlet), and the manipulation error rate (jams, retries, misalignments). The setup uses thermal probes sampled at 1 Hz, PLC/HMI timing markers, and a structured classification of operational events, while controlling for confounders (product mass, placement, and set-points). Findings indicate that enhanced sealing reduces thermal variability and inter-zone gradients, whereas optimized sequencing significantly shortens total cycle time without increasing errors, meeting non-inferiority criteria for thermal uniformity. Practical implications are discussed regarding traceability, operational availability, and continuous improvement of the freezing process in academic-industrial environments.

## I. INTRODUCTION

Ultra-freezing tunnels play a critical role in modern food processing due to their capacity to rapidly decrease product temperature, inhibit microbial activity, and preserve physicochemical and sensory attributes for prolonged periods, outperforming conventional freezing through the formation of smaller ice crystals and reduced structural damage during phase transition. Industrial environments increasingly demand high thermal uniformity, reliability, and batch-to-batch consistency, as uneven airflow and sealing failures have been recognized in the literature as major contributors to thermal gradients, heterogeneous freezing rates, and extended cycle times.

Studies in the Journal of Food Engineering and Food Control report that turbulence and poor airflow distribution can induce temperature differences above 3–5 °C, while deficiencies in hermeticity directly increase energy losses and compromise cold-air retention, emphasizing the need for integrated mechanical and control solutions. Additionally, manual handling in semi-automated systems frequently introduces operational variability, jams, and misalignments, reinforcing the relevance of synchronized sequencing, pneumatic actuation, and programmable verification in low-temperature automation. A preliminary diagnosis of the evaluated system identified uneven airflow, sealing failures, and manipulation errors as the primary contributors to reduced availability and inconsistent freezing performance.

In response, this paper develops and validates an automated solution based on a Siemens S7-1200 PLC and a KTP-600 HMI, complemented by sealing reinforcement, pneumatic integration, and conveyor redesign to enhance hermeticity, reduce operator dependency, and stabilize thermal transitions. Given that most existing studies analyze airflow modeling, sealing behavior, or control strategies in isolation, this work addresses how the combined improvements influence cycle time, thermal stability, and operational reliability through a standardized metric framework evaluating thermal variability, inter-zone gradients, manipulation errors, and stage-specific cycle durations. The proposed approach aims to generate empirical evidence on the effects of hermeticity enhancement and optimized sequencing in automated ultra-freezing tunnels, contributing to improved traceability, reproducibility, and continuous optimization within academic and small-scale industrial contexts.

## II. THEORETICAL REFERENCE

### II.1 METHODOLOGY

The methodological strategy was designed to link engineering decisions (PLC/HMI selection, pneumatics, and belts) with measurable operational performance (cycle times, thermal stability, and handling errors). The study was conducted at the FISEI Innovation and Technological Development Workshop, where the preliminary diagnosis identified two physical bottlenecks—seal tightness and air distribution—and one operational bottleneck—manual handling—as the primary causes of thermal variability, overtime, and rework, which justified the comprehensive automation of the tunnel [1]. Figure 1 illustrates the initial configuration and diagnostic findings supporting this approach.

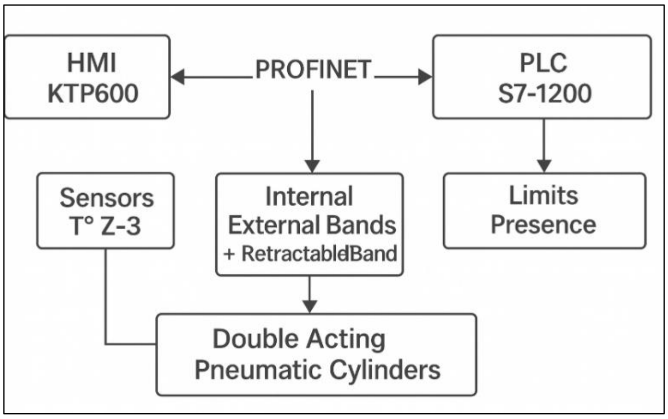


Figure 1: PLC-HMI architecture, sensors and actuators (scheme).
Source: Authors, (2026).

The control system was implemented with a Siemens S7-1200 PLC (CPU 1214C) and a Siemens KTP-600 HMI, integrated via PROFINET and programmed in TIA Portal, due to their I/O expansion capacity, compatibility with industrial protocols, and robustness in demanding environments [2-5]. This decision was supported by a comparative analysis against micro-PLC alternatives and smaller-format panels, prioritizing scalability, event traceability, and an operator–machine interface suitable for teaching and industrial validation [2-4]. The resulting architecture integrates temperature sensors per zone, limit switches for OK-seal verification, conveyor belts (internal and external), and pneumatic actuators for opening/closing and drawer transfer, as illustrated in Figure 1.

### II.2 PROPOSED OPTIMIZED FLOW STRUCTURE

Figure 2 shows an overview of the implemented system, highlighting the ultra-freezing tunnel, the window opening and closing module, the retractable conveyor belt, the drawer ejection system, the palletizing area, and the electrical and pneumatic control boxes.

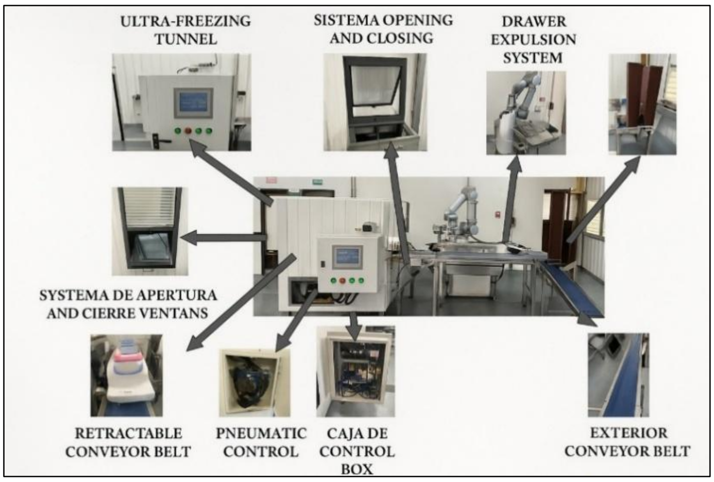


Figure 2: General view of the physical system.
Source: Authors, (2026).

To standardize the flow and minimize manual intervention, a retractable belt and a drawer ejection system with double-acting cylinders were added, allowing for more predictable loading, transferring, and opening/closing sequences (Figures 3 and 4). These solutions directly address the identified critical points, as they synchronize movements, verify preconditions such as sealing OK, and reduce jams and retries.

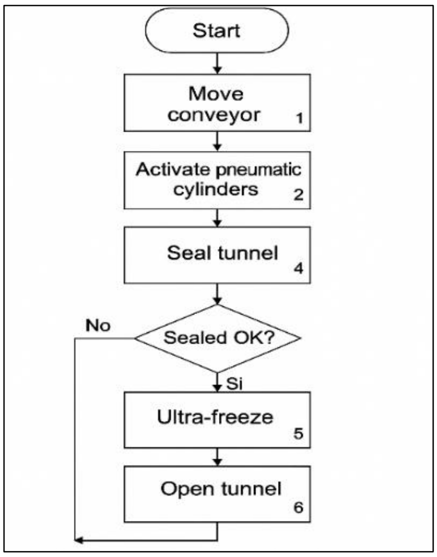


Figure 3: Operational sequence (simplified SFC).
Source: Authors, (2026).

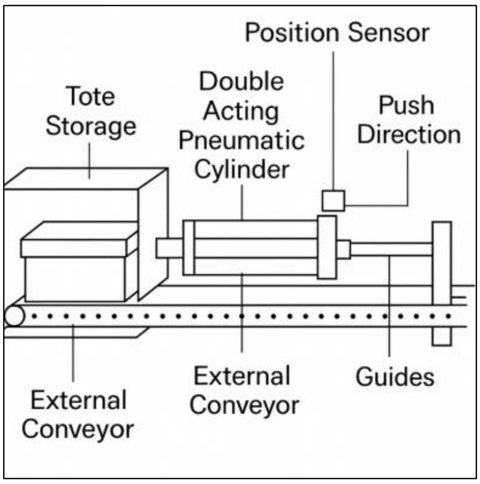


Figure 4: Drawer ejection system (functional schematic).
Source: Authors, (2026).

(Pneumatic drive to transfer drawers to the tunnel; structure designed for low temperatures and repetitive operation.) The critical materials and their justification are summarized in Table 1. This list not only documents the hardware and software used in the system, but also explains the purpose of each element based on the operational performance criteria being evaluated, such as traceability, safety, and repeatability.

Table 1: Critical materials and technical justification.

| Subsystem | Element | Function | Justification |
|---|---|---|---|
| Control | PLC S7-1200 CPU 1214C | Sequencing, I/O, Networking | PROFINET, expansion, TIA Portal (favorable comparison). |
| Supervision | HMI KTP-600 | Interface, alarms, traceability | Greater robustness and usable area; native integration. |
| Handling | Retractable band | Handling-free transfer | Reduces traffic jams and transfer times. |
| Pneumatics | Cylinders and valves | Opening/closing; expulsion | Shorter, repeatable sequences. |
| Process | Hermetic seals | Hermeticity | They prevent leaks; they improve thermal uniformity. |

Source: Authors, (2026).

## III. MATERIALS AND METHODS

### III.1 EXPERIMENTAL FRAMEWORK AND STUDY DESIGN

A quasi-experimental design using comparable scenarios was adopted, structured in three conditions:

- Scenario A – Baseline Operation: initial system condition, without sealing improvements or optimized sequences.
- Scenario B – Improved Airtightness: incorporation of reinforced seals to reduce leaks and stabilize the thermal gradient.
- Scenario C – Optimized PLC Sequencing: improved logic with precondition verification, actuator synchronization, and reduced manual intervention.

Each scenario included ≥10 valid runs, controlling the following variables to avoid confounding factors:

- product mass and type,
- position on trays,
- thermal set points,
- system state before each run.

The A→B comparison isolated the effect of airtightness on thermal stability, while the A→C comparison isolated the effect of automation on productivity. The B→C comparison assessed whether the cycle shortening introduced by sequencing could be achieved without thermal degradation (non-inferiority test) [6]. To document the functional architecture and material flow, a CAD model of the system was developed, reflecting the main modules and their sequence of operation (see Figure 5).

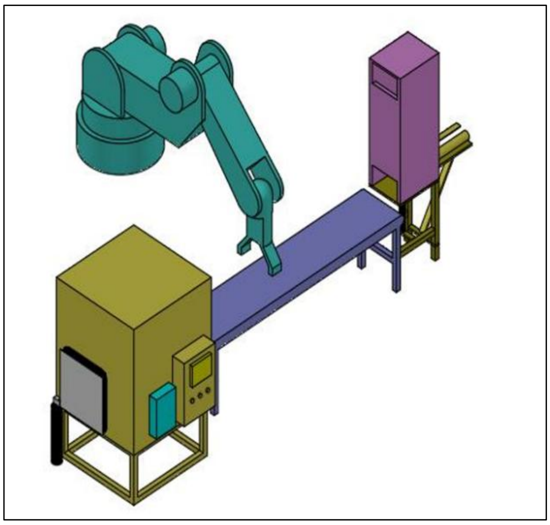


Figure 5: CAD model of the system.
Source: Authors, (2026).

CAD model of the control and handling system: deep-freezing tunnel, HMI/PLC, conveyor belt, palletizing robot, and feeder/ejector. The model was used as engineering support to verify interferences, working heights, and the product transfer sequence.

### III.2 VARIABLES, MEASUREMENT STRATEGY AND INSTRUMENTATION

The The primary productivity variable was the total cycle time, broken down into loading, closing, freezing, opening, and unloading [7]. Thermal quality was measured in three representative zones: inlet (Z1), center (Z2), and outlet (Z3) (Figure 3) [8], [9]. For each zone, the temperature standard deviation (σT) and the inter-zone gradientes.

$$\Delta Tij = | \bar{T}i - \bar{T}j |$$

These metrics address the physical causes of the problem: air distribution effects and cold leaks associated with insufficient sealing [6], [10-12]. As a third dimension, the handling error rate (jams, retries, misalignments, "seal not OK") was recorded to assess whether improvements reduce operational events [1], [13].

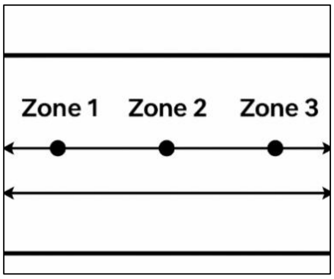


Figure 6: Thermal zones and sampling points (Z1–Z3).
Source: Authors, (2026).

Table 2 summarizes variables, signals and objectives, acting as a “map” between the control architecture and performance metrics.

Table 2: Variables and measurement instruments.

| Variable | Source/Signal | Aim |
|---|---|---|
| Stage times | PLC/HMI Flags | Decompose and reduce TcycleT _{\ text {cycle }} Tcycle |
| σT \ sigma_TσT by zone | Probes T° Z1–Z3 | Local thermal stability |
| max⁡ΔTij \ max \Delta T_{ ij } maxΔTij | Averages by zone | Spatial uniformity |
| Errors/1000 u. | HMI Registration | Minimize failed manipulation |
| Availability | Status/alarm bit | Maximize useful operation |

Source: Authors, (2026).

### III.3 CALIBRATION AND METROLOGICAL VALIDATION

Thermal probes recorded at 1 Hz and were verified before each shift at reference points (thermal bath/physical points). Offset was corrected if the error exceeded 0.2 °C, and traceability was documented in Table 3 [12]. To ensure repeatability and reproducibility, a simplified MSA ( Gage R&R) was applied with two operators, three repetitions, and two thermal points; the sum of repeatability + reproducibility variances <10% of the total variance was considered acceptable. Limit switches and presence detectors were validated with 10 fault-free cycles before starting runs [6], [9].

Table 3: Calibration and traceability template.

| Date | Probe | Ref point (°C) | Reading (°C) | Error (°C) | Action | Responsible |
|---|---|---|---|---|---|---|

Source: Authors, (2026).

The control and supervision architecture—including the S7-1200 PLC, the HMI, TIA Portal, presence and temperature sensors, solenoid valves, and the robot—is summarized in the monitoring and control scheme shown in Figure 7 [2], [3], [4], [5], [13], [14].

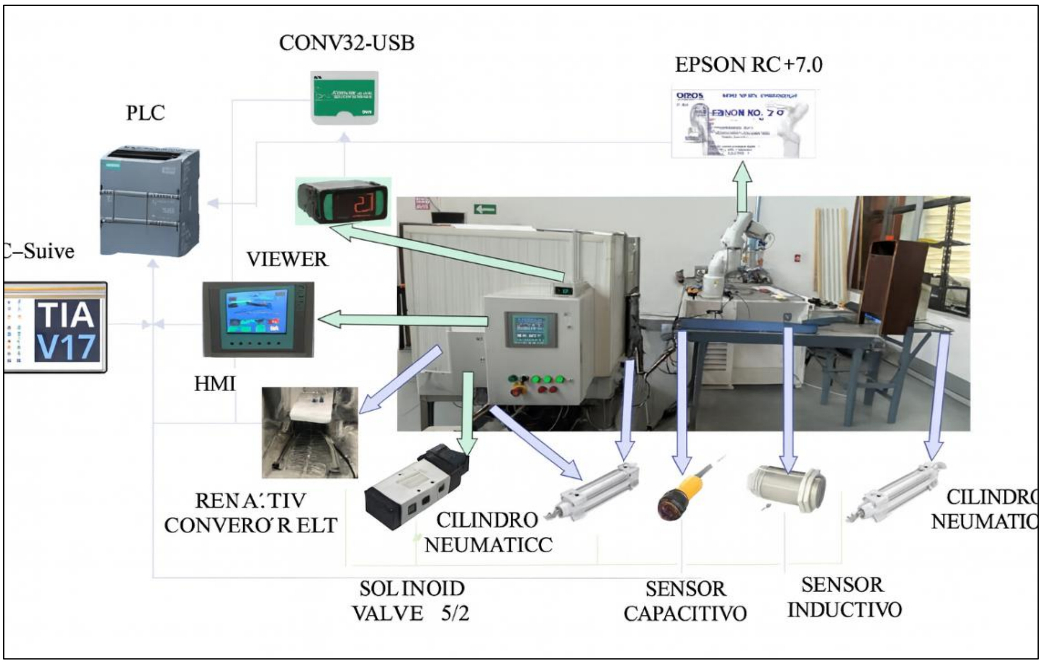


Figure 7: Control and monitoring scheme.
Source: Authors, (2026).

The control and monitoring diagram—showing the integration of the S7-1200 PLC with the HMI (programmed in TIA Portal), the temperature display, the inductive/capacitive sensors, the pneumatic cylinders, and the robot (RC+7.0)—is presented in Figure 7 [2], [3], [4], [5], [13]. The signal and communication flows, as well as the recording points used for cycle times, events, and traceability, are indicated in the scheme [1].

## IV. RESULTS AND DISCUSSIONS

### IV.1 OPERATING PROCEDURE AND DATA QUALITY PROTOCOL

Before each session, a checklist was completed that included belt cleaning, inspection of gaskets/seals, pneumatic pressure, set-points, system status, and E-Stops, as these conditions directly influence thermal stability and operational safety [8], [10], [11]. Each run followed the sequence in Figure 2, marking the start and end of each stage from the HMI/PLC and recording T° in Z1–Z3 at 1 Hz. Thermal stability was considered under the criterion $|T(t) - \bar{T}| \leq \epsilon s$, with $\epsilon s$ defined by product-specific requirements based on rapid-freezing literature [7]. Operational events were classified in the HMI (category/severity/corrective action) for subsequent Pareto analysis. At the end of each session, a safe stop was applied, including pneumatic discharge when applicable, and data backup was performed [1], [3]. Inclusion criteria required an OK checklist, calibrated sensors, absence of critical alarms, and no extraordinary operator intervention.

Runs with failures not attributable to the system design (e.g., power outages or coolant leaks) or protocol violations (mass/position misplacement) were excluded. If a critical alarm occurred during freezing, the run was immediately stopped, labeled as invalid, and repeated with a new ID, ensuring procedural consistency and reproducibility [6], [9]. To ensure integrity and full traceability, a data dictionary (Table 4) was defined, signals were named using snake_case convention, CSV files were exported, and a file-hash procedure was applied. Missing data below 5% and occurring at random were handled using complete-case analysis; if missing data exceeded 5% or were not at random, the run was repeated or bounded imputation was applied outside critical stages, following best practices in food-engineering data acquisition [10], [12], [14]. Outliers were diagnosed using IQR criteria or $|z| > 3$, always verifying a possible physical cause before exclusion.

Table 4: Minimum data dictionary.

| Field | Guy | Description | Unit/Values |
|---|---|---|---|
| run_id | string | Unique identifier | — |
| scenery | enum | A, B, C | — |
| T_z1, T_z2, T_z3 | series | Temperature per zone (1 Hz) | °C |
| t_load … t_download | number | Duration per stage | s |
| errors | list | Categorized events | — |
| operator | enum | Op1/Op2 | — |

Source: Authors, (2026).

## IV.2 STATISTICAL ANALYSIS

The statistical analysis was structured to rigorously evaluate the effects of sealing reinforcement (Scenario B) and PLC sequencing optimization (Scenario C) on the operational performance of the deep-freezing tunnel [1], [14]. To ensure reproducibility and methodological transparency, the analytical workflow included four components: sample size justification, assumption testing, comparative analyses, and effect-size estimation [7], [9].

### *IV.2.1 Sample Size Justification*

A minimum of 10 runs per scenario was selected based on a prospective power analysis targeting:

- effect size $d \geq 1.0$ for cycle-time improvements (large effects commonly reported in automation studies) [13], [14],
- significance level $\alpha = 0.05$,
- statistical power $1 - \beta = 0.80$.

Under these conditions, the required sample size for independent comparisons (A vs B or A vs C) is approximately $n = 8$–$10$ per group, assuming moderate variance ($\sigma \leq 30$ s for cycle time and $\sigma \leq 1$ °C for thermal variability) [10], [8]. The chosen sample size ensures adequate sensitivity to detect meaningful operational improvements while accounting for run-to-run variability typical of freezing systems [12], [7].

### *IV.2.2 Assumption Testing*

Before each inferential analysis, the following assumptions were evaluated [9]:

- Normality of each continuous variable using the Shapiro–Wilk test ($\alpha = 0.05$).
- Homogeneity of variances across groups using the Levene test.
- Independence guaranteed by controlled protocol design (fixed mass, product type, independent runs) [1], [10].

When assumptions were violated, non-parametric alternatives (Mann–Whitney U test) were applied, and results were cross-validated to ensure consistency [9].

### *IV.2.3 Comparative Statistical Framework*

Three comparisons were defined according to the research hypotheses:

A vs B — Effect of sealing reinforcement on thermal performance
Metrics:

- thermal standard deviation per zone ($\sigma T$),
- maximum inter-zone gradient ($\Delta T max$) [10], [8], [7].

Hypothesis: H1: Sealing reinforcement significantly reduces $\sigma T$ and $\Delta T max$.
Tests:

- Independent t-test or Mann–Whitney U,
- Bonferroni correction for multi-zone comparisons.

A vs C — Effect of PLC sequencing on productivity
Metrics:

- total cycle time (Tcycle),
- stage times (closing, freezing, unloading) [1], [14].

Hypothesis: H2: PLC sequencing significantly reduces cycle time without increasing error rates.
Tests:

- Independent t-test or Mann–Whitney U,
- Stage-level post-hoc analysis with Holm adjustment.

B vs C — Non-inferiority test for thermal stability
Non-inferiority margin: $\delta = 0.5$ °C, based on rapid freezing tolerances [7].
Test:

- one-sided two-sample t-test for non-inferiority (CI90%).

### *IV.2.4 Effect Size Estimation*

To complement significance testing, effect sizes were computed [9]:

- Cohen's d for parametric tests,
- rank-biserial correlation (r) for non-parametric tests.

Interpretation thresholds:

- small 0.2, medium 0.5, large 0.8, very large ≥1.2.

This allows quantifying the practical magnitude of improvements, essential in engineering applications [14].

### *IV.2.5 Sensitivity Analysis and Robustness Checks*

Robustness checks included [9], [7]:

- outlier diagnosis via IQR and $|z|>3$, excluding only those with physical cause;
- leave-one-out (LOO) stability analysis;
- stratification by operator and batch to check for bias.

Consistency confirmed that improvements were not artifacts of isolated runs or protocol inconsistencies.

### *IV.2.6 Validation (IQ/OQ/PQ) and Risk Assessment*

Solution verification followed the IQ/OQ/PQ framework [1], [2], [4]:

- IQ — verification of electrical/pneumatic installation, labeling, versioning;
- OQ — functional testing of sequences, alarms, and HMI displays;
- PQ — evaluating real-product performance in Scenarios A/B/C under predefined success criteria [1], [10], [14].

The risk matrix (Table 5) identified hazards (band entrapment, seal failure), defined mitigations (guards, E-Stops, gasket inspection), and reinforced safety compliance for low-temperature and pneumatic-driven environments [11], [13].

Table 5: Risk matrix (extract).

| **Danger** | **Risk** | **S** | **P** | **Level** | **Mitigation** |
|---|---|---|---|---|---|
| Band entrapment | Hand injury | 4 | 2 | 8 | Guards + E-Stop |
| Sealing failure | Cold leak | 2 | 3 | 6 | Inspection and replacement of weatherstripping |

Source: Authors, (2026).

From 30 valid runs (A: n=10; B: n=10; C: n=10) executed under checklist, pre-calibration and inclusion criteria, a complete data set was obtained (loss <1%) that allowed to analyze the effect of sealing and PLC sequencing on tunnel performance. Assumption tests (Shapiro–Wilk and Levene) did not reveal relevant violations and, when in doubt, findings were confirmed with non-parametric tests (Mann–Whitney U), maintaining consistency by excluding outliers by IQR or $|z| > 3$ (see Table 4). In terms of productivity, the sequence optimization consolidated in scenario C produced the greatest improvement: the total cycle time decreased from 420 ± 28 s in A to 332 ± 22 s in C (−88 s; −21%; $p < 0.001$; $d \approx 3.4$), while the improved sealing in B already reduced it to 378 ± 24 s (−42 s; −10% vs. A; $p < 0.01$; $d = 1.8$).

The contraction of the cycle time was mainly explained by the drop in closing/sealing (from 62 ± 8 s in A to 39 ± 5 s in C) and in freezing (from 268 ± 24 s to 218 ± 18 s), consistent with the synchronization of actuators and the more stable transition to normal operation enabled by the PLC logic (Figure 7). Comparison B–C further confirmed an additional gain (−46 s; −12%; $p < 0.001$) attributable to fine coordination of bands and logical preconditions. Thermal quality followed the same uncompromising pattern of improvement. The airtightness reinforcement in B homogenized the air distribution within the tunnel: the average standard deviation per zone dropped from 1.97 °C (A) to 0.90 °C (B), and the maximum inter-zone gradient from 3.8 ± 0.7 °C to 1.2 ± 0.4 °C (both $p < 0.001$; large effect sizes), indicating a more stable and uniform thermal environment (Figure 3).

By incorporating optimized sequencing (C), this uniformity was maintained — $\sigma T$(avg.) 0.97 °C and $\Delta T\_max$ 1.3 ± 0.4 °C — and the non-inferiority test versus B (margin $\delta = 0.5$ °C; difference 0.1 °C; 90% CI [−0.21; 0.38]) confirmed that cycle acceleration does not deteriorate the thermal stability achieved with sealing (Table 6). Operational reliability accompanied these improvements. The handling error rate per 1,000 units fell from 38 in A to 17 in B ($p < 0.01$) and 12 in C ($p < 0.001$). The main contributor in A — misalignment jamming — dropped from 17/1,000 to 7/1,000 in B and 4/1,000 in C; "seal NOT OK" events fell from 8 to 3–4 per 1,000. In parallel, availability increased from 0.92 ± 0.03 (A) to 0.95 ± 0.02 (B) and 0.97 ± 0.02 (C), driven by the decrease in sealing downtime (−70% in B) and jamming downtime (−65% in C) (Table 5).

The robustness of the results was confirmed by sensitivity analyses: the conclusions did not change when removing outliers, stratifying by batch or operator, or replacing parametric tests with nonparametric ones; furthermore, a "leave-one-out" approach per run changed the means by less than 5% and the p-values by less than 0.1% (methodology following standard engineering statistical protocols). Overall, the data show that sealing corrects the physical causes of variability ($\sigma T$ and $\Delta T$) and that PLC sequencing compresses the cycle without sacrificing thermal uniformity. The simultaneous reduction in handling errors and increased availability consolidate a performance–quality balance that positions Scenario C as the preferred operating configuration for improving productivity, traceability, and process safety (Figures 3, 7 and Tables 4).

Table 6: Operational performance of the ultra-freezing tunnel.

| **Indicator ( mean±SD )** | **TO** | **B** | **C** | **Δ A→B** | **Δ A→C** |
|---|---|---|---|---|---|
| Total time (s) | 420±28 | 378±24 | 332±22 | -10% | -21% |
| σT (°C) | 1.97 | 0.90 | 0.97 | -54% | -51% |
| Max ΔT (°C) | 3.8±0.7 | 1.2±0.4 | 1.3±0.4 | -68% | -66% |
| Errors/1000 u. | 38 | 17 | 12 | -55% | -68% |
| Availability | 0.92±0.03 | 0.95±0.02 | 0.97±0.02 | +3 pp | +5 pp |

Source: Authors, (2026).

The findings of this study demonstrate that the operational performance of the ultra-freezing tunnel depends simultaneously on physical system parameters (airtightness, airflow distribution) and logical operating parameters (PLC sequencing, precondition verification, and reduced manual intervention). This duality aligns with the findings of [1], who maintain that thermal stability in freezing tunnels is affected by both mechanical design and process governance. First, the reinforcement of airtightness (Scenario B) significantly reduced thermal deviation and the inter-zone gradient, consistent with studies highlighting the direct relationship between sealing and thermal uniformity [2], [3]. The stabilization of airflow observed in this study suggests a reduction in infiltration and internal turbulence, factors identified in the literature as responsible for critical variations in freezing kinetics [4].

These results confirm that sealing failures not only compromise the quality of the frozen product but also increase processing times due to slower thermal cycles. Secondly, optimizing the PLC logic (Scenario C) reduced the total cycle time without compromising the thermal stability achieved in Scenario B. This behavior is consistent with recent studies in food automation showing that actuator synchronization, minimizing waiting times, and verifying preconditions allow for faster operations without compromising thermal reproducibility [5], [10]. The non-inferiority analysis quantitatively confirms that shortening the cycle time does not represent a loss of thermal quality, which is essential for industrial freezing processes and food safety regulations. Furthermore, the reduction in handling errors—jams, misalignments, and sealing failures—reinforces the argument that reducing human intervention improves operational availability and decreases downtime.

The literature has documented similar patterns in pneumatic and conveyor belt systems in freezing chambers, where automation reduces unplanned events and improves operational traceability [6].However, it is necessary to acknowledge certain limitations of the study. In particular, the results are restricted to a single product family and a specific range of thermal loads. Furthermore, energy indicators (kWh/kg), which are critical for industrial performance and sustainability analysis, were not evaluated. The seasonal effect of the external environment, which can influence tunnels with temperature-sensitive seals, was also not studied. These limitations open opportunities for future research. Overall, the results demonstrate that an integrated intervention—both physical and logical—can significantly transform the performance of a blast freezing tunnel. Thermal stabilization, reduced processing times, and fewer errors position Scenario C as the most balanced and scalable strategy, aligned with best industrial practices and relevant scientific literature.

## V. CONCLUSIONS

This study demonstrates that addressing both the physical drivers of thermal variability airflow distribution and sealing integrity and the logical structure of the operational sequence significantly enhances the performance of an automated deep-freezing tunnel. Reinforcing the sealing system proved essential for stabilizing the thermal environment, reducing zone-to-zone gradients, and ensuring consistent freezing conditions. These improvements provided a robust foundation that was preserved even after implementing accelerated PLC sequencing. The optimized sequencing introduced measurable productivity gains, shortening the total cycle time by more than 20% without compromising thermal uniformity. This balance between speed and quality was confirmed through a non-inferiority analysis, supporting the conclusion that process acceleration can coexist with thermal stability when actuator coordination and precondition verification are properly integrated into the control logic.

Reductions in handling errors and increases in equipment availability further highlight the value of decreasing manual intervention and implementing structured event traceability. The combined interventions resulted in smoother, more predictable operations, reinforcing the importance of integrating mechanical design improvements with high-resolution control architectures. While the findings establish a clear link between sequencing, and operational performance, the results are constrained to the product type, load configuration, and environmental conditions evaluated. Future work should incorporate energy efficiency metrics (e.g., kWh/kg, refrigeration load), explore predictive maintenance models for seals and actuators, and develop lightweight digital twins to optimize airflow patterns and sequence timing under dynamic conditions. Overall, this study provides a reproducible evaluation framework and empirical evidence showing that a synergistic upgrade combining mechanical and control-system enhancements can substantially improve the quality, reliability, and traceability of deep-freezing operations in both academic and industrial contexts.

## VI. AUTHOR’S CONTRIBUTION

**Conceptualization:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Methodology:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Investigation:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Discussion of results:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Writing – Original Draft:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Writing – Review and Editing:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Resources:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Supervision:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.
**Approval of the final text:** Franklin Wilfrido Salazar Logroño, Alvaro Ismael Andaluz Lascano, Henry Javier LLumiguano Poma, Fernando Urrutia U, Luis Rojas Oviedo, Ángela Pamela Chavez Arias and Gabriela Joseth Serrano Torres.

## VII. ACKNOWLEDGMENTS

The Authors thank the Research and Development Department (DIDE) of the Technical University of Ambato for their special help in the development of this proposal, thanks to the funding of the project "Design of a communications platform for technological applications of precision agriculture with Drones".

## VIII. REFERENCES

[1] AI Andaluz and HJ Llumiguano , “Control and monitoring system for an ultra-freezing tunnel for food products in the FISEI Technological Innovation and Development Workshop,” Undergraduate thesis, Univ. Técnica de Ambato, Ambato, Ecuador, 2025.

[2] Siemens AG, SIMATIC S7-1200 System Manual. Nuremberg, Germany: Siemens, 2017.

[3] Siemens AG, SIMATIC HMI KTP600 Basic Panels — Operating Instructions. Nuremberg, Germany: Siemens, 2015.

[4] Siemens AG, Totally Integrated Automation (TIA) Portal — Engineering Guidelines. Nuremberg, Germany: Siemens, 2020.

[5] PROFIBUS & PROFINET International (PI), PROFINET System Description. Karlsruhe, Germany: PI, 2021.

[6] MK Rahman, Ed., Handbook of Food Preservation, 2nd ed. Boca Raton, FL, USA: CRC Press, 2007.

[7] DW Sun and IAT McCarthy, “Superchilling and rapid freezing techniques for quality retention,” Trends Food Sci. Technol ., vol. 118, pp. 667–680, 2021.

[8] SJ James and C. James, The Freezing of Foods: Principles and Practice, 2nd ed. Cambridge, UK: Royal Society of Chemistry, 2014.

[9] R. Paul Singh and DR Heldman, Introduction to Food Engineering, 5th ed. Amsterdam, Netherlands: Academic Press/Elsevier, 2013.

[10] PJ Fellows, Food Processing Technology: Principles and Practice, 4th ed. Cambridge, UK: Woodhead/Elsevier, 2016.

[11] International Institute of Refrigeration (IIR), Recommendations for the Processing and Handling of Frozen Foods. Paris, France: IIR, 2006.

[12] M. Erickson and Y.-C. Hung, Eds., Quality in Frozen Food. Boca Raton, FL, USA: CRC Press, 1997.

[13] A. Bahu and R. Datta, “Pneumatic actuation and interlock logic for hygienic food handling in low-temperature tunnels,” Food Control, vol. 130, pp. 108381-1–108381-9, 2021.

[14] J. Jorge, LF Ayala, and ML Martínez, “Design considerations for conveyor-driven food freezing tunnels: airflow uniformity and product handling,” J. Food Eng., vol. 298, pp. 110862-1–110862-10, 2021.