

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Conceptual Design and Validation of an Industry 4.0-Oriented Retrofit Strategy

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Masters in Mechanical Engineering: Manufacturing

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Abstract

Fluctuations in ambient temperature and relative humidity within automotive spray booths disrupt paint viscosity, solvent evaporation rates, and electrostatic deposition. In legacy brownfield plants, air handling units often rely on decoupled heating and humidification controls paired with discrete manual sampling, causing unmonitored environmental drift. This study presents an operational retrofitting framework to stabilize microclimatic conditions in existing paint booths without replacing primary HVAC infrastructure. To guide the investigation, three core research questions were formulated: (1) to what extent does environmental humidity variability affect top-coat defect rates; (2) how can capital-constrained engineering management systematically prioritize technical retrofit requirements when historical data is sparse; and (3) can a non-linear thermal-fluid simulation provide sufficient risk-management value to evaluate control boundaries prior to physical deployment?

It was hypothesized that relative humidity stabilization significantly suppresses climate-sensitive surface defects, that combining diagnostic FMEA with technical-economic matrices effectively ranks execution requirements under budget constraints, and that a lumped-parameter psychrometric model captures transient dynamics sufficiently to guide control design. The methodology combines empirical shop-floor diagnostics, statistical process control (SPC), dynamic physical modeling, and cost evaluation. Analysis of baseline operating data from an active top-coat line revealed relative humidity non-compliance reaching 86% of monthly readings during seasonal transitions. Laney U' control charts handled defect data overdispersion ($\sigma^2 \gg \mu$), while Pearson correlation analysis confirmed strong dependencies between mean booth temperature and paint sagging ($r = 0.788$, $p < 0.01$), as well as relative humidity and overspray rate ($r = -0.654$, $p < 0.05$).

To correct these control gaps, an upgraded architecture was defined using continuous ATEX-certified instrumentation, variable-frequency pump actuation, and coordinated PLC logic. Lumped-parameter moist-air modeling in MATLAB/Simscape validated the physical plausibility of the control logic, demonstrating that coordinated regulation eliminates transient humidity drops caused by sensible air heating under seasonal extreme boundaries. Financial evaluation confirmed that the primary project return stems from defect risk mitigation and process repeatability rather than direct utility reduction. The results support all three hypotheses, providing a reproducible decision-support framework for modernizing environmental controls in legacy manufacturing facilities.

Keywords: Automotive paint booth • FMEA • Brownfield automation • Humidity control • Process stabilisation • Industrial retrofit • PLC integration

Resumo

As flutuações de temperatura ambiente e humidade relativa em cabines de pintura automóvel alteram a viscosidade da tinta, a cinética de evaporação dos solventes e a deposição eletrostática. Em instalações industriais existentes (*brownfield*), as unidades de tratamento de ar dependem frequentemente de controlos desacoplados de aquecimento e humidificação, combinados com amostragens manuais discretas, resultando em desvios ambientais não monitorizados. Este estudo apresenta uma metodologia operacional de *retrofit* para estabilizar as condições microclimáticas em cabines de pintura existentes, sem necessidade de substituir a infraestrutura principal de AVAC. Para orientar a investigação, foram formuladas três questões centrais de investigação: (1) até que ponto a variabilidade da humidade ambiental afeta as taxas de defeitos no *top-coat*; (2) como pode a gestão de engenharia, sob restrições orçamentais, priorizar sistematicamente os requisitos técnicos de *retrofit* quando os dados históricos são reduzidos; e (3) poderá uma simulação térmico-fluídica não linear fornecer valor suficiente em gestão de risco para avaliar os limites de controlo antes da implementação física?

Hipotetizou-se que a estabilização da humidade relativa reduz significativamente os defeitos superficiais sensíveis ao clima, que a combinação do FMEA de diagnóstico com matrizes técnico-económicas hierarquiza eficazmente os requisitos de execução sob restrições orçamentais, e que um modelo psicrométrico de parâmetros concentrados captura adequadamente a dinâmica transiente para orientar o projeto de controlo. A metodologia combina diagnósticos empíricos em chão de fábrica, Controlo Estatístico do Processo (SPC), modelação física dinâmica e avaliação de custos. A análise dos dados operacionais de referência de uma linha de *top-coat* em exploração revelou que o incumprimento da humidade relativa atingiu 86% das medições mensais durante as transições sazonais. As cartas de controlo U' de Laney trataram a sobredispersão dos dados de defeitos ($\sigma^2 \gg \mu$), enquanto a análise de correlação de Pearson confirmou fortes dependências entre a temperatura média da cabine e o escoamento de tinta ($r = 0,788$, $p < 0,01$), bem como entre a humidade relativa e a taxa de sobrepulverização ($r = -0,654$, $p < 0,05$).

Para corrigir estas lacunas de controlo, foi definida uma arquitetura otimizada recorrendo a instrumentação contínua com certificação ATEX, atuação de bombas por variador de frequência e lógica coordenada de PLC. A modelação de ar húmido por parâmetros concentrados em MATLAB/Simscape validou a plausibilidade física da lógica de controlo, demonstrando que a regulação coordenada elimina quedas transientes de humidade provocadas pelo aquecimento sensível do ar sob condições limites de extremos sazonais. A avaliação financeira confirmou que o retorno principal do projeto provém da mitigação do risco de defeitos e da repetibilidade do processo, em detrimento da redução direta do consumo de fluidos industriais. Os resultados apoiam as três hipóteses, fornecendo uma estrutura reprodutível de apoio à decisão para a modernização do controlo ambiental em instalações fabris existentes.

Palavras-chave: Cabine de pintura automóvel • FMEA • Automação *brownfield* • Controlo de humidade • Estabilização do processo • *Retrofit* industrial • Integração de PLC

The United Nations Sustainable Development Goals

The United Nations SDG provide a global framework for addressing social, environmental and economic challenges. In the scope of this dissertation, the most relevant contributions are indirect and are related to industrial process stability, safer operation, infrastructure modernisation and improved resource awareness in a legacy automotive paint booth.

SDG	Target	Contribution	Indicators / Metrics
8	8.2	Supports industrial productivity by improving process stability, reducing manual/reactive control and strengthening environmental control capability.	Relative humidity stability; out-of-specification frequency; reduction of manual interventions.
9	9.4	Contributes to the modernisation of legacy industrial infrastructure through monitoring, automation, PLC/HMI integration and data traceability.	Number of monitored variables; implementation of automatic control architecture; availability of historical data.
12	12.2 / 12.5	Supports more responsible production by enabling better control of water use, maintenance needs and future reduction of rework or material waste.	Water quality monitoring; pump operation data; energy/water indicators; future defect or rework comparison.

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Luísa Soares de Oliveira Costa Mendes

Declaration of Honour

I declare that this dissertation is my own work and has not previously been submitted or assessed at this or any other institution. References to other authors (statements, ideas, thoughts), as well as the use of published works, strictly comply with the rules of attribution and are duly identified in the text and in the bibliographic references, in accordance with the applicable referencing standards. I am aware that the practice of plagiarism or self-plagiarism constitutes an academic offence, as established in the U.Porto Code of Ethics.

I also declare that I have used Artificial Intelligence tools (Perplexity, Gemini, and ChatGPT) to complete part of this dissertation. The use of these tools was limited to technical support, specifically for the structuring and formatting of LaTeX tables, generation of code for data visualization (MATLAB/Python) and syntax optimization. I declare that the results were carefully checked for errors, inaccuracies, and biases. All theoretical foundation, critical analysis, results and conclusions are original and of my sole authorship, having been validated and integrated manually into this document.

Porto, July 5, 2026

Luísa Soares de Oliveira Costa Mendes

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Abbreviations and Symbols

ASU	Air Supply Unit
ATEX	ATmosphères EXplosible
ANDF	Architecture-Neutral Distribution Format
ASU	Air Supply Unit
CBR	Cost-Benefit Ratio
HVAC	Heating, Ventilation and Air Conditioning
IPA	Investment Project Analysis
BIW	Body-In-White
CAD	Computer-Aided Design
CKD	Completely Knocked Down
LC70	Land Cruiser 70
MRL	Manufacturing Readiness Level
SMD	Sauter Mean Diameter
SPC	Statistical Process Control
PLC	Programmable Logic Controller
RH	Relative Humidity
TCAP	Toyota Caetano Portugal
TME	Toyota Motor Europe
TRL	Technology Readiness Level
UCL	Upper Control Limit
LCL	Lower Control Limit
UV	Ultraviolet Radiation
VFD	Variable Frequency Drive

Chapter 1

Introduction

1.1 Industrial Context and Motivation

Automotive painting represents one of the most critical and energy-intensive stages in modern vehicle manufacturing, directly dictating corrosion resistance, aesthetic finish quality, and macroscopic process stability. Within manual electrostatic spray application, the physical and cosmetic repeatability of the deposited wet film is highly sensitive to the immediate thermodynamic parameters of the paint booth microclimate. Variations in dry-bulb temperature and relative humidity alter solvent evaporation rates, modify paint fluid rheology, influence atomized droplet transport efficiency, and impact the continuous dissipation of static charges. Consequently, tight environmental control is mandatory to suppress process non-conformities.

This dissertation was developed in partnership with Toyota Caetano Portugal at the Ovar manufacturing plant (Figure 1.1a), specifically embedded within the assembly and top-coat painting sequence of the Toyota Land Cruiser Series 70 production line (Figure 1.1b).



(a) Toyota Caetano Portugal Ovar plant



(b) Land Cruiser 70

Figure 1.1: Industrial context

The project is physically framed within the assembly and painting infrastructure of Toyota Caetano Portugal in Ovar [1]. While the plant transitions toward smart manufacturing platforms and navigates the emerging paradigms of Industry 5.0 [2], aligning legacy brownfield equipment with updated interoperability standards remains a critical requirement for modern automotive

ecosystems [3]. The targeted manufacturing environment consists of a manual electrostatic mono-coat application booth supplied by two independent parallel Air Supply Units (ASU1 and ASU2). These dual air handling systems filter, sensibly heat via indirect gas-fired burners, and adiabatically humidify 100% fresh outdoor intake air before directing it to the paint application zones.

The underlying motivation for this research stems from the systemic challenges of achieving environmental stability within a legacy brownfield infrastructure. Currently, the humidification process relies on manual, binary (ON/OFF) operational decisions with highly restricted instrumentation tracking. Under shifting seasonal and intra-shift atmospheric conditions, microclimatic deviations are difficult to track, interpret and correct systematically. This operational vulnerability creates an uncompensated gap in manufacturing process capability, justifying a structured approach toward modernization.

1.2 Problem Statement

Automotive coating quality depends heavily on booth microclimate stability. Temperature and relative humidity directly influence solvent evaporation rates and paint rheology, making environmental control a critical process variable rather than a simple facility utility.

The paint booth under analysis relies on legacy brownfield infrastructure that lacks continuous measurement, data traceability, and standardized control logic. As a result, the system cannot maintain the target environmental conditions required for repeatable coating deposition.

This instability is systemic: ageing humidification hardware, uncoordinated heating-moisture loops and a reliance on manual, low-frequency measurements create significant process variance. Operators are forced to rely on subjective interventions to counter environmental drift, a practice that undermines manufacturing repeatability, prevents effective root-cause troubleshooting, and restricts data-driven quality control.

This dissertation addresses the following core engineering challenge:

How can a legacy automotive paint booth be retrofitted to establish an automated environmental control baseline, improving process stability and quality, without replacing the existing capital-intensive air supply infrastructure?

1.3 Research Objectives, Questions and Hypotheses

The primary objective of this dissertation is to develop an operations-driven engineering framework to design, evaluate, and conceptually assess a brownfield environmental retrofit within a legacy industrial manufacturing line. The project focuses on transitioning from reactive, operator-dependent practices to an automated process-monitoring and control baseline, balancing strict capital expenditure constraints with the quality requirements of liquid coating application.

To establish a rigorous scientific methodology at the interface of manufacturing operations management and materials process engineering, this research addresses three core research questions, each associated with an objective, testable hypothesis:

1. *To what extent does environmental humidity variability significantly affect the overall quality performance and defect rates within the painting booth?*

Hypothesis 1 (H_1): The stabilization of relative humidity within a controlled process window establishes a repeatable application environment that significantly reduces the frequency of climate-sensitive surface defects compared to legacy manual operations.

2. *How can capital-constrained engineering management systematically prioritize technical retrofit requirements when historical manufacturing data and direct causal evidence are sparse?*

Hypothesis 2 (H_2): A structured combination of diagnostic Failure Mode and Effects Analysis (FMEA) and technical-economic trade-off matrices can successfully identify and rank brownfield execution requirements under explicit project budgetary constraints, acting as a decision-support mechanism rather than an absolute causal proof.

3. *Can a simplified, non-linear thermal-fluid simulation provide sufficient risk-management value to support engineering design decisions and evaluate paint rheology boundaries prior to physical deployment?*

Hypothesis 3 (H_3): A non-linear, lumped-parameter psychrometric representation is sufficient to capture transient sensible heating and evaporative cooling trends, defining the operational boundaries necessary to evaluate temperature-dependent paint viscosity fluctuations and expected coating performance scenarios without requiring full industrial commissioning.

By systematically evaluating these questions and testing these hypotheses in a simulation environment, this dissertation establishes a reproducible framework for manufacturing managers to modernize legacy assets while safeguarding the physical consistency of materials processing.

1.4 Scope and Limitations

This research focuses on the environmental monitoring and humidity regulation of the top-coat paint booth at Toyota Caetano Portugal. The engineering scope is limited to the psychrometric air treatment pathway of ASU1 and ASU2, the associated instrumentation, and the definition of the control logic.

The project encompasses the following milestones:

- Mapping the current AS-IS system layout through on-site field audits.
- Analyzing historical environmental data and its correlation with defect rates using statistical process control.
- Prioritizing technical dependencies and failure modes using a diagnostic FMEA.

- Defining the TO-BE architecture, including sensor selection, VFD-controlled pump requirements, safety interlocks and PLC algorithms.
- Profiling capital investment and operational cost scenarios.
- Developing a Simscape-based physical model to make an engineering assessment of the thermodynamic trends of the proposed control logic.

To ensure the project remains feasible within the constraints of active brownfield manufacturing, the following items are excluded:

- Full infrastructure replacement, detailed component supplier engineering and final procurement-level execution drawings.
- Physical installation, real-time industrial commissioning of the PLC network, and post-implementation hardware tuning, as these fall outside of the dissertation's timeframe and factory uptime requirements.
- Quantitative validation of factory defect reductions or predictive modeling of coating flow, as the existing low-frequency data baseline is insufficient for micro-level causal modeling.

1.5 Methodology

This dissertation follows a disciplined, sequential engineering framework tailored to brownfield industrial optimization, executing a cyclical progression from field diagnosis to conceptual design and simulation-based assessment.

The operational research is executed across four main sequential phases:

1. **Empirical System Diagnostics:** Direct shop-floor mapping (Gemba observation) and interviews with plant maintenance, quality, and manufacturing engineering personnel are combined with low-frequency historical environmental data. This phase targets compliance checking against process specifications and establishes a baseline under real factory layout constraints.
2. **Risk and Data Prioritization:** The diagnostic insights are structured using exploratory statistical indicators, correlation assessments, and an adapted Failure Mode and Effects Analysis. This methodology isolates high-priority requirements based on severity and control gaps, ensuring the subsequent engineering focus is directed toward systemic errors.
3. **Conceptual Design and Specification:** The prioritized gaps are translated into quantitative TO-BE design targets. This phase covers fundamental psychrometric calculations, energy-mass balances, instrumentation strategies, automated control loop algorithms, safety interlock definitions, and scenario-based investment evaluation.

4. **Simulation-Based Engineering Evaluation:** To verify the physical plausibility and conceptual validity of the integrated proposal, a lumped-parameter moist-air network simulation is built using the MATLAB/Simscape environment. This model evaluates the transient cross-coupling between sensible heating and evaporative cooling under representative boundary loads, closing the engineering assessment loop prior to hardware deployment.

1.6 Dissertation Structure

The structural design of this dissertation is organized into six interdependent chapters, tracking the logical progression of the engineering framework:

- **Chapter 1 Introduction:** Outlines the industrial background, formalizes the problem statement, introduces research hypotheses, defines operational boundaries and details the framework methodology.
- **Chapter 2 — Literature Review:** Establishes the academic and technical foundation of the research, reviewing fluid deposition dynamics, electrostatic application parameters, psychrometric air conditioning physics, statistical quality assurance tools, and industrial automation architectures.
- **Chapter 3 — Process Analysis and AS-IS Diagnosis:** Presents the empirical baseline analysis of the Toyota Caetano plant, compiling SPC trends, correlation assessments, field audit measurements, and the diagnostic FMEA.
- **Chapter 4 — TO-BE Proposed Solution:** Details the engineered retrofit strategy, including mass-energy balances, hardware selection boundaries, multi-variable control algorithms, safety requirements and the investment scenario profiles.
- **Chapter 5 — Simulation-Based Engineering Assessment:** Documents the configuration, mathematical assumptions, and boundary test scenarios of the Simscape physical simulation model, reviewing the thermodynamic plausibility of the proposed loop responses.
- **Chapter 6 — Conclusions and Future Work:** Summarizes the main scientific, industrial, and technical contributions, evaluates the research hypotheses, states execution limitations and outlines the strategic roadmap for future deployment.

Chapter 2

Literature Review

2.1 Literature Review Methodology

The literature review was structured to identify the main technical domains supporting the dissertation: automotive coating processes, electrostatic spray application, environmental influence on coating quality, paint booth HVAC, process stability, solvent based paintings and control for painting booth and they were conducted in databases such as SCOPUS, ScienceDirect, IEE Explore and Web of Science.

2.1.1 PRISMA Review

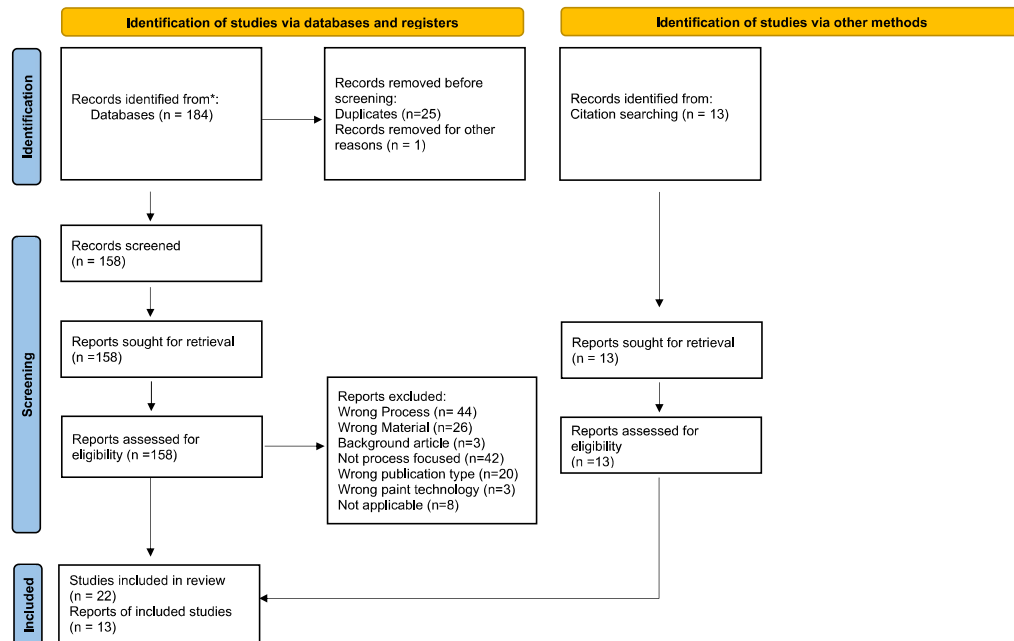


Figure 2.1: PRISMA 2020 systematic literature mapping flow diagram [4].

The literature review, in Table 2.1 establishes the technical basis for analysing environmental control in a legacy automotive paint booth. It first reviews automotive coating and electrostatic spray application, with emphasis on how temperature, relative humidity and airflow influence coating stability. It then addresses paint-booth HVAC and psychrometric control, process diagnosis and prioritisation methods, and sensor-based retrofit strategies for improving monitoring and control in legacy industrial systems.

Table 2.1: PRISMA synthesis matrix of studies retained after full-text screening.

Study	Domain	Main contribution	Relevance to this research
Akafuah et al. [5]	Automotive coating	Reviews coating-layer evolution, process sequence, curing stages and common defect mechanisms.	Frames topcoat application as a multi-stage process sensitive to material, equipment and environmental conditions.
Pendar et al. [6]	Paint-shop process	Reviews paint-shop layout, coating materials, application technologies and curing requirements.	Supports the role of booth temperature and humidity as process variables affecting rheology, atomisation and film formation.
Poozesh, Akafuah and Saito [7]	Spray application	Analyses spray mechanisms and process factors affecting transfer efficiency.	Supports the need for stable spray and electrostatic application conditions in manual topcoat operations.

Continued on next page

Table 2.1: PRISMA synthesis matrix (continued).

Study	Domain	Main contribution	Relevance to this research
Randall [8]	Solvent coating	Discusses solvent-based coating processes, transfer efficiency and pollution-prevention strategies.	Contextualises coating performance, ventilation and environmental control as interdependent booth functions.
Lee and Cho [9]	Coating quality	Quantifies the influence of spray distance, application method and process parameters on film thickness and gloss.	Shows that coating quality can be related to measurable application and booth-condition variables.
Almansoori et al. [10]	Manual painting	Shows that manual spray-painting quality is affected by process parameters and operator-induced variation.	Supports stabilising controllable booth conditions to reduce non-controlled variability in manual application.
Lou and Huang [11]	Quality control	Develops a hierarchical decision-support approach for proactive automotive coating quality control.	Supports prevention-oriented monitoring instead of relying only on final inspection.
Sakinah et al. [12]	Coating defects	Investigates blistering as a multi-factor defect influenced by moisture, process parameters and operating conditions.	Supports humidity monitoring and control as relevant to moisture-sensitive coating defects.
Alt and Sawodny [13]	Booth HVAC control	Develops model-based control for coupled temperature and humidity dynamics in a paint-booth HVAC system.	Provides a theoretical basis for treating temperature and relative humidity as coupled control variables.
Guan et al. [14]	Booth air conditioning	Evaluates liquid-desiccant air-conditioning for large spray-paint booths, considering humidity and energy performance.	Supports active humidity control in enclosed painting environments and highlights energy implications.
Kaminski et al. [15]	Ventilation diagnosis	Uses temperature-based information to diagnose and balance supply and exhaust airflow.	Demonstrates the value of sensor-based diagnosis for ventilation and air-handling systems.
Su et al. [16]	Humidity-control technology	Reviews dehumidification technologies and compares efficiency, applicability and operating constraints.	Provides a reference for positioning humidity-control technologies according to industrial requirements.
Giampieri et al. [17]	T/RH conditioning	Evaluates heat-recovery and liquid-desiccant air-conditioning strategies in automotive paint shops.	Supports analysis of environmental conditioning as both a process-control and energy-performance issue.
Sadeghipour et al. [18]	HVAC energy control	Analyses paint-booth HVAC energy use and proposes control strategies considering finish quality and energy demand.	Shows that booth control strategies can be assessed through both quality and energy-performance criteria.
Davarpanah et al. [19]	VOC treatment	Studies the influence of temperature and relative humidity on VOC adsorption efficiency.	Extends T/RH relevance from coating application to exhaust-treatment performance.
Feng and Mears [20]	Paint-shop energy	Models HVAC energy consumption in automotive paint shops under different air-handling scenarios.	Supports considering booth conditioning as a major contributor to paint-shop energy demand.
Giampieri et al. [21]	Manufacturing energy	Reviews energy consumption in automotive manufacturing and identifies paint shops as highly energy-intensive areas.	Frames paint-shop environmental control as a relevant target for energy-efficiency and modernisation.
Rivera and Reyes-Carrillo [22]	Energy and environment	Proposes a framework for analysing environmental and energy performance in automobile painting.	Supports structured assessment of improvement opportunities in painting operations.
Roelant et al. [23]	Sustainability assessment	Assesses automotive painting from energy, environmental and economic perspectives.	Supports evaluating paint-process improvements beyond isolated technical performance.

Continued on next page

Table 2.1: PRISMA synthesis matrix (continued).

Study	Domain	Main contribution	Relevance to this research
Kim [24]	VOC emissions	Reviews VOC emissions from solvent-based automotive painting and related control technologies.	Contextualises solvent-based booths as systems linking process control, ventilation and compliance.
Kluczek and Gladysz [25]	Decision support	Applies multi-criteria decision methods to rank environmental improvement options in painting.	Supports structured prioritisation when translating diagnostic findings into improvement actions.
Sanz et al. [26]	Industry 4.0 paint shop	Presents a paint-shop Industry 4.0 framework based on sensors, communication and real-time data management.	Supports the transition from isolated measurements to sensor-based monitoring and diagnostic capability.

2.2 Literature Review Discussion

Based on the final selection of the sources validated through the PRISMA 2020 protocol, this review synthesizes the state of the art in automotive painting. The literature is structured into three thematic pillars: coating rheology and microclimate interaction, psychrometric energy requirements, and operational decision-making in digitalized environments. By confronting foundational mechanical studies [5, 8] with contemporary Industry 4.0 frameworks [26], this section exposes the research gap between idealized high-fidelity models and the reality of brownfield operations.

2.2.1 Coating Rheology and Quality Stability

The interaction between spray booth microclimates and fluid film formation represents a complex thermodynamic problem. Early foundational work by Randall [8] established that environmental control is an interdependent booth function, a premise further refined by Akafuah et al. [5] and Pendar, Páscoa, and Moreira [6], who detail the transition toward multi-layered processing and automated rheological control.

While Poozesh, Akafuah, and Saito [7] and Lee and Cho [9] demonstrated that coating quality is highly sensitive to measurable spray distance and transfer efficiency, Almansoori et al. [10] highlight that manual painting introduces operator-induced variability often ignored in theoretical models. The critical limitation of these frameworks is their reliance on deterministic baselines. This gap was evidenced by Wan Hamzah et al. [12], whose empirical study of multi-factor blistering revealed that industrial practice struggles with dynamic environmental drift, a reality also acknowledged by Sadeghipour, Westervelt, and Bhattacharya [18] in their assessment of finish quality versus operational demand.

2.2.2 Psychrometric Air Treatment and Energy

Sustainable environmental control necessitates an energy-intensive infrastructure. Giampieri et al. [21] and Feng and Mears [20] identify paint shops as dominant utility consumers, while Roelant, Kemppainen, and Shonnard [23] and Rivera and Reyes-Carrillo [22] emphasize the need for

holistic sustainability assessments.

To mitigate these demands, recent literature proposes technological interventions: Giampieri et al. [17] and Guan, Liu, and Zhang [14] evaluate heat-recovery and liquid desiccant systems, while Su et al. [16] compares advanced dehumidification constraints. However, these frameworks often overlook the transient risks identified by Davarpanah et al. [19], where uncompensated humidity surges degrade VOC adsorption efficiency, a process also tied to solvent emission compliance as reviewed by Kim [24]. The methodological divergence persists: while Alt and Sawodny [13] and Kaminski et al. [15] provide strong model-based control bases, their implementations often assume steady-state conditions, ignoring the transient cross-coupling inherent in legacy Air Supply Units.

2.2.3 Operational Decision and Industry 4.0 Feasibility

Modern control architectures seek to bridge the physical-digital divide through cyber-physical systems. Sanz, Blesa, and Puig [26] propose frameworks centered on edge computing and predictive diagnostics; however, these models encounter significant limitations in real-world application. Lou and Huang [11] demonstrate that the predictive accuracy of AI-driven quality systems degrades sharply under data-sparse conditions.

This creates a persistent methodological disconnect: while cutting-edge Industry 4.0 frameworks [26] prioritize continuous, high-frequency telemetry, legacy facilities require robust, low-data-intensity decision tools. Approaches such as those proposed by Kluczek and Gładysz [25], which utilize multi-attribute decision-making (AHP/TOPSIS), offer a conceptual pathway for ranking improvement options. Yet, these methods often remain confined to static administrative prioritization, failing to provide the dynamic, physics-based diagnostic depth required for real-time process stabilization.

2.2.4 Research Gap

The systematic confrontation of these twenty-two primary sources exposes three core scientific contradictions that define the current research gap:

1. **Material vs. control decoupling:** Existing literature often bifurcates the field into either macro-process overviews [5, 7] or micro-climate HVAC control modeling [13, 14]. There is a lack of integrated frameworks that bridge the gap between HVAC transient control overshoot and the resulting rheological film formation defects on the vehicle surface.
2. **Greenfield vs. brownfield paradox:** Dominant thermodynamic and digital frameworks [17, 26] presuppose extensive capital expenditure and high-fidelity sensor density. These approaches implicitly exclude the instrumentation scarcity and fiscal constraints inherent in legacy brownfield operations [10, 25].

3. **Diagnostic depth vs. operational integration:** While proactive quality tools [11] provide macro-level priority indexing, they remain uncoupled from the physics-based transient simulations required to evaluate operational risk. Consequently, there is an absence of methodologies that synthesize root-cause diagnostic findings [12] into actionable, low-CAPEX operational risk metrics suitable for constrained production environments.

This dissertation bridges this gap by utilizing an adapted FMEA calibrated for data-sparse operations, bypassing the greenfield requirements of Sanz, Blesa, and Puig and addressing the defect variability identified by Wan Hamzah et al. Despite these developments, current literature lacks robust modeling approaches that integrate the transient cross-coupling between environmental variables, highlighting a critical gap in maintaining process safety margins

2.3 Automotive Coating Process

Automotive painting is a critical manufacturing process because the coating system must provide corrosion protection, surface appearance, weather resistance and long-term durability [5, 6, 27]. The paint shop typically includes several stages, such as pre-treatment, electro-coating, primer or surfacer application, topcoat application and curing, depending on the product, coating technology and plant configuration [5, 6, 27]. A simplified representation of a generic automotive painting process is shown in Figure 2.2.

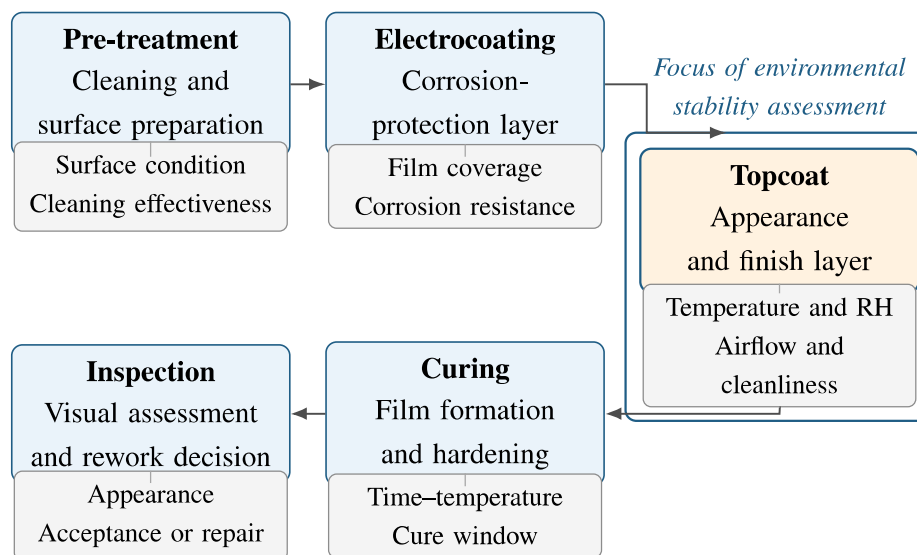


Figure 2.2: Representation of the main automotive coating process stages.

In automotive OEM lines, coating defects necessitate repair protocols that significantly impact throughput and unit costs. "First Run OK" (FROK) efficiency is typically targeted near 92%, with the remaining percentage requiring corrective measures ranging from minor polishing to full-body re-processing. These defects often stem from breached process boundaries, such as unstable paint

viscosity or environmental contamination. Consequently, prioritizing upstream process stability is the primary strategy to minimize reliance on labor-intensive, costly repair cycles [28, 29].

2.4 Coating Materials and Electrostatic Painting Physics

Coating materials are complex systems whose behaviour depends on chemical composition, rheology, application method and environmental conditions. In liquid automotive coatings, the main constituents include binders or resins, pigments, additives and solvents [8, 27, 29] as it is illustrated in 2.3.

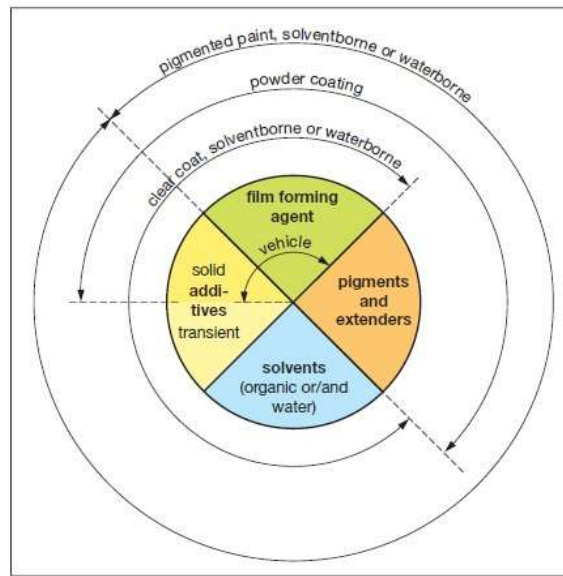


Figure 2.3: Composition of paint [29]

The binder contributes to film formation and mechanical properties, pigments provide colour and hiding power, additives modify processing and performance, and solvents regulate viscosity and application behaviour [27, 29].

For the purpose of this dissertation, the most relevant material aspects are solvent evaporation, viscosity and film formation. Solvents are required to provide adequate flow-ability during application, particularly on vertical surfaces, but they must evaporate in a controlled manner to allow the coating film to level and form correctly [20]. Temperature and airflow influence solvent evaporation, while viscosity affects atomisation, droplet formation and the resulting spray pattern. Consequently, environmental instability in the booth may affect the repeatability of manual spray application [9, 10, 30].

Modern automotive coating systems are commonly multilayer systems [29]. According to Streitberger and Dossel, the coating sequence may include pre-treatment, electro-coating, topcoat, and clear coat. Each layer contributes to a different functional requirement, including corrosion protection, adhesion, colour, gloss, mechanical resistance, and weathering performance [5, 6, 27].

In automotive applications, the topcoat has a strong influence on visual appearance, gloss, colour and surface durability. Its performance depends on the coating material itself, but also on surface preparation, application parameters, film thickness, curing and environmental conditions during application [9, 27, 29]. This link between material behaviour and process conditions justifies the analysis of temperature and relative humidity as manufacturing process variables.

2.4.1 Atomisation and Film Deposition

Spray application requires the coating material to be atomised into droplets that are transported to the surface and subsequently converted into a continuous film. Atomisation can be produced by different mechanisms, including pneumatic energy, centrifugal forces, hydraulic pressure or electrostatic forces, as shown in Figure 2.4[7, 27, 29].

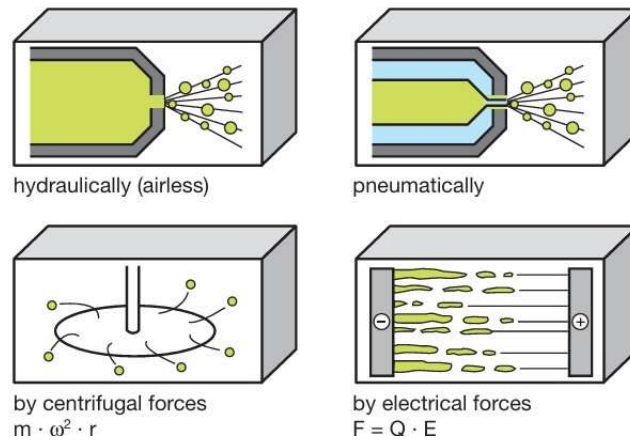


Figure 2.4: Main atomisation mechanisms used in coating application [29].

In pneumatic spray application, droplet formation depends on air flow, paint flow, nozzle geometry, viscosity, surface tension and application pressure. These variables influence droplet size distribution, transfer efficiency, overspray and film uniformity. In manual spraying, additional variability is introduced by gun distance, spray angle, overlap, speed and operator technique [7, 29, 30].

The Sauter mean diameter provides a useful indication of droplet size in spray processes, in Equation 2.1:

$$d_{32} = 51 \cdot Re^{-0.39} \cdot We^{-0.18} \cdot \left(\frac{\dot{m}_{paint}}{\dot{m}_{air}} \right)^{0.29} \cdot d_D \quad (2.1)$$

In Equation (2.1), Re and We represent the Reynolds and Weber numbers, $\dot{m}_{paint}$ and $\dot{m}_{air}$ represent the paint and air mass flow rates, and d_D represents the nozzle diameter. The equation shows that droplet size is linked to flow rates, viscosity, surface tension and nozzle geometry. Since paint viscosity and solvent evaporation are temperature-dependent, environmental stability contributes indirectly to application repeatability [29].

The coating application depends on more factors, as illustrated by Figure 2.5.

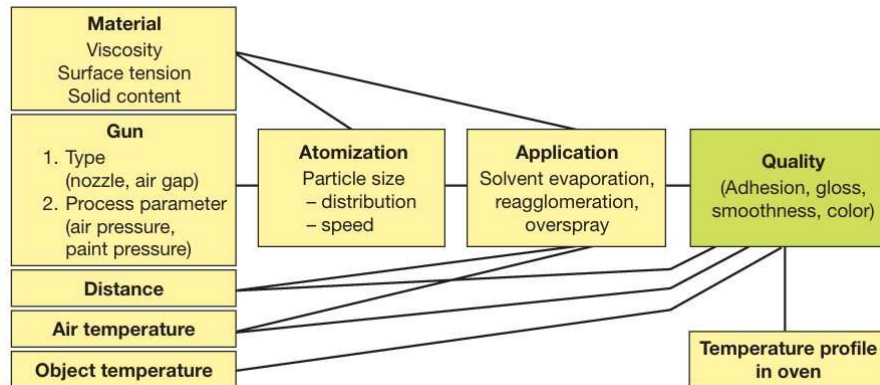


Figure 2.5: Influencing factors on coating quality for spray application [29].

The rheological behavior of materials in automotive painting, specifically paint viscosity serves as a primary quality boundary condition. Viscosity is highly sensitive to environmental fluctuations, particularly air and material temperature, and directly influences atomization dynamics, transfer efficiency, and the final surface finish. To ensure process stability, the Quality department mandates rigorous rheological characterization. Standard laboratory procedures, such as the use of rotational viscometers, illustrated in Figure 2.6, (e.g., DIN or ISO flow cups for quick field assessment or Brookfield viscometers for precise shear-rate dependent measurements), are employed to map the material's behavior against ambient temperature variations [27, 29].

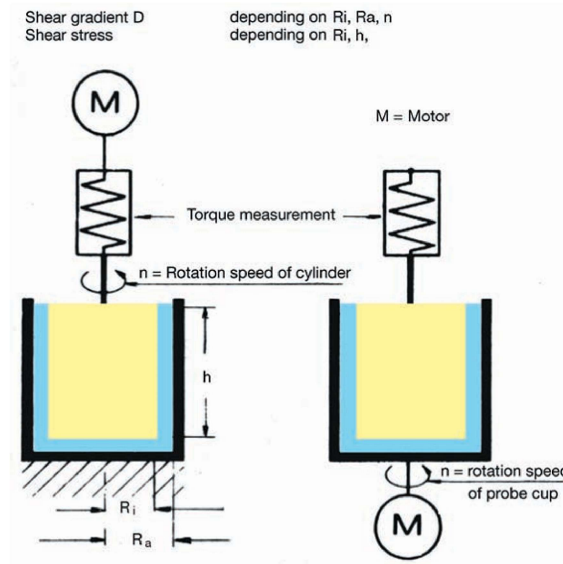


Figure 2.6: Cross-section of viscometer [29]

By defining these viscosity ranges as an operational boundary, the system can dynamically adjust control parameters, ensuring that the process remains within the required technical specifications despite environmental volatility. In manual spray application, the distance between the

gun and the painted object, combined with the experience of the painter, can vary and may be used to compensate for changes in ambient or application conditions [9, 10] to compensate these variations.

2.4.2 Electrostatic Spray Coating

In electrostatic spray coating, paint droplets are electrically charged and attracted towards the grounded workpiece. The electrostatic force acting on a charged droplet can be expressed as:

$$F = Q \cdot E \quad (2.2)$$

where Q is the droplet charge and E is the electric field strength. This principle improves transfer efficiency because charged droplets tend to follow the electric field lines towards the workpiece, reducing material losses compared with purely pneumatic deposition [29].

The electrostatic field is non-homogeneous and depends on the geometry of the part, the electrode configuration, the applied voltage, the grounding condition and the dielectric properties of the coating material[29, 31]. This contributes to the wrap-around effect, where paint particles are attracted to edges and surfaces not directly facing the spray gun. However, cavities and recessed areas may be affected by the Faraday cage effect, reducing deposition efficiency in these regions[7, 29, 31].

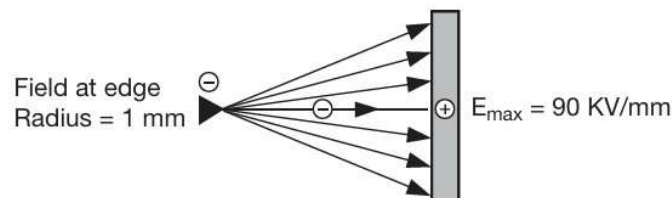


Figure 2.7: Non-homogeneous electric field in electrostatic spray coating [29].

Environmental conditions are relevant in electrostatic painting because relative humidity affects static charge dissipation, dust attraction and the stability of the electrostatic process. Low humidity conditions may increase static build-up, while excessive humidity may interfere with coating behaviour and drying. Therefore, humidity control contributes not only to coating application repeatability, but also to operator safety and contamination reduction [29, 32, 33].

2.5 Environmental Influence on Coating Quality

Paint-booth environmental conditions influence coating application through physical and operational mechanisms such as solvent evaporation, paint rheology, droplet transport, electrostatic behaviour, dust attraction and operator working conditions. Temperature and relative humidity are therefore relevant process variables, especially in booths supplied with 100% fresh air, where

outdoor-air variability directly changes the heating and humidification load required to maintain stable booth conditions [17, 20, 21]. Table 2.2 summarises the main effects associated with low and high relative humidity conditions.

Table 2.2: Effect of booth temperature and relative humidity on coating application.

Condition	Main mechanism	Potential consequence
Low relative humidity	Reduced relative humidity after air heating; higher static-charge accumulation, faster solvent evaporation [32–34].	Dust attraction, electrostatic risk, poorer droplet levelling and possible reduction in transfer efficiency [20, 32, 35].
High relative humidity	Slower solvent evaporation and altered film formation, depending on coating formulation and airflow [32, 33].	Risk of blistering, sagging or poor surface appearance when outside the process window [6, 12].
Low temperature	Higher paint viscosity, slower solvent evaporation and reduced spreading/levelling tendency [5, 6].	Poor flow, orange-peel appearance, inadequate levelling or incomplete film formation [6, 27].
High temperature	Lower paint viscosity and faster solvent evaporation before deposition or levelling [5, 6].	Dry spray, poor wetting, reduced levelling time and surface roughness [6, 11].
Outdoor-air variability	Seasonal changes in dry-bulb temperature, humidity ratio and ventilation load [33, 34].	Higher heating, cooling or humidification demand, especially with 100% fresh-air supply [17, 20, 21].

Environmental anomalies inside the booth are directly linked to structural coating failures, such as blistering, paint sagging, and local thickness deviations [9, 12]. Furthermore, uncoordinated climate control heavily penalizes the paint transfer efficiency of the atomizers, turning the paint shop into the most energy-intensive hub of the entire assembly facility [7, 8].

2.6 Paint Booth HVAC and Psychrometric Control

2.6.1 Air Handling and Airflow

Design and operation in paint booths must comply with safety regulations and must also maintain the environmental limits and tolerances specified for the coating process. In manual spray applications, the ventilation system must remove solvent vapours and overspray from the operator breathing zone and from the painted part, while supplying conditioned and filtered air to the booth [24, 27, 35]. For these conditions there are some requirements that are imperative to have such as:

- **Airflow:** the airflow needs to be sufficient to maintain a safe working environment and prevent the accumulation of flammable substances by diluting pollutants and solvent vapours [24, 27, 35].

- **Air speed in the booth:** air velocity must remove paint fumes and overspray away from both the operator and the part being painted. Typical values reported for spray booths are around 0.3–0.5 m/s [27, 33].
- **Fresh air supply:** in manual solvent-based applications, booth ventilation commonly relies on high fresh-air rates to avoid recirculation of hazardous substances and to maintain safe operating conditions[17, 24].
- **Incoming air filtration:** intake filtration is required to reduce dust, pollen and other particles that could contaminate the coating surface. Filter selection may be guided by standards such as ISO 16890 [27, 29].
- **Exhaust air filtration:** exhaust filtration reduces the concentration of paint particles and pollutants leaving the booth [24].

2.6.1.1 Booth Systems

To ensure coating quality and safe operation, paint booths must control airflow, temperature, humidity and pollutant removal. The booth ventilation system captures overspray generated during painting and directs contaminated air towards the exhaust or washout system. This continuous airflow also reduces the accumulation of solvent vapours that could become flammable or explosive at high concentrations [27, 33].

Booths can be designed with different airflow patterns, including down-draft, side-draft or cross draft configurations. There is also the possibility of having recirculated air booths (Figure 2.8) and fresh air booths. When it comes to manual application, it is not possible to use recirculated air, due to safety and health concerns. The choice depends on the application process, component geometry, quality requirements, available infrastructure and investment constraints. Many industrial booths are equipped with air make-up or air supply units that condition the intake air before it enters the application zone [14, 27, 29].

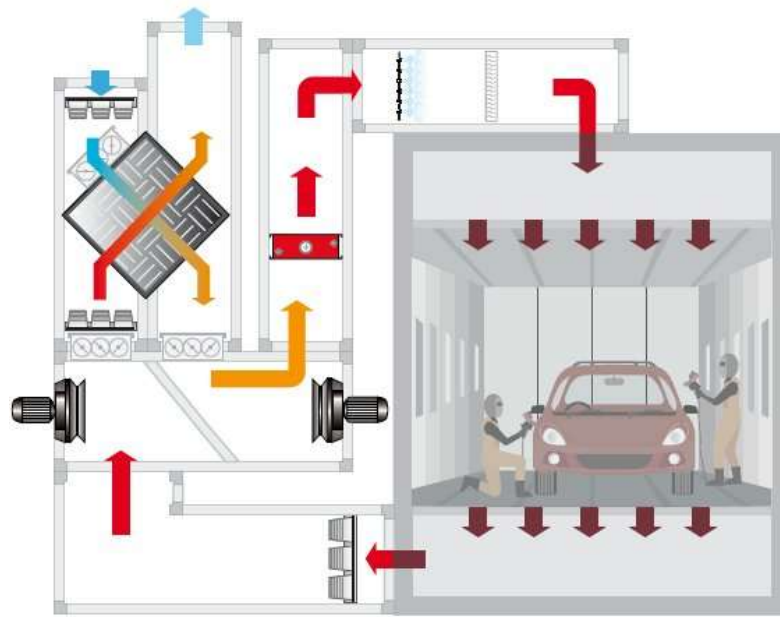


Figure 2.8: Example of a recirculated air painting booth with heat exchanger [33].

2.6.2 Heating Systems

In paint booths supplied with outdoor air, heating is required to reach the specified dry-bulb temperature set-point during cold operating conditions. This heating process also changes the relative humidity of the air. Sensible heating increases dry-bulb temperature without adding moisture, which lowers the relative humidity and can increase the humidification load required downstream.

In direct gas-fired burners, combustion occurs directly in the air stream. This configuration can provide high thermal efficiency, illustrated in Figure 2.9, but it may introduce combustion products into the supplied air, depending on the system design and combustion quality.

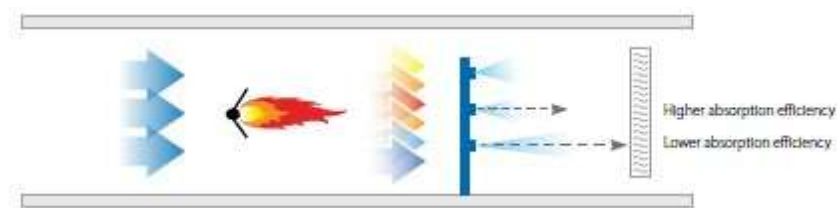


Figure 2.9: Direct open-flame gas-fired burner [33].

Direct combustion heating systems cannot be used in manual application, due to safety and health concerns of painters breathing toxic gases [20]. In indirect heating, as shown in Figure 2.10, combustion gases are separated from the process air by a heat exchange surface. This avoids direct contact between the combustion products and the air supplied to the booth while having lower efficiency [36, 37].

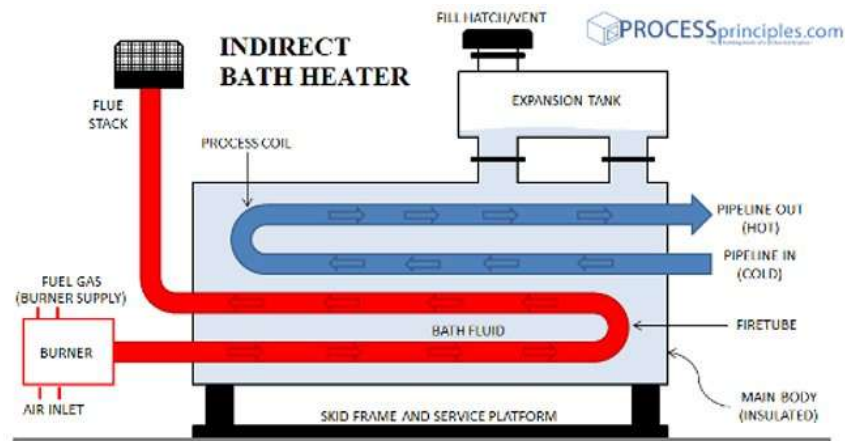


Figure 2.10: Indirect gas-fired burner [37].

2.6.3 Humidification Technologies

Humidity control is required in paint booths to maintain stable application conditions, reduce static-related risks and support coating repeatability. The humidification load depends on outdoor air conditions, booth airflow rate, heating strategy, process set-points and the type of humidification equipment used [17, 33].

In industrial air treatment, a fundamental distinction is made between isothermal and adiabatic humidification. In isothermal humidification, water is added to the air as steam or vapour. In adiabatic humidification, liquid water is sprayed, atomised or exposed to the air and evaporates within the air stream. Figure 2.11 summarises the main difference between these two principles.

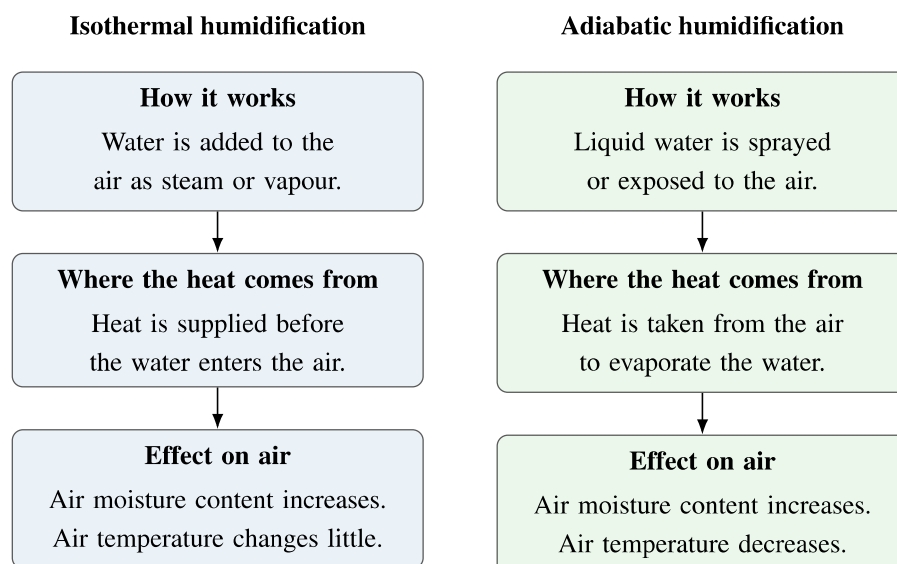


Figure 2.11: Comparison between isothermal and adiabatic humidification.

This distinction is important in paint-booth air supply systems because temperature and relative humidity are physically coupled. Heating and humidification must therefore be analysed as

interacting psychrometric processes rather than as fully independent functions [13, 18, 38].

Several humidification technologies are used in industrial HVAC and air-handling applications and their suitability depends on the required humidity range, airflow rate, inlet air state, available absorption distance, water quality, maintenance requirements, control strategy and energy demand [33, 38].

In adiabatic atomising systems, water is introduced into the air stream as droplets or mist. Effective moisture transfer depends on the ability of the air stream to absorb the injected water before liquid carry-over, surface wetting or drainage occurs. This behaviour is influenced by droplet size, air temperature, relative humidity, air velocity, residence time, distribution uniformity and the presence of mist elimination or post-evaporation elements [38, 39].

The psychrometric effect of heating and humidification is illustrated in Figure 2.12. While Figure 2.11 provides a conceptual comparison of humidification principles, Figure 2.12 represents the corresponding air-state transformation on a psychrometric chart.

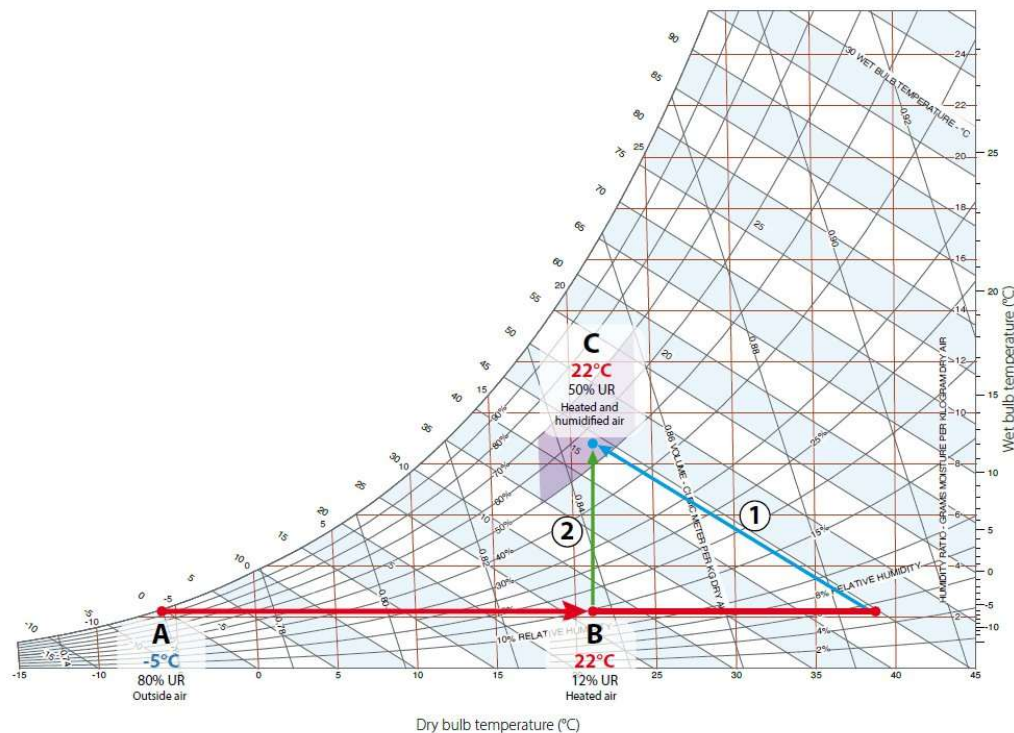


Figure 2.12: Psychrometric representation of outdoor-air heating and humidification towards a target booth condition [33].

Table 2.3: Key to the psychrometric states and thermodynamic processes.

Label	Point/Process	Description
A	Intake air	Outdoor air conditions before treatment.
B	Heated air	Air state after sensible heating and before humidification.
C	Supply air	Final conditioned air state at the booth supply condition.
1	Adiabatic humidification	Liquid water evaporates into the air stream, increasing moisture content while absorbing heat from the air.
2	Isothermal humidification	Water vapour or steam is added to the air stream with limited dry-bulb temperature change.

The transformation from A to B represents sensible heating. During this step, dry-bulb temperature increases without moisture addition, reducing relative humidity. The transformation from B to C represents humidification towards the target booth condition. In the adiabatic case, this process increases air moisture content while reducing dry-bulb temperature through evaporative cooling [33].

2.6.3.1 Water Quality, Corrosion and Material Selection

Industrial humidification systems operate at the intersection of public health regulations and infrastructure integrity. In Portugal, the management of aerosol-generating systems is governed by Law No. 52/2018 and Portaria No. 25/2021, mandating rigorous risk assessment and maintenance to mitigate *Legionella* proliferation [40, 41]. These requirements necessitate proactive water treatment, which directly influences the chemical environment of the distribution network. Water quality and piping integrity are inextricably linked. Water acts as an electrolyte, where conductivity, a function of ion concentration, pH, and dissolved solids, drives electrochemical degradation [42, 43]. A primary concern in ageing or retrofit infrastructure is galvanic corrosion (Figure 2.13), which occurs when dissimilar metals with distinct electrode potentials are in electrical contact [43].



Figure 2.13: Galvanic corrosion [44]

The severity of this process is proportional to the potential difference between materials and the conductivity of the fluid [43]. Due to the likely presence of biocides, the pitting corrosion (Figure 2.14) in stainless steel pipes also needs to be taken into account.

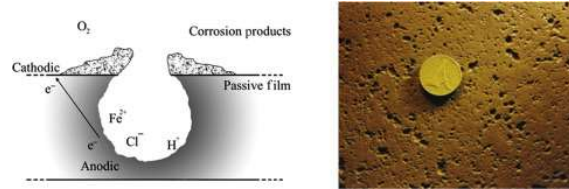


Figure 2.14: Pitting corrosion [45]

Consequently, material selection in retrofit environments requires an evaluation of electrochemical compatibility to prevent anodic dissolution, where more active metals sacrifice their integrity to protect cathodic components.

This challenge is compounded by the necessity of microbial control. While biocides are essential for *Legionella* suppression, chemical disinfectants often increase the oxidizing potential of the water, accelerating the corrosion of metallic surfaces [38]. Therefore, the design of distribution infrastructure must treat material selection (Figure 2.15) as a primary constraint[46].

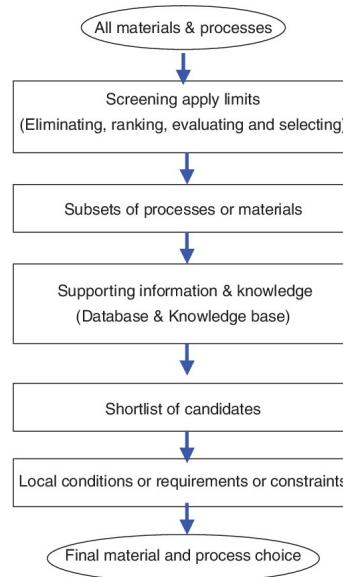


Figure 2.15: Material selection strategy [46]

Balancing structural requirements with chemical and biological process control necessitates the use of materials, such as high-grade stainless steels or chemically inert polymers, that can withstand both the electrochemical demands of the fluid and the oxidative stress imposed by water treatment protocols [34].

2.7 Safety and Regulatory Constraints in Solvent-Based Paint Booths

Solvent-based paint booths operate under specific safety and regulatory constraints because they combine flammable coating materials, solvent vapours, ventilation systems, electrostatic application and worker exposure risks. For this reason, booth design and operation must consider not only coating quality and process stability, but also explosion prevention, ventilation performance, equipment suitability, emissions control and compliance with applicable safety standards.

2.7.1 ATEX Zones

The term ATEX derives from the French expression *ATmosphère EXplosive* and is associated with European requirements for equipment and protective systems intended for use in potentially explosive atmospheres. In solvent-based painting, hazardous atmospheres may occur due to the presence of flammable vapours, mists or overspray, depending on solvent concentration, ventilation effectiveness and the specific zone classification assessment[35].

Paint booths using solvent-based coatings may therefore contain areas requiring ATEX classification. Equipment installed in these areas, including sensors, actuators, motors, lighting and electrical components, must be selected according to the applicable hazardous-zone requirements and the final risk assessment without introducing ignition risks[27].



Figure 2.16: ATEX symbol [33].

Hazardous areas are commonly classified according to the frequency and duration of occurrence of an explosive atmosphere, as summarised in Table 2.4.

Table 2.4: Classification of ATEX hazardous zones for gases and vapours[33].

Zone	Atmospheric condition and occurrence
Zone 0	Explosive atmosphere is present continuously, for long periods or frequently.
Zone 1	Explosive atmosphere is likely to occur occasionally during normal operation.
Zone 2	Explosive atmosphere is not likely to occur during normal operation, or occurs only for a short duration.

The classification of ATEX zones and their safety standards heavily condition the choice of materials and location of equipments, therefore, all the equipments and their locations should be approved by the safety department to ensure compliance.

2.7.2 Regulatory Framework and Safety Standards

The painting booth is installed in a industrial plant and must comply with requirements that ensure worker safety, safe equipment operation, environmental protection and system performance.

In legacy installations that predate several modern standards currently used in industrial equipment design. For this reason, modern regulations and standards are used in this as technical guidance requirements. The safety and health requirements for the use of work equipment remain relevant, including Directive 2009/104/EC, transposed in Portugal by Decreto-Lei n.º 50/2005.

The standards and references considered in the analysis are summarised in Table 2.5.

Table 2.5: Regulatory framework and technical standards relevant to painting-booth operation.

Reference area	Technical scope in painting-booth operation
Work equipment safety	
DL n.º 50/2005 (2005); Directive 2009/104/EC (2009) [47, 48]	Minimum safety and health requirements for work equipment used by workers.
Machinery safety	
Directive 2006/42/EC (2006) [49]	Essential health and safety requirements for machinery design, integration, and CE marking.
Spray-booth safety	
EN 16985:2018 (2018); EN 12215:2004+A1:2009 (2009) [35, 50]	Spray-booth safety requirements related to ventilation, fire/explosion risk, and user information.
ATEX equipment	
Directive 2014/34/EU (2014) [51]	Requirements for equipment used in potentially explosive atmospheres.
Electrostatic application	
EN 50176:2009 (2009) [52]	Safety requirements for electrostatic application equipment for ignitable liquid coating materials.
Air filtration	
ISO 16890-1:2016 (2016) [53]	Classification and testing of air filters for ventilation.
VOC emissions	
Directive 2010/75/EU (2010) [54]	Industrial emissions requirements relevant to solvent-using activities.
Control safety	
ISO 13849-1:2023 (2023) [55]	Design principles for safety-related parts of machinery control systems.

This regulatory framework should be included in technical specifications in the painting shop and painting booth systems.

2.8 Process Stability and Diagnostic Prioritisation Methods

This section presents the main methods used to assess process stability, identify root causes and prioritise improvement actions in industrial manufacturing processes.

2.8.1 Industrial Problem-Solving Tools

In manufacturing environments, process stability and continuous improvement are commonly supported by structured problem-solving methods. These methods emphasise direct observation, standardisation, root-cause analysis and systematic follow-up, and are closely aligned with Toyota-style improvement practices such as *Genchi Genbutsu*¹, standardised work and continuous improvement, standardised work and continuous improvement [56, 57]. They provide a practical framework for analysing production processes whose performance depends on the interaction between equipment condition, operating procedures, maintenance practices and environmental variables. Table 2.6 summarises the main diagnostic tools considered in this context.

Table 2.6: Problem-solving tools relevant to process diagnosis and prioritisation.

Tool	Purpose	Diagnostic contribution
Gemba observation	Direct observation of the process in its real operating context [56].	Supports understanding of current operating conditions, operator interaction and practical constraints.
Ishikawa diagram	Structured identification of possible root causes associated with a defined problem [56].	Organises potential causes before deeper analysis or prioritisation.
5 Whys	Root-cause exploration through successive questioning [56].	Helps distinguish visible symptoms from underlying process or system limitations.
A3 problem solving	Structured improvement cycle linking problem definition, analysis, counter-measures and follow-up [56, 57].	Provides a logical sequence for diagnosis, action planning and verification.
Control chart	Statistical monitoring of process variation over time [58].	Supports the distinction between stable variation and abnormal process behaviour.
FMEA	Structured identification and prioritisation of potential failure modes [59].	Ranks limitations according to their effect, occurrence and detection capability.

¹ *Genchi Genbutsu* is a Toyota management principle commonly interpreted as “go and see”. It refers to understanding a problem by observing the real process at the actual workplace, where facts can be verified directly.

2.8.2 Statistical Process Control and Process Stability

Statistical Process Control (SPC) provides a framework for distinguishing natural process variation from abnormal variation. Natural variation, also referred to as common-cause or chance variation, is inherent to the process and is expected even when the system is operating normally. In contrast, special-cause or assignable variation is associated with abnormal disturbances such as equipment maladjustment, operator errors, material problems or changes in process conditions [58]. A process affected only by common causes is considered to be in statistical control, whereas the presence of assignable causes indicates an out-of-control condition.

The control chart is one of the central tools of SPC. It represents a process statistic over time and compares it with a centre line and control limits. In the general Shewhart formulation, if w is the statistic plotted on the chart, with mean μ_w and standard deviation σ_w , the control limits are defined as:

$$UCL = \mu_w + L\sigma_w \quad (2.3)$$

$$CL = \mu_w \quad (2.4)$$

$$LCL = \mu_w - L\sigma_w \quad (2.5)$$

where L is the distance between the centre line and the control limits, expressed in standard-deviation units. In industrial practice, $L = 3$ is commonly used, resulting in the classical three-sigma control limits [58]. A point outside these limits suggests the possible presence of an assignable cause. However, a process may also be considered suspicious when points remain inside the limits but exhibit non-random patterns, such as long runs, trends or cyclic behaviour.

Control charts are commonly classified according to the nature of the monitored data. Variable control charts are used when the quality characteristic is measured on a continuous scale, such as temperature, relative humidity, pressure, flow rate or coating thickness. Attribute control charts are used when the response is a count, a proportion or a classification, such as the number of defects or the number of nonconforming units. Figure 2.17 summarises the main control-chart families and their typical fields of application.

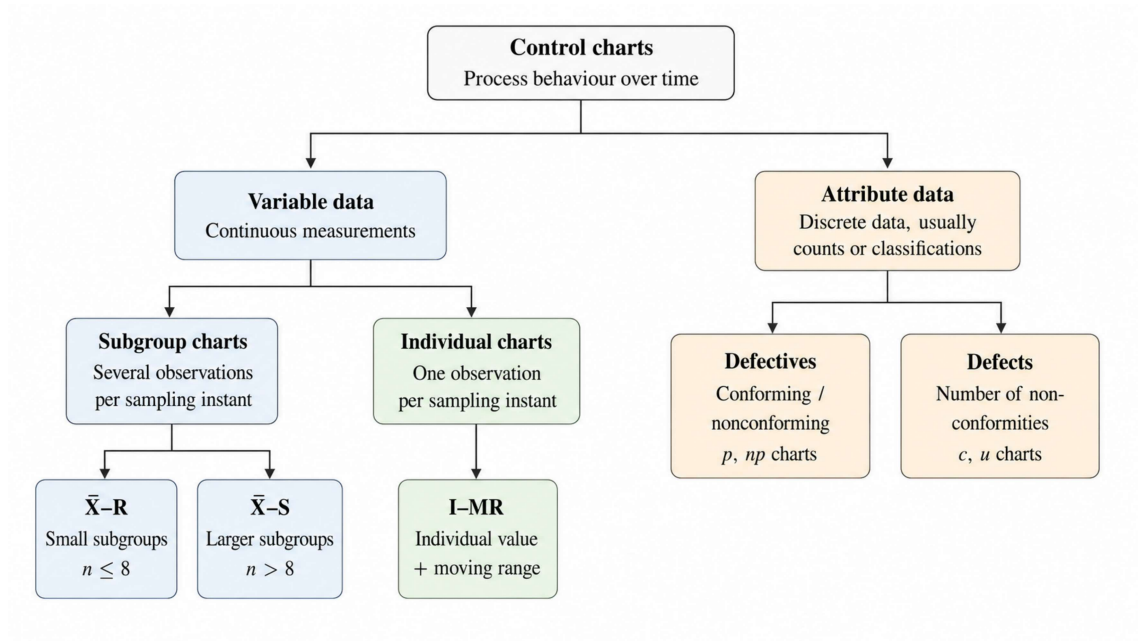


Figure 2.17: Control charts families

Variable control charts are used when the monitored characteristic is numerical and continuous. In manufacturing and process monitoring, this is the most relevant family of charts for physical process variables such as temperature, relative humidity, pressure or flow rate. These charts are usually designed to monitor two aspects of the process: location, represented by the mean or individual value, and dispersion, represented by the range, standard deviation or moving range [58].

The selection of the appropriate variable chart depends strongly on the sampling structure. If several observations are collected at each sampling instant, subgroup-based charts can be used. If only one observation is available at each time point, individual-value charts are more appropriate. This distinction is important because the method used to estimate process variability changes depending on whether rational subgroups exist.

2.8.2.1 Basic Statistics for Subgrouped Data

Assume that the process is sampled at k different sampling instants, and that each subgroup contains n observations. For subgroup i , the subgroup mean is:

$$\bar{X}_i = \frac{1}{n} \sum_{j=1}^n X_{ij} \quad (2.6)$$

The subgroup range is:

$$R_i = X_{i,\max} - X_{i,\min} \quad (2.7)$$

The subgroup standard deviation is:

$$S_i = \sqrt{\frac{\sum_{j=1}^n (X_{ij} - \bar{X}_i)^2}{n-1}} \quad (2.8)$$

Across all k subgroups, the grand mean, average range and average standard deviation are given by:

$$\bar{\bar{X}} = \frac{1}{k} \sum_{i=1}^k \bar{X}_i \quad (2.9)$$

$$\bar{R} = \frac{1}{k} \sum_{i=1}^k R_i \quad (2.10)$$

$$\bar{S} = \frac{1}{k} \sum_{i=1}^k S_i \quad (2.11)$$

2.8.2.2 $\bar{X}$ -R Charts

The $\bar{X}$ -R scheme is one of the most common approaches for subgrouped variable data. It uses two charts: the $\bar{X}$ chart monitors the process mean, while the R chart monitors within-subgroup variability. This combination is particularly useful when subgroup sizes are relatively small, because the range provides a practical estimate of short-term variation [58].

For the $\bar{X}$ chart based on the average range, the control limits are:

$$CL_{\bar{X}} = \bar{\bar{X}} \quad (2.12)$$

$$UCL_{\bar{X}} = \bar{\bar{X}} + A_2 \bar{R} \quad (2.13)$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - A_2 \bar{R} \quad (2.14)$$

For the R chart, the control limits are:

$$CL_R = \bar{R} \quad (2.15)$$

$$UCL_R = D_4 \bar{R} \quad (2.16)$$

$$LCL_R = D_3 \bar{R} \quad (2.17)$$

The constants A_2 , D_3 and D_4 depend on subgroup size and are obtained from standard SPC constant tables [58]. The $\bar{X}$ chart is used to detect changes in the average value of the process, while the R chart is used to detect changes in the short-term variability within each subgroup. Therefore, both charts must be analysed together: a process can become unstable because its average shifts, because its variability increases, or because both occur at the same time.

2.8.2.3 Individuals and Moving Range Charts

When only one observation is available at each sampling instant, subgroup-based estimates of short-term variation cannot be calculated. In this case, the Individuals and Moving Range scheme is commonly used. The Individuals chart monitors the measured value itself, while the Moving Range chart monitors the absolute difference between consecutive observations [58].

For a sequence of m individual observations, the moving range is:

$$MR_i = |X_i - X_{i-1}|, \quad i = 2, 3, \dots, m \quad (2.18)$$

The average moving range is:

$$\overline{MR} = \frac{1}{m-1} \sum_{i=2}^m MR_i \quad (2.19)$$

For the Individuals chart, the control limits are:

$$CL_I = \bar{X} \quad (2.20)$$

$$UCL_I = \bar{X} + E_2 \overline{MR} \quad (2.21)$$

$$LCL_I = \bar{X} - E_2 \overline{MR} \quad (2.22)$$

where $E_2 = 3/d_2$. For a moving range of two consecutive observations, E_2 is commonly approximated as 2.66.

For the Moving Range chart, the limits are:

$$CL_{MR} = \overline{MR} \quad (2.23)$$

$$UCL_{MR} = D_4 \overline{MR} \quad (2.24)$$

$$LCL_{MR} = D_3 \overline{MR} \quad (2.25)$$

For a moving range of two observations, the constants are commonly $D_3 = 0$ and $D_4 = 3.267$ [58]. The Individuals chart therefore evaluates process level over time, while the Moving Range chart evaluates short-term point-to-point variation.

2.8.2.4 Rational Subgroups and Chart Selection

Rational subgroups are defined such that within-subgroup variation reflects only common-cause variation, while between-subgroup differences highlight assignable causes [58]. Forcing data into artificial subgroups distorts variability estimates and weakens statistical interpretation. When rational subgroups are unavailable, I-MR charts are preferred as they estimate short-term variation from consecutive observations [58].

Variable control charts detect abnormal process behavior but do not identify physical root causes. Consequently, chart results must be interpreted alongside process knowledge, measurement-system limitations, and complementary diagnostic methods to determine the actual driver of process instability.

2.8.2.5 Statistical Support for Defect and Environmental Analysis

In addition to SPC, complementary statistical checks were considered to support the interpretation of process-stability results. Since I-MR charts are based on individual time-ordered observations, their interpretation should consider normality, independence and sampling-frequency limitations [58]. Normality can be assessed through histograms, normal probability plots and formal tests such as the Anderson–Darling test [28, 58]. Independence can be evaluated using autocorrelation analysis, since time-dependent observations may affect the interpretation of control-chart signals [58]. Sampling frequency must also be considered, because low-frequency measurements may reveal broad trends while missing short-duration disturbances between observations.

For defect analysis, absolute defect counts should be normalised when the number of inspected units varies between periods. A defect rate can be defined as:

$$DR_i = \frac{D_i}{N_i} \quad (2.26)$$

where DR_i is the defect rate for period i , D_i is the number of observed defects and N_i is the number of inspected units in the same period. This normalisation allows quality outcomes to be compared on a common basis and reduces the risk of interpreting changes in production volume as changes in defect behaviour.

Exploratory correlation analysis can then be used to investigate possible associations between process indicators and normalised defect rates. The Pearson correlation coefficient measures the strength and direction of a linear relationship between two numerical variables:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (2.27)$$

For small datasets or data affected by outliers, Spearman correlation may also be used because it evaluates monotonic relationships based on ranks rather than on the original numerical values [60].

Correlation results must not be interpreted as proof of causality. In coating processes, defects are usually multi-factorial and may depend on material behaviour, application parameters, equipment condition, operator technique and environmental variables such as temperature, relative humidity and airflow [5, 6, 27]. Therefore, statistical associations should be interpreted together with process knowledge, root-cause analysis and measurement limitations.

Table 2.7: Statistical methods used to support defect and environmental analysis.

Method	Purpose	Interpretation role
Normality check	Assess whether data distribution strongly departs from normal behaviour.	Supports cautious interpretation of I-MR chart limits.
Autocorrelation analysis	Evaluate dependence between consecutive observations.	Identifies possible time-dependence in time-ordered data.
Sampling-frequency assessment	Evaluate the temporal resolution of the available measurements.	Defines what type of short-term variation may be missed.
Defect-rate normalisation	Convert defect counts into rates when inspection volume varies.	Allows comparison between periods with different production volumes.
Correlation analysis	Explore associations between process indicators and defect rates.	Supports diagnosis, but does not prove causality.

2.8.2.6 Attribute Control Charts for Nonconformities

Attribute control charts are required when process quality is monitored through the classification or counting of nonconformities. When the sample size (or area of opportunity) for inspection varies over time, the u -chart is the appropriate model for monitoring the average number of defects per unit.

The u -chart assumes that the occurrence of nonconformities follows a Poisson distribution, where the probability of a defect occurring is small but the number of potential opportunities is large [58]. For a sequence of subgroups with varying inspection sizes n_i , the u -statistic for each subgroup i is calculated as:

$$u_i = \frac{c_i}{n_i} \quad (2.28)$$

where c_i is the count of nonconformities in subgroup i . The center line is defined by the process average $\bar{u}$, and the control limits are calculated as:

$$UCL, LCL = \bar{u} \pm 3\sqrt{\frac{\bar{u}}{n_i}} \quad (2.29)$$

Unlike variable charts, the u -chart features "stair-stepped" control limits. Because the width of the limits is a function of the inspection size n_i , the control limits adjust dynamically to account for variations in production volume [58]. This characteristic makes the u -chart particularly robust for industrial applications where inspection throughput is inconsistent, ensuring that detected process signals reflect true nonconformity shifts rather than artifacts of volume fluctuation.

2.8.3 Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is a structured risk-analysis method used to identify potential failure modes, evaluate their effects and support the prioritisation of preventive or corrective actions. In manufacturing processes, FMEA promotes prevention-oriented thinking by linking process functions, potential failure modes, failure effects, causes, current controls and recommended actions [59].

In the AIAG-VDA approach, risk evaluation is based on three main dimensions: Severity, Occurrence and Detection. Severity describes the seriousness of the potential effect of a failure mode. Occurrence describes the likelihood that the associated cause or failure mechanism will occur. Detection describes the ability of current controls to detect, prevent or contain the failure mode before its effect reaches the next process step or the final user [59].

- **Severity (S):** seriousness of the potential effect of the failure mode.
- **Occurrence (O):** likelihood that the cause or failure mechanism will occur.
- **Detection (D):** ability of existing controls to detect, prevent or contain the failure mode.

The combination of Severity, Occurrence and Detection supports the definition of an Action Priority (AP), which guides whether further action is required. Compared with a purely numerical risk ranking, the AIAG-VDA Action Priority approach emphasises the interpretation of risk combinations and the need to prioritise actions according to the criticality of the potential effect, the likelihood of occurrence and the strength of existing controls [59].

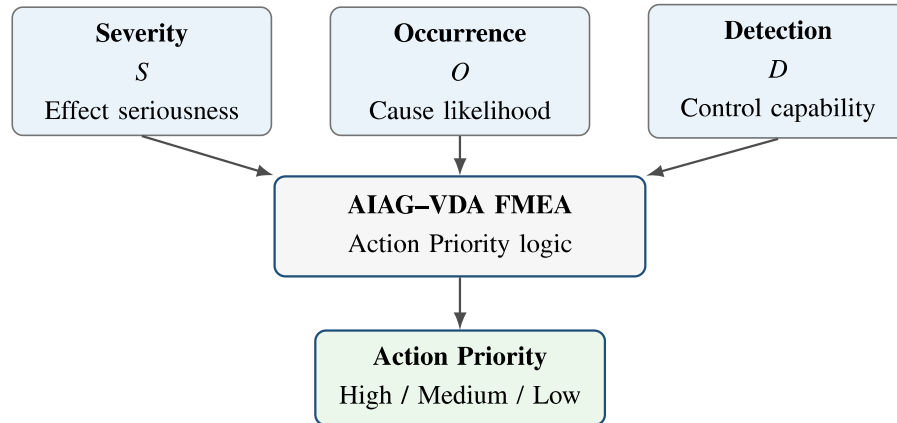


Figure 2.18: AIAG-VDA FMEA prioritisation logic.

In process-improvement contexts, FMEA is useful because it translates technical and operational knowledge into a structured prioritisation framework. It does not identify root causes by itself, but it helps organise known or suspected failure mechanisms, compare their relative risk and define where additional investigation, monitoring or control may be required.

2.9 Process Control and Monitoring in Painting Systems

2.9.1 Determinants of Coating Stability

The performance of an automotive coating process is inherently linked to the stability of the environmental conditions within the spray booth and air supply system. Variations in temperature, relative humidity, and airflow exert a direct influence on the rheological properties of the paint, the atomisation process, and the final film formation [5, 7]. Literature indicates that deviations in these variables are primary drivers of common process defects, such as blistering or gloss non-uniformity [12]. Achieving consistent application performance and finish quality requires not only advanced coating chemistry but also a robust, well-instrumented environmental conditioning infrastructure [8].

2.9.2 Monitoring Architectures in Industrial Painting

Effective environmental control depends on the accuracy and robustness of the instrumentation deployed within the paint shop. In legacy facilities, the challenge lies in separating the physical process from the digital infrastructure required to supervise it. The monitoring architecture follows a functional hierarchy:

- **Sensing Layer:** Monitoring of psychrometric conditions (temperature and relative humidity) and aerodynamic variables (differential pressure and airflow uniformity) [13, 19].
- **Control Layer:** Execution of control logic to maintain immediate process setpoints, ensuring system reliability [6].
- **Diagnostic Layer:** Identification of long-term process drifts, which are often the result of degradation in air supply units, heat exchangers, or humidification circuits [14, 15].

This distinction is critical for retrofit projects: control-critical sensors guarantee immediate process stability, while diagnostic sensors provide the historical visibility required to troubleshoot intermittent defects and optimize long-term performance.

2.9.3 Data-Supported Process Analysis

A shift toward data-supported process management is observable in contemporary industrial literature. Rather than relying solely on static setpoints, modern approaches integrate historical sensor data to analyse the correlation between environmental swings and quality output [11, 26].

The framework for such systems involves:

1. **Data Acquisition:** Bridging the gap between the physical booth environment and the monitoring system [22].
2. **Process Mapping:** Using historical trends to establish the thermodynamic baseline of the paint shop, moving beyond reactive troubleshooting [20, 21].
3. **Human-Machine Interaction:** Supporting the operator's decision-making process by reducing the ambiguity of diagnostic alarms, which is essential for process resilience in semi-manual or data-constrained environments [10, 25].

These diagnostic models, from basic monitoring-oriented systems to simulation-supported frameworks, provide the visibility necessary to mitigate operational risk [61]. The ultimate objective is not the digital system itself, but the achievement of a stable, repeatable, and energy-efficient paint application process, where digital tools act as the "eyes" for process diagnostics [18].

2.10 Economic Evaluation of Engineering Improvement Projects

Industrial engineering projects are not always justified by direct profit generation. In manufacturing environments, improvement projects are often motivated by technical needs such as process stability, quality control, energy efficiency, reliability, safety, traceability and maintenance performance. Even so, the proposed solution must be economically evaluated to determine whether the required investment is reasonable when compared with the expected operational benefits and implementation risks.

Engineering economy provides the basis for comparing alternatives that require an initial investment and generate costs or benefits over time [62–64]. For this reason, the evaluation should consider both capital expenditure and operating expenditure. Capital expenditure, or CAPEX, corresponds to the investment required to acquire and implement the proposed system, including equipment, instrumentation, automation hardware, installation, commissioning, training, documentation and contingency:

$$CAPEX_{total} = C_{eq} + C_{inst} + C_{comm} + C_{auto} + C_{train} + C_{cont} \quad (2.30)$$

where C_{eq} is the cost of equipment and instrumentation, C_{inst} is the installation cost, C_{comm} is the commissioning cost, C_{auto} represents automation and integration costs, C_{train} represents training and documentation costs, and C_{cont} is the contingency allowance.

Operating expenditure, or OPEX, represents the recurring annual cost required to operate and maintain the solution after implementation. In industrial monitoring and automation projects, this may include calibration, maintenance, spare parts, sensor replacement, software licences, energy and utilities:

$$OPEX_{annual} = C_{cal} + C_{maint} + C_{spares} + C_{rep} + C_{soft} + C_{energy} + C_{utilities} \quad (2.31)$$

where C_{cal} is the calibration cost, C_{maint} is the maintenance cost, C_{spares} is the cost of spare parts, C_{rep} is the annualised replacement cost, C_{soft} is the software cost, C_{energy} is the energy cost, and $C_{utilities}$ represents other utility costs.

A life-cycle costing perspective is relevant because industrial assets generate costs throughout their useful life, not only at the acquisition stage. ISO 15686-5 defines life-cycle costing as the evaluation of relevant costs and cash flows associated with an asset over a defined period, including acquisition, operation, maintenance and end-of-life stages [65]. This approach is suitable for industrial engineering projects because recurring costs such as calibration, maintenance, energy consumption and component replacement may significantly affect the total cost of ownership.

The annual net benefit can be expressed as:

$$B_{net} = B_{annual} - OPEX_{additional} \quad (2.32)$$

where B_{annual} represents the annual quantified benefits and $OPEX_{additional}$ represents the additional annual operating cost introduced by the solution. In a conservative engineering analysis, only benefits supported by measured data or technically defensible estimates should be monetised. Benefits such as improved traceability, faster fault detection, better maintenance visibility or reduced defect risk may be relevant, but should remain qualitative unless a reliable financial basis is available.

The most common economic indicators used in engineering investment analysis are payback period, return on investment, net present value and cost-benefit ratio [62–64]. The payback period estimates the time required to recover the initial investment:

$$PB = \frac{CAPEX_{total}}{B_{net}} \quad (2.33)$$

Return on investment relates the annual net benefit to the initial investment:

$$ROI = \frac{B_{net}}{CAPEX_{total}} \times 100 \quad (2.34)$$

Net present value accounts for the time value of money by discounting future cash flows over the analysis period:

$$NPV = \sum_{t=1}^n \frac{CF_t}{(1+r)^t} - CAPEX_{total} \quad (2.35)$$

where CF_t is the net cash flow in year t , r is the discount rate, and n is the analysis period. The cost-benefit ratio (CBR) compares the present value of benefits with the present value of costs:

$$CBR = \frac{PV(Benefits)}{PV(Costs)} \quad (2.36)$$

Cost estimates should also reflect the maturity of the project. AACE International states that cost estimates must be interpreted according to the level of project definition and estimate maturity [66]. This is important in industrial thesis projects, where the proposed solution may be specified and conceptually validated but not fully implemented. For this reason, contingency is included to account for uncertainty within the defined project scope:

$$C_{cont} = p_{cont} \times C_{base} \quad (2.37)$$

where p_{cont} is the contingency percentage and C_{base} is the base estimated cost before contingency.

While direct financial gains from energy or material savings are quantifiable, qualitative benefits such as improved operator situational awareness and diagnostic capability are essential for long-term process resilience and should be factored into the decision-making process alongside hard economic metrics.

Finally, because economic conclusions depend on uncertain assumptions, sensitivity analysis is required. Engineering decisions are influenced by cost, schedule, risk, useful life and performance uncertainty [67]. Therefore, pessimistic, expected and optimistic scenarios should be used to test whether the investment remains reasonable when CAPEX, OPEX or expected benefits vary. This is particularly important when some benefits, such as defect reduction or downtime reduction, are estimated rather than directly measured.

The analysis distinguishes measured, estimated and qualitative benefits, applies conservative assumptions, and uses sensitivity analysis to avoid overstating the economic justification.

2.10.1 Technology and Manufacturing Readiness Assessment

Readiness assessment frameworks are used in engineering to evaluate how mature a technology, process or system is before full-scale implementation. Their main value is that maturity is assessed according to demonstrated evidence, rather than only by technical expectation or qualitative judgement. The Technology Readiness Level (TRL) framework is one of the most established approaches for this purpose, describing the progression from basic principles and concept formulation to validation and operation in the intended environment [67, 68]. ISO 16290 formalises this logic by defining TRLs and the criteria required for their assessment, reinforcing the distinction between conceptual feasibility, validation and operational demonstration [68].

In manufacturing projects, however, technical maturity does not necessarily imply implementation readiness. A technically feasible solution may still require production capability, supplier readiness, quality assurance, workforce preparation, maintenance planning, commissioning and risk reduction before it can be introduced into an industrial process. Manufacturing Readiness Levels (MRLs) address this limitation by extending maturity assessment to the manufacturing system and its ability to support production with acceptable risk [69].

Table 2.8: Complementary role of TRL and MRL frameworks in engineering projects.

Framework	Main focus	Typical evidence considered
TRL	Technical maturity of a technology, from concept formulation to operation in the intended environment.	Concept definition, analytical validation, experimental testing, prototype demonstration, validation in relevant environments and operational performance [67, 68].
MRL	Manufacturing and implementation readiness of a process, system or technology.	Production capability, quality assurance, cost, facilities, supply chain, workforce readiness, process capability and manufacturing risk management [69].

The distinction between TRL and MRL is particularly relevant for industrial retrofit projects. These projects are not developed in ideal greenfield conditions. They must be integrated into existing equipment, maintenance structures and production routines. As a result, simulation, analytical modelling or supplier evaluation may support the feasibility of a proposed solution, but they do not replace industrial validation. Full implementation requires installation, commissioning, operator training, maintenance integration and post-implementation performance monitoring under real production conditions [68, 69].

2.11 Research Gap and Chapter Summary

This chapter reviewed the main technical domains required to frame the dissertation: automotive coating quality, paint-booth environmental control, process monitoring, FMEA-based prioritisation, industrial digitalisation and simulation-based validation. The literature confirms that coating quality depends on the interaction between material behaviour, application conditions, airflow, temperature, humidity and process stability.

The main research gap identified is the limited treatment of retrofit-oriented environmental control in legacy automotive paint booths. While modern HVAC control, monitoring and Industry 4.0 concepts are well established, fewer studies address their practical integration in solvent-based, manually operated electrostatic booths with decoupled heating and humidification, limited data acquisition and strong production-continuity constraints.

This dissertation addresses that gap by combining AS-IS diagnosis, diagnostic FMEA, TO-BE automation requirements and simulation-based feasibility assessment into a single retrofit-oriented methodology. The literature review therefore provides the technical basis for the diagnostic, design and validation chapters that follow.

Chapter 3

Process Analysis and AS-IS Diagnosis

This chapter characterizes the AS-IS state of the top coat painting booth's environmental control system, identifying key limitations in its heating, humidification, and airflow operations. By combining quantitative environmental data with qualitative maintenance feedback, the analysis assesses process variability and compliance. Following Lean Manufacturing principles and the standard Toyota Production System (TPS) framework, a series of on-site Gemba observations were conducted [56, 57]. This systematic process mapping utilized the structured continuous improvement architecture to isolate operational wastes from root environmental causes [70]. The chapter concludes with a root-cause analysis and FMEA-based diagnosis, providing the foundation for the TO-BE strategy in Chapter 4.

3.1 Process Overview

The Toyota Land Cruiser 70 (Figure 3.1), manufactured at the Toyota Caetano Portugal S.A. facility, is a heavy-duty vehicle designed for extreme operational environments. Consequently, the manufacturing process must adhere to stringent quality and warranty standards, particularly regarding corrosion resistance and structural durability.



Figure 3.1: Land Cruiser 70

As the production of this model utilizes Completely Knocked Down (CKD) kits, the manufacturing process is systematically organized into four primary areas, as illustrated in the macro-process overview (Figure 3.2).

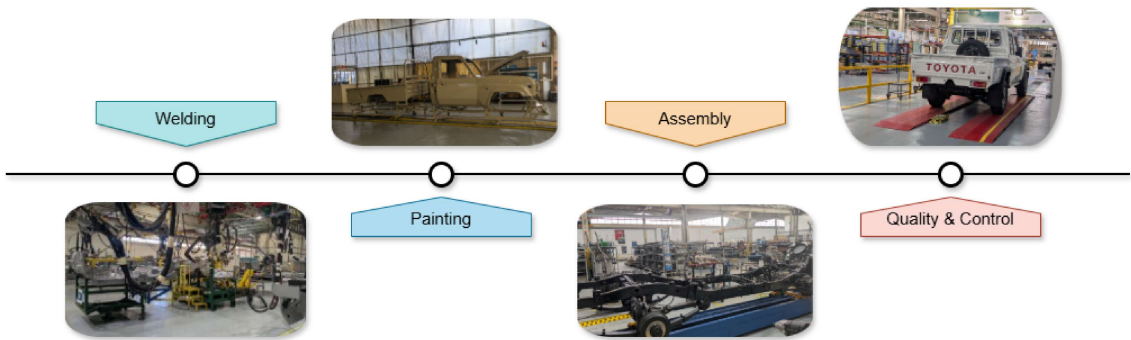


Figure 3.2: Macro process overview

The paint shop operations for the Land Cruiser 70 are distinct from standard high-volume automotive production. Unlike the multi-layered coating systems prevalent in modern passenger vehicles, the Land Cruiser 70 employs a specialized mono-coat application. This choice is deliberate, maintained to preserve the legacy and original specifications of the platform. The composition of these coating layers is detailed in Figure 3.3.

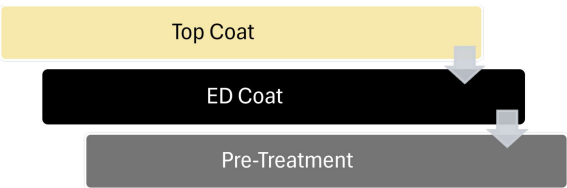


Figure 3.3: Coatings layers on the LC70

Beyond the application of the mono-coat, the painting line plays a critical role in ensuring the vehicle’s long-term integrity against environmental degradation, including exposure to moisture and ultraviolet (UV) radiation. This responsibility extends to the preparation of the substrate, the manual application of sealers and polyvinyl chloride (PVC) layers and the optimization of inter-layer adhesion. The comprehensive operational sequence and the configuration of the work centres within the painting line are presented in the following process flow schematic, in Figure 3.4.



Figure 3.4: Painting line of LC70

It is critical to note that the coating layers function as an integrated system, where each must provide specific performance characteristics. The topcoat is primarily responsible for the vehicle's aesthetic presentation, offering essential UV resistance and the specific colour finish required by the customer. At the Ovar plant, current production specifications limit the available colour palette to beige and white, reflecting the vehicle's specialized application requirements. The operational sequence for the topcoat application process is detailed in Figure 3.5.

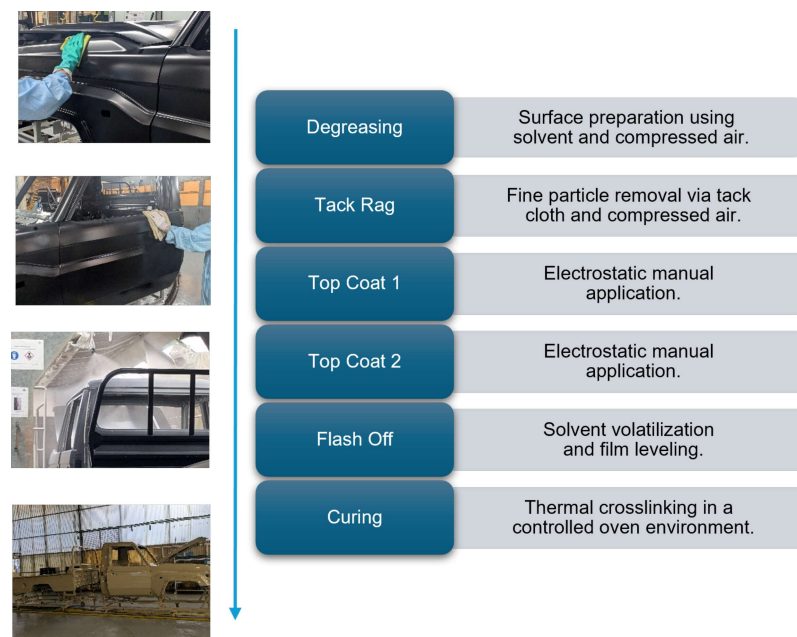


Figure 3.5: Top coat process

Note: Flash-off photography was restricted due to ATEX safety regulations and thermal constraints, consequently it is not represented.

The top coat application is done inside a painting booth, using an electrostatic gun in a manual process. The spray booth is divided in two sections that apply the top coat in different areas of the vehicle, depending on the different parts that are being painted. In the painting application, it is imperative to control environmental conditions and process conditions (Figure 3.6) as temperature and relative humidity, to ensure quality and safety of the process [5].

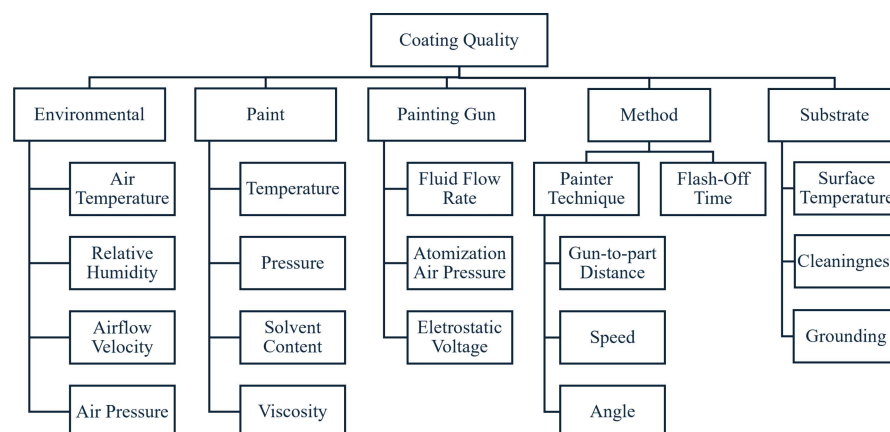


Figure 3.6: Variables in manual electrostatic painting process

3.2 Environmental Control

As previously mentioned, the painting process is very sensitive to environmental conditions. To have a better process stability and control, the painting booth is an imperative equipment to have

in automotive painting processes. There are various types of technologies behind the "ecosystem" that is a painting booth, the technologies used depend on each variable of the process.

3.2.1 Airflow in the Paint Booth

The paint booth is responsible for the environmental and safety control of the top coat painting process, it should provide a controlled environment for workers and the top coat application[21]. Similarly to most automotive painting booths, this plant's painting booth is characterized by being a 100% fresh air down-draft booth with two distinct Air Supply Units (ASU1 & ASU2) as we can see in the Figure 3.7.

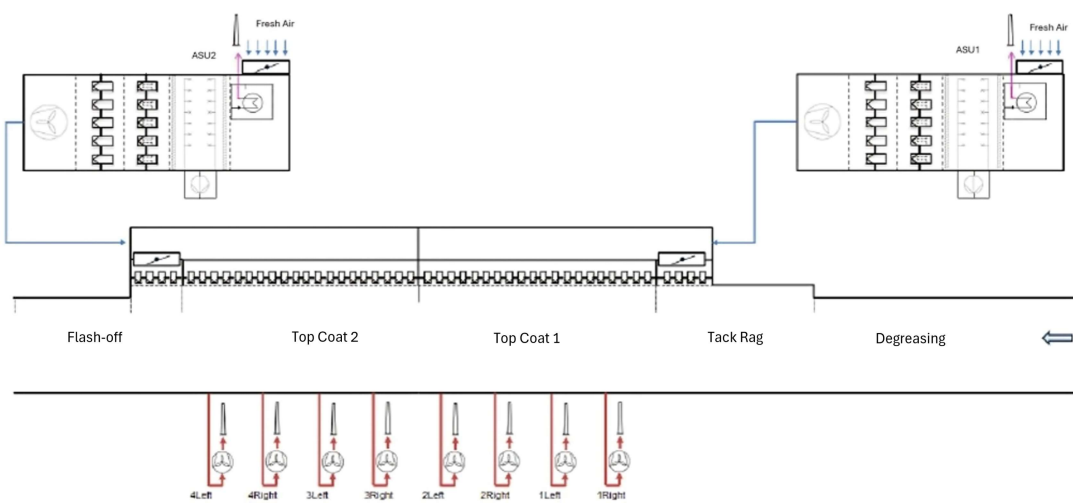


Figure 3.7: Schematic of the painting booth

As shown in Table 3.1, these air supply units are composed by 5 main components.

Table 3.1: HVAC and spray booth infrastructure components.

Indirect Burner	Humidifier	Oil Filters	Bag Filters	Double-ear Fan
				

Each Air Supply Unit (Air Supply Unit) is responsible for treating the air and guarantee that the production conditions on the cabin are ideal. After passing through the air treatment, the air goes into the application booth. This booth is divided into the pre-plenum, where the flow arrives at high velocity and it is distributed to the entire booth. Passes through the plenum, where the

flow homogenizes and achieves laminar flow. The airflow slowly descends through the application booth, parallel to the walls, removing any paint particles that remain suspended in air after painting the bodies, as can be seen in Figure 3.8.

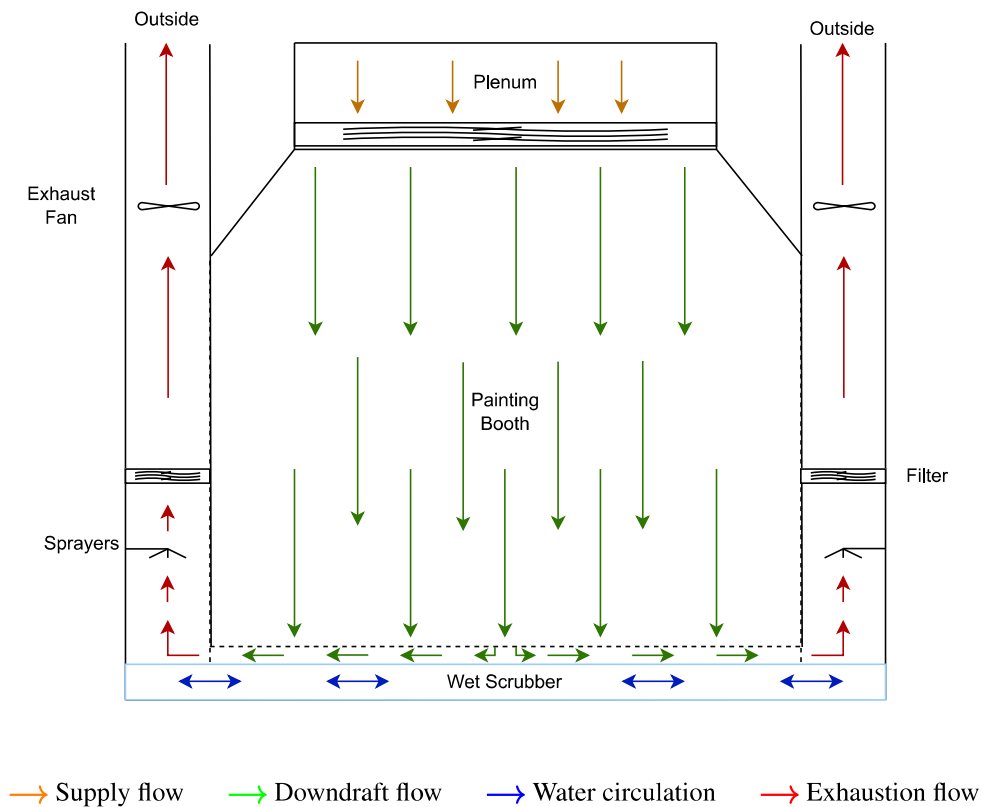


Figure 3.8: Downdraft painting booth

Finally, the air combined with the paint passes through a wet scrubber, as shown in Figure 3.9 where the paint particles are separated from air. This air is then expelled by the 8 extraction fans system. The system works as a whole and offers an equilibrium of relative humidity, pressure and temperature for the ideal conditions for this painting process.



Figure 3.9: Painting booth: wet scrub

3.2.2 Temperature and Humidity Control

To be able to control the environmental variables inside the painting booth, the system is equipped with two Air Supply Units, responsible to supply the treated air into the painting booth.

3.2.2.1 Air Supply Units (ASU) Technical Description

The air conditioning process is performed by two independent units, ASU1 and ASU2. Their current hardware configuration is summarized in Table 3.2.

Table 3.2: Technical Specifications of the current Air Supply Units.

Sub-system	Current Component and Technology
Inlet Control	Manual entrance dampers for air intake regulation.
Heating	Indirect gas-fired burner with modulating power.
Humidification	Fixed-flow water pump feeding a series of spray nozzles (adiabatic).
Filtration	Two-stage filtration: oil separation and bag filters.
Airflow	Centrifugal supply fan with indirect-drive transmission.

The air treatment follows a linear sequence: outside air is drawn through the dampers, heated by the burner, and humidified by water spray. Once treated, the air is forced through distribution ductwork to the booth’s plenum, as we can see in 3.10.

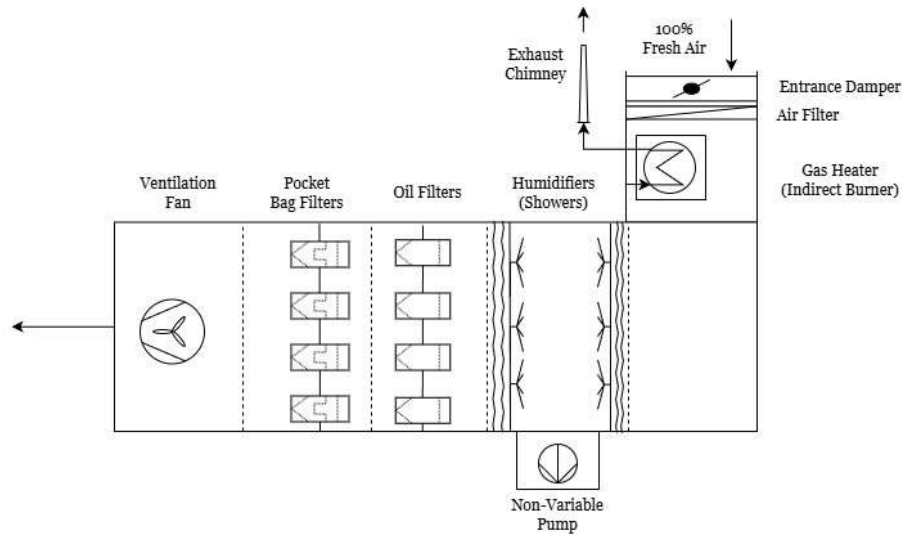


Figure 3.10: Schematic of the intake air supply

Thermal regulation in the ASU is provided by an indirect gas burner, which heats the incoming air before it is supplied to the painting booth. Humidification is performed downstream through an adiabatic water-spray system. In this configuration, liquid water is introduced into the air stream and evaporates by absorbing heat from the air, increasing the humidity ratio while producing an associated cooling effect. The humidification system operates with a fixed-flow pump, meaning that the supplied water flow is not continuously adjusted according to the instantaneous intake-air condition.

The combined heating and humidification stages define the final supply-air condition delivered to the booth. Therefore, the resulting booth temperature and relative humidity depend not only on the burner and humidifier operation, but also on the outdoor-air condition, airflow rate, evaporation efficiency and the interaction between sensible heating and adiabatic humidification[34].

3.2.3 Comparative Analysis: ASU1 vs. ASU2

Despite sharing the same technical specifications, the performance of the two units differs significantly due to the plant's physical layout and the constraints of fixed dampers, as summarized in Table 3.3.

Table 3.3: Comparative analysis of ASU1 and ASU2 operational status.

Feature	ASU1 (Zone 1)	ASU2 (Zone 2)
Distance to Booth	Short (Direct connection)	Long (Significant thermal loss)
Response Time	Stable and near-instant	High transport delay (τ_d)
Control Set-point	Fixed at 22°C	Manual operator overrides
System Stability	Moderate reliability	High volatility / Slow ramp-up

A relevant observation is the physical separation between the Air Supply Units (ASUs) and the paint application point. Although this distance may contribute to some delay or difference between the air condition controlled at the ASU and the condition experienced in the painting booth, the magnitude of this effect has not yet been experimentally confirmed. Therefore, it should be treated as a possible contributing factor instead.

Shop-floor observations and team feedback indicate that operators manually adjust the ASU burner set-points according to perceived booth conditions. During high-temperature periods, the set-point may be reduced to avoid additional heating of an already warm booth, while during cold weather or morning start-up it may be increased to accelerate warm-up. Since the system has no active cooling function, reducing the burner set-point should be interpreted as a reduction of heating demand, not as active cooling.

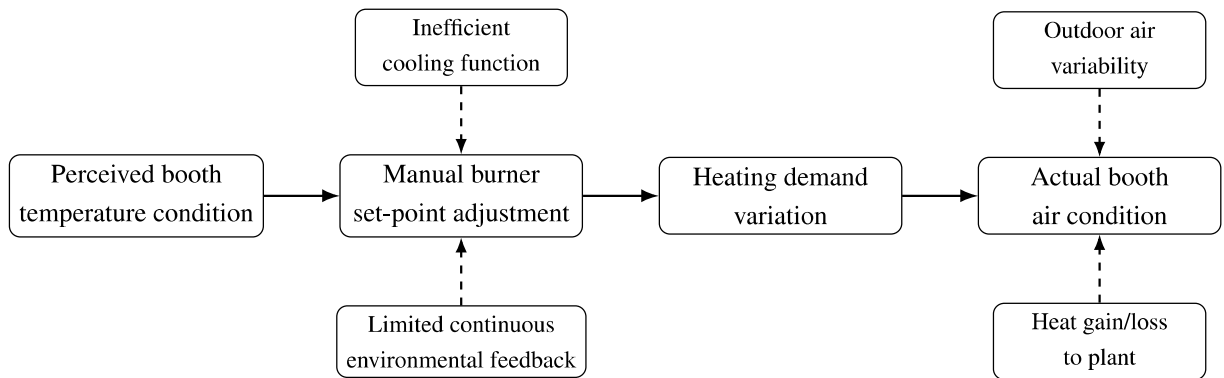


Figure 3.11: Observed manual burner set-point adjustment mechanism and feedback limitations.

This behaviour suggests that manual set-point adjustment is used as an operational compensation mechanism. The underlying issue is therefore not the operator intervention itself, but the limited feedback between measured booth conditions, ASU control settings and standardised reaction logic. The root-cause logic associated with this observation is analysed through the 5 Whys method in Table 3.4.

Table 3.4: Root Cause Analysis: Manual Burner Set-point Adjustments

Level	Question	Answer
1	Why are burner set-points manually adjusted during production?	Operators use the burner set-point to react to perceived booth temperature conditions.
2	Why is the burner set-point used as a reaction variable?	It is one of the few available local adjustments that can influence heating demand during production.
3	Why can this create inconsistent process control?	The burner set-point does not necessarily correspond to the actual booth condition; measured booth temperature may differ from the selected set-point.
4	Why is the actual booth condition not managed through a standardised response?	Environmental information is limited and the reaction to temperature and humidity deviations is not formally defined at the control interface.
5	Root cause	The current environmental control approach relies on manual interpretation of booth conditions, with limited feedback between measured air conditions, set-point adjustment and process-control requirements.

This method allowed to reach a root cause to be addressed in the to-be proposal and a significant area of improvement in the confort of paint operators.

3.3 Measurement System

In this painting booth, the parameters measured are the temperature and humidity. They are measured in two spots, to reflect the conditions in two places, inside the cabin and at the entrance before the cabin. The measurement takes place two times a day, in both places, to reflect the daily variations of humidity and temperature in the intake air. The current manual measurement protocol (twice a day) is insufficient to capture the intra-shift environmental volatility. Since the process is highly sensitive to external weather changes and the heat load from the oven, a discrete sampling method fails to provide the high-frequency data required for a closed-loop control system. There is no standard measurement protocol, only an accepted procedure, in which a hygrometer is used (Figure 3.12).



Figure 3.12: Measurement instrument: digital hygrometer used for manual data collection.

The measurement instrument was not ATEX/CE approved and lacked its calibration and maintenance plan, so this author will interpret the data collected as a direction and not as certain values. As regards booth pressure balance, no dedicated differential pressure measurement device was available during the AS-IS diagnosis. The only existing indication consisted of adhesive tape placed at the entrance and exit of the painting booth, as shown in Figure 3.13. This method does not quantify the pressure differential; it only provides a qualitative indication of the direction of air movement through the booth openings.



Figure 3.13: Qualitative visual indication of booth pressure balance using adhesive tape.

The interpretation adopted for this visual method is summarised in Figure 3.14. A tape deflection towards the inside of the booth indicates negative pressure, while a deflection outwards indicates positive pressure. If the tape remains approximately vertical, the booth is interpreted as being close to a balanced pressure condition.

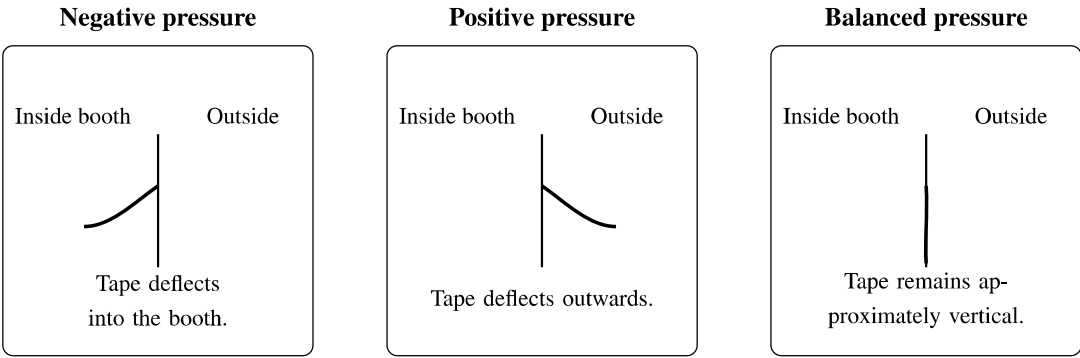


Figure 3.14: Qualitative interpretation of booth pressure balance using adhesive tape deflection.

This observation is relevant because booth pressure balance affects both application quality and safety. Negative pressure can support containment of solvent-laden air within the booth, whereas positive pressure can reduce the ingress of external dust and contaminants. However, excessive deviation in either direction may disturb airflow, overspray evacuation and booth cleanliness. Therefore, the desired condition should not be interpreted as an uncontrolled positive or negative state, but as a controlled pressure balance consistent with the booth design intent and safety requirements [35, 71].

The use of adhesive tape is therefore considered a qualitative visual check, not an adequate measurement method for process control. The absence of dedicated differential pressure instrumentation limits the ability to quantify booth balance, detect gradual airflow degradation and link pressure deviations to coating quality or alarms in ventilation performance.

3.4 Data Recording and Usage

After taking the measurements, manually and without any standard protocol or timing, the values are registered in a control chart similar to the one shown in Figure 3.15.

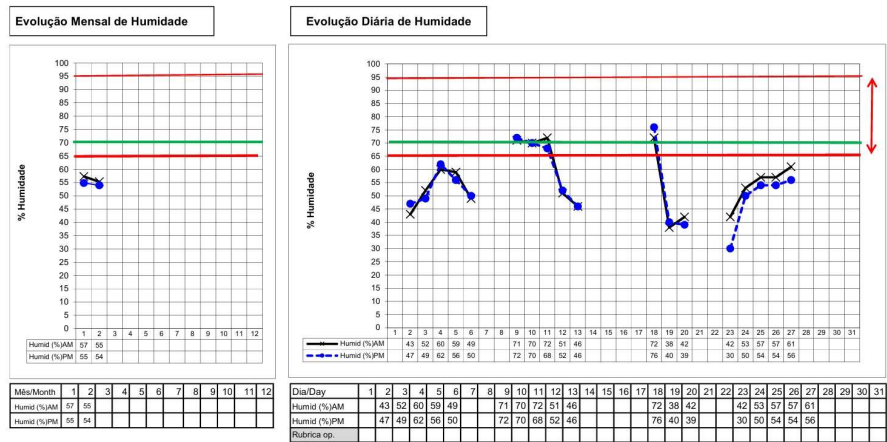


Figure 3.15: Manual control chart used for recording daily temperature and humidity variations.

After researching documentation and comparing with the standards of the process, this author realized that the limits on the control chart were not reflecting the process parameters of the Ryohin Joken. Despite having a registry of the values of temperature and humidity, if these values fall outside the standard that was displayed in the control chart, there was no decision of stopping production. This data recording was merely a recording with no actionable protocol associated with it.

3.5 Identified Limitations

The diagnostic phase, supported by the Gemba walk and interviews with Maintenance, Manufacturing Engineering and Shop Floor members and an internal audit from an expert, revealed a complex set of limitations. These were categorized to better understand the gap between the current state and the standards.

3.5.1 Infrastructure and Equipment Reliability

From the maintenance and facilities perspective, the primary concern is the advanced age of the installation (dating back to the 1970s) and the lack of a proactive technical strategy. However, the diagnosis observations do not restrict to those areas, and can be enumerated as follows:

- **Structural degradation:** Generalized corrosion in the main booth structure, posing risks of particle contamination and poor thermal isolation.
- **Condensation and acidic corrosion at the burner chimney:** Evidence of condensation was observed in the exhaust chimneys of both ASUs. Technical assessment indicates that the burners' minimum power rating is over dimensioned for specific operational phases, preventing exhaust gases from remaining above the dew point. This results in the formation of acidic condensate (containing sulphuric and nitric gas), which leads to accelerated chemical corrosion of the chimney structure and poses a long-term risk to asset integrity.



Figure 3.16: Acidic corrosion on the burner chimney

- **Sub-system failures:** Recurrent breakdowns in aspiration water pumps and filtration showers, compromising air cleaning efficiency. There is a documented leak from the showers compartment to the air intake compartment.
- **Humidifier inefficiency:** The adiabatic system suffers from poor atomization and leaks, leading to water accumulation in the intake system. Comparing the original requirements and the technical data of the installed pumps, it was noted that the pump utilized on this system did not have sufficient flow to correspond to the systems requirement.
- **Lack of predictive maintenance:** Maintenance is restricted to a "run-to-fail" approach or general annual shutdowns, with no predictive monitoring of critical ASU components.
- **Industrial water use:** The current facility is using industrial water in the humidification system. This can be connected to the inefficiency of the humidifiers nozzles and concerns about defects and elevated electrical conductivity.
- **No water monitoring or cleaning system:** According to Verein Deutscher Ingenieure, in all water systems, it is necessary to have a bacteria control. There is also no presence of bacteria control system or a conductivity sensor to understand the purity of the water and consequently, no purge and refill protocol to renovate this water, which can be highlighted by Figure 3.17.

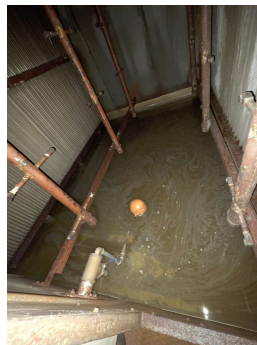


Figure 3.17: Water condition in the air washers

- **Wrong lighting system:** The burner on ASU2 displays a warning light "Burner Mal-function" despite being correctly functioning. This happens because of faulty wiring that switched the warning light in the normal functioning light.



Figure 3.18: Electrical board: ASU2 burner malfunctioning light

3.5.2 Process Stability and Thermal Dynamics

The physical behaviour of the booth reveals deep thermodynamic inconsistencies:

- **Thermodynamic Conflict:** The burner's heat input lowers Relative Humidity, while the fixed-flow water atomization induces evaporative cooling (latent heat). This forces the burner to over-compensate for the humidifier's cooling effect, resulting in chronic instability and wasted gas and water consumption.
- **Thermal Imbalance:** A localized "heat pocket" at the end of Painting Zone 2, exacerbated by the distance from ASU2 and radiation and airflow from the drying oven.
- **Intra-shift volatility:** High variability in temperature and humidity makes it impossible to maintain steady painting viscosity, forcing painters to manually compensate via fluid tip adjustments.
- **Excessive overspray:** It was reported and observed in *Gemba*, that there is an excessive overspray of paint when painting units.
- **Lack of seasonal logic:** Static ASU parameters regardless of intake air enthalpy lead to significant stability gaps during seasonal transitions (Winter/Summer).

3.5.3 Operational Control and Safety

Interviews revealed a lack of robust procedural support and critical safety concerns:

- **Electrostatic safety risks:** Painters reported frequent electrostatic shocks when contacting car bodies. This is a critical safety issue directly linked to low relative humidity levels (<50%) which favour static charge accumulation. It was also observed that the gloves on the painters were not conductive. The viscosity of the paint promoted isolation of the painters booths and clothes and consequently the accumulation of charges.
- **Measurement subjectivity:** Absence of a standardized measurement protocol (frequency and location) leads to unreliable data for decision-making.

- **Passive Recording Structure:** Lack of "Go/No-Go" logic or a formal reaction plan means production continues even when environmental conditions are out-of-spec.
- **Decoupled regulation:** The burner (modulating) and the humidifier (binary ON/OFF) operate independently. The lack of integration means moisture injection does not adapt to heat input, causing uncompensated humidity drops.
- **Reactive monitoring:** Sensing is restricted to the plenum. Without intake air characterization, the system cannot anticipate ambient changes, failing to stabilize during rapid morning-to-afternoon transitions.
- **Absence of light in the in-production inspection post:** Team members check the painting results before the flash-off, however there were voiced concerns that there is not enough light on this space to make adequate inspection.

3.5.4 Water Quality Assessment

To support a more data-driven assessment of the humidification water system, pH and conductivity measurements were performed using available plant measurement instruments. These parameters were selected because they provide an accessible indication of water chemistry and dissolved ionic content and their standard values can be shown in Table 3.5.

Table 3.5: Reference values for industrial water quality in spray-humidification systems.

Parameter	Minimum Reference	Maximum Reference	Reference
pH	6.0	8.5	[73, 74]
Conductivity (mS)	0.5	0.7	[73, 74]

The measured values were measured in a controlled environment, in the plant laboratory, resulting in Table 3.6.

Table 3.6: Conductivity and pH measurements of ASU water.

Sample	pH	Conductivity (mS)
1	8.81	5.50
2	8.77	5.52
3	8.79	5.38
Mean	8.79	5.47

The measured pH indicates slightly alkaline conditions. Although this value alone does not determine water suitability for humidification, alkaline conditions combined with elevated conductivity suggest significant dissolved mineral content. Electrical conductivity is commonly used

as an indirect indicator of dissolved ionic species and total dissolved solids (TDS), with higher conductivity values generally corresponding to higher concentrations of dissolved minerals and salts [73, 75].

In humidification equipment, elevated dissolved solids may contribute to precipitation, scaling, nozzle fouling and increased maintenance requirements. These phenomena can reduce atomisation quality and weaken the consistency of the humidification response [76]. Therefore, water quality monitoring should be considered part of the TO-BE environmental control strategy, especially if the system is expected to operate with variable-flow control and diagnostic feedback based on Industry 4.0 principles.

It is important to note that conductivity alone does not fully determine water suitability. The measured values should be interpreted as evidence of increased water quality risk that can indicate the presence of iron, which can be supported by evidence in Table 3.6, dissolved into the water and water that will accelerate corrosion process.

3.5.5 Internal Audit Data

Due to the instability presented on the painting booth, an internal audit was made with experts capable of gathering more data about the behaviour of the air flow in the painting booth. This audit was done in 2025 and the goal was to assess the operational conditions of the facility, as show in Table 3.7

Table 3.7: Downdraft Measurement Protocol in m/s

Status	Range (m/s)	Zone name	m	L2	L1	M	R1	R2
Optimal	0,50 – 0,60	Painting Area 2	18					
Acceptable	0,40 – 0,49		17		0,55	0,47	0,65	
Below Target	0,25 – 0,39		16		0,39	0,48	0,54	
Above Target	0,61 – 0,70		15		0,36	0,28	0,53	
Critical High	> 0,70		14		0,45	0,35	0,32	
Very Low / Reverse Flow	< 0,25		13		0,32	0,36	0,37	
			12		0,55	0,65	0,53	
			11		0,57	0,66	0,61	
		Painting Area 1	10		0,94	0,47	0,61	
			9		0,22	0,34	0,41	
			8		0,35	0,33	0,3	
			7		0,37	0,36	0,39	
			6		0,39	0,52	0,42	
			5		0,35	0,39	0,45	
			4		0,35	-0,33	0,26	
			3		0,38	0,42	0,63	
			2		0,43	0,48	0,4	

Comments:

Inlet damper ASU1 adjusted at 5%.

Inlet damper ASU2 adjusted at 27%.

As it can be observed in the Table 3.7, the painting booth does not have a homogeneous downdraft flow. This can cause vortices in the air that cause imbalances in the booth and do not contribute to capture the overspray, that can be evidenced by negative values and inconsistencies

inside the same painting zone. The inlet dampers adjustment is also reported in this audit. The ASU1 inlet damper is adjusted at 5% and the ASU2 inlet damper is adjusted at 27%. This imbalanced and very constricted airflow contributes to turbulence and excess effort of the ventilator on each ASU.

3.6 Climate Stability and Trend Analysis

Despite the observations made in the previous section, it was important to understand the climate stability of the process and the conclusions we could extract from the current records. Using Power BI, DAX functions and queries, this author will consider this data with the limitations of the present measuring system and will focus on trends and variations and not exact values, hence why some of the graphs do not have the values presented.

To firstly understand our process, this author's first question was if the process parameters were stable during the day. For this analysis, we compared the measurements taken in the morning and the afternoon for temperature and relative humidity. As we can observe in the Figure 3.19, the relative humidity presents significant oscillations between the AM and PM period. The afternoon period less humid that the morning period.

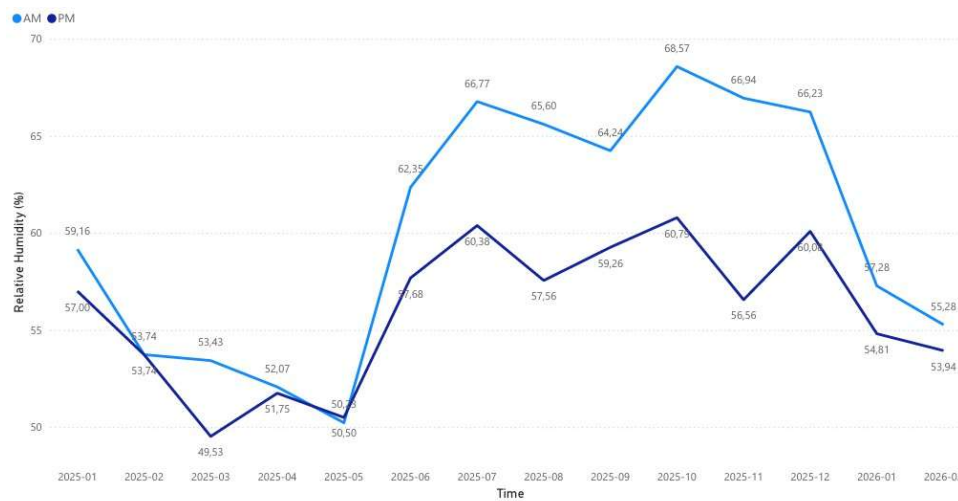


Figure 3.19: Intra-shift variability of relative humidity

This means that the process is not stable and cannot maintain the relative humidity, during the day, in fact we can observe an intra-shift variability, being more prominent in the cold months, having variation values up to 10,38% and a average of 4,20% all year. This variations of intra-shift volatility show that the present process cannot maintain a relative humidity through the day, which can cause higher probability of defects and ignitions within the ATEX zone. This volatility also demands that the painters have to adjust to their conditions at the start of the painting process. Understanding the temperature is also important in the manual process, since it can affect the

viscosity of the paint as well as the comfort of the painters [32]. It was firstly analysed the status of the temperature measurements, as shown in Figure 3.20.

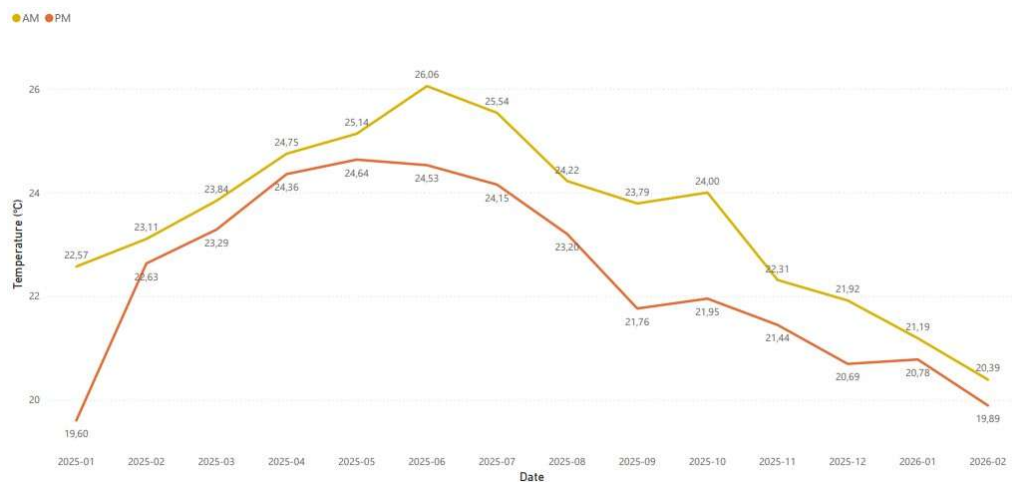


Figure 3.20: Intra-shift variability of temperature

We can see that there is also a variability of temperature between the shifts, despite being less significant. There is up to a 2°C difference between the morning period and the afternoon, however the monthly average stays at 1,14°C variation. According to [29], a variation on 1°C results in a variation of viscosity of . This variation of 2°C in the monthly average can be translated into the adjustments of the viscosity adjustments the experienced painters were observed to do. Consequently, this adjustments resulted into time losses and deviation of standardized work.

In a production point of view, when analysing a process that requires controlled temperature and relative humidity, the first question one should ask is if these parameters are within the interval of production, the Ryohin Joken standards (Table 3.8).

Table 3.8: Process values for relative humidity and temperature.

Environment	Relative Humidity (%)	Temperature (°C)
Painting Booth	55–80%	18–28°C

These values are demonstrated in the figures bellow (Figures 3.21 and 3.22) in red lining, highlighting the process parameters window when compared to actual monthly values of the process.

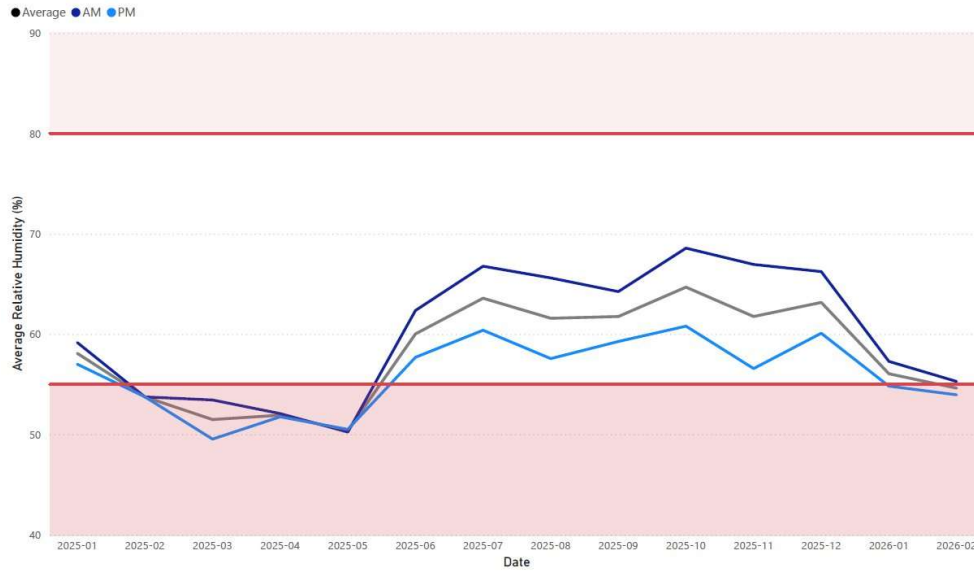


Figure 3.21: Go/No-Go standards of production: relative humidity

In Figure 3.21, we can observe that during the months of February, March, April and May, the monthly average of the relative humidity inside the paint booth was outside the production standards, by up to 5% of deviation. Allowing production to continue on these occasions introduces a high risk for process stability and the final product quality [11, 33]. Furthermore, low humidity values are associated with high electrical conductivity of the air [33]. The measured conductivity values were above the recommended operating range, increasing the risk of electrostatic discharge during paint application and possible ignition. Under these conditions, an electric arc may occur between the spray gun and the vehicle body or other conductive elements if charge dissipation is not adequately controlled. Since the coating operation takes place in an ATEX-classified area, this represents a relevant safety risk, as solvent vapours and paint aerosols may contribute to the formation of a potentially ignition.

This figure also highlights the incapability of this process to stay within the process parameters and justifies the need for a control system that can better regulate the relative humidity of the booth air.



Figure 3.22: Go/No-Go standards of production: temperature

In the figure 3.22, it was observed that the temperature values are consistently inside the Ryohin Joken standards. This is justified by the existence of a temperature control system, that is regulated by a sensor (Pt100) placed inside the ventilation duct of each ASU. This ASU is 100% fresh air system, which means that an unregulated system is highly subjected to the outside conditions, both in relative humidity (Figure 3.23).



Figure 3.23: Comparison between outside air and booth: relative humidity

In regards to relative humidity, the Figure 3.23, it is possible to conclude a few key points. The relative humidity does not depend on the outside air humidity, despite having a close connection in the months of July and August. Coincidentally, these months are the hotter months of year, where the painters have reported to shutdown the burner. When in use, the burner as a natural

dehumidifier function, as well as increasing the temperature of the air, which can explain this proximity of values during these months since it is not working in this period. An 100% fresh air system means that is highly subjected to the outside conditions, also in temperature that can be illustrated by Figure 3.23.

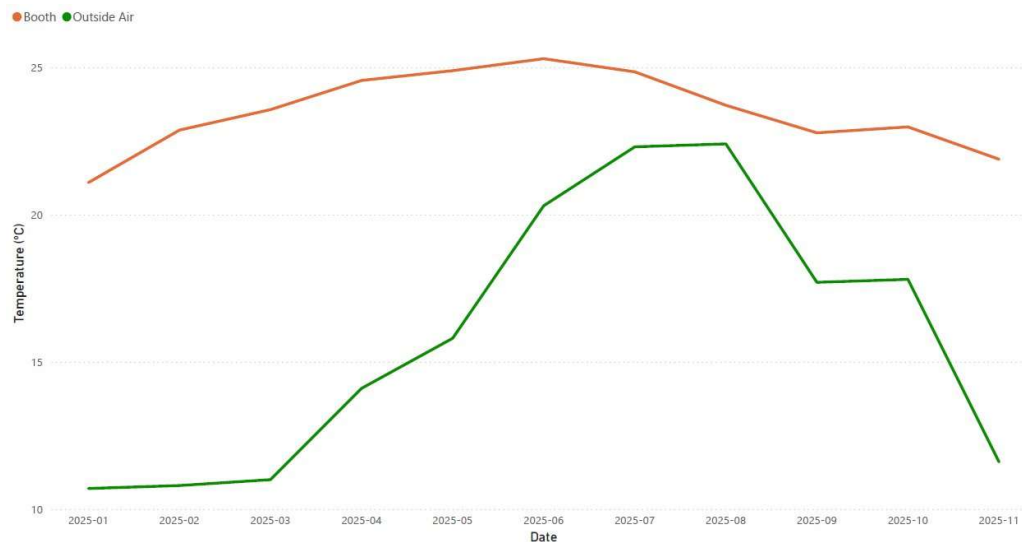


Figure 3.24: Comparison between outside air and booth: temperature

Figure 3.24 illustrates the internal temperature profile of the painting booth, which is consistently maintained within the 20–27°C operational window. Data indicates an upward thermal drift during the months of March to July, where average temperatures trend above the 22.0°C set point. This internal temperature rise correlates with seasonal external heat variations, highlighting that the current cooling infrastructure lacks the capacity to decouple internal process conditions from ambient thermal fluctuations.

In Figure 3.25, we have the relationship between the temperature and relative humidity. This is an critical relationship, as a general rule, the temperature is inversely proportional to the relative humidity.

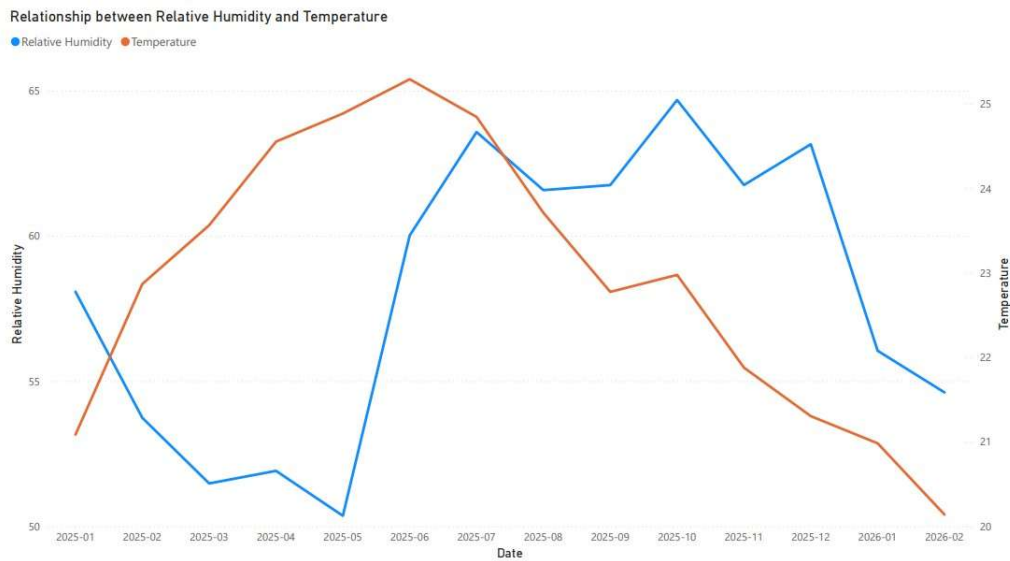


Figure 3.25: Relationship between Temperature and relative humidity

Figure 3.25 shows that, during colder months, when the system requires more heating to reach the required temperature range, relative humidity tends to decrease. This indicates that the humidification system is not able to fully compensate for the RH reduction caused by air heating, which is one of the main limitations of the current environmental-control process. This Figure 3.25, it was possible to highlight that temperature and relative humidity and temperature are connected through psychrometric relationships. To stabilize the variables of the painting booth, it will be important to take into consideration this relationship.

Through climate stability analysis, it was possible to understand the stability of relative humidity and temperature in this painting booth, and the relationship between the two variables. Being an 100% fresh booth, it was possible to quantify the influence of outside air conditions on the painting booth environmental condition. This will be crucial to understand the AS-IS status and choose the adequate strategy to stabilize and allow the repeatability of the process.

3.7 Statistical Process Control

The available dataset consisted of monthly defect records and bi-daily environmental measurements taken in the morning and afternoon. These records were done manually, so it was necessary to clean and treat the 2025 data.

3.7.1 Data Treatment and Classification

Since the number of inspected vehicles varied between months, defect counts were normalised by the number of inspected units before correlation analysis. Therefore, defect rates were used instead of absolute defect counts.

3.7.1.1 Defects Analysis

The quality control of this process is done visually, with human inspections on the post QCTC1, focused on quality appearance (Figure 3.26).



Figure 3.26: Quality control top-coat inspection post (QCT1)

The inspectors perform a lot of technical, appearance and measurements specifications with the goal of detecting and mitigating defects, constraining them in the painting sector. This quality control is essential in the automotive manufacturing process and allows for a analysis of the main defects and defect rate of the manufacturing process in the painting shop, which includes more than top coat application. The defect data collection is done manually, through a written report that is then , monthly, updated to an excel for the monthly report analysis. To ensure systematic data collection and root-cause analysis, all observed defects are categorized according to a standardized taxonomy. This classification structure facilitates the segregation of defects by severity, location, and nature, enabling targeted process improvements.

3.7.1.2 Defect Classification

The defect data is classified based on the following three criteria:

- **Spatial Zone:** Defects are mapped to specific regions of the vehicle body (e.g., hood, doors, roof) and the defects are classified according with their location, as illustrated in Figure 3.27. The criticality of each zones is tightly linked to client observation of the production, for example, inside the wheel cover is a less critical zone than the hood, since the last one is much more visible and easily inspected by the final client.

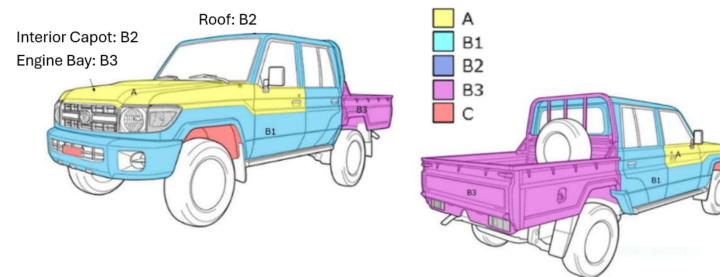


Figure 3.27: Standard of spacial zones for defect analysis

- **Severity and Appearance:** Defects are graded based on their visual impact, ranging from *Minor* (polishing required) to *Major* (rework/repaint required). This degree of appearance is critical for cost-of-quality calculations.
- **Dimensional Magnitude:** Defects are categorized by size (< 1 mm, $1 - 3$ mm, > 3 mm). Larger defects often suggest contamination or mechanical failures, whereas smaller defects are typically related to rheology issues.

Table 3.9 provides a summary of the classification methodology used during the inspection process.

Table 3.9: Defect classification.

Category	Classification Criteria
Zone	Vehicle body map sectors (visible vs. non-visible surfaces).
Degree of Appearance	Scale 1–5: Visual impact and potential for rework.
Dimension	Size grouping for statistical frequency tracking.
Nature	Type (e.g., Sag, Boiling, Pinhole) based on Toyota’s quality standards.

Combining the ranking of the four areas of classification, the quality control post defines if the defect will go to rectification post and the degree of reparations that would be made, illustrated in Figure 3.28.



Figure 3.28: Rectification post

3.7.1.3 Pareto Analysis of Process Defects

Using the annual defect report of 2025 for QCT1, it was identified that the repair rate was 100% every month. Compared with the 2 value of 8%, this is a contrast of realities between legacy paint shops and the present day standards of automated industries. This also highlights a greater opportunity for process improvement on this painting shop line that will drive this research. It was necessary to first identify the specific defects that appear more often, using Pareto analysis, in Figure 3.29 breaks down all recorded defects for 2025, applying the Pareto Principle (80/20) to separate the "vital few" from the "useful many" and allow to prioritize and refine our analysis.

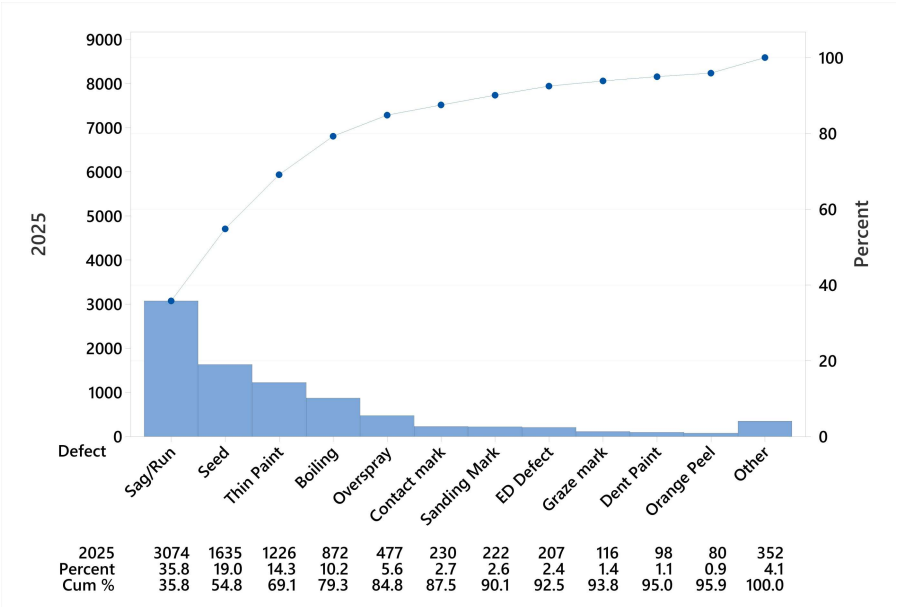


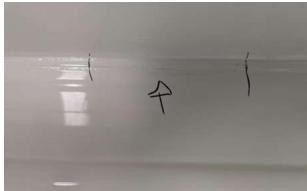
Figure 3.29: Pareto analysis of 2025 top coat defects.

The clustering of *Sag/Run*, *Seed*, *Thin Paint* and *Thin Paint*, representing 82% of detected defects, indicates a process highly susceptible to rheological variance and impurities and cleaning abnormalities (*Seeds*). The high presence of sealer related defects can be attributed to a new defect classification that occurred in 2025, related to sealer defects that cause a spike in this type of defects. In interviews with quality department, the accumulation of seeds in the top coat application stage is result of an ageing and poorly controlled structure. The accumulation of dust, poor isolation of dust inclined areas and general manual handling of car conveyors contribute to this type of defect.

While this analysis provides a comprehensive overview, this research focuses specifically on the top-coat application stage. Defects originating in earlier stages, such as sealer anomalies or

general substrate issues, are outside the scope of this study. To isolate the effects of the booth climate, we identify six primary defect modes as visualized in Table 3.10.

Table 3.10: Classification of observed automotive coating defects.

Sag/Runs	Orange Peel	Thin Paint
		
Popping/Pinhole	Overspray	Boiling
		

Note: Defect detection requires trained visual and tactile inspection.

In Table 3.11, we can have a preliminary theoretical root cause, using information from suppliers sources and inspection team leaders[29, 77]. This mapping categorizes the defects with an example of defects on the Land Cruiser 70.

Table 3.11: Climatic dependency matrix for top-coat defect modes [27, 29, 77].

Defect Category	Climate Driver	Physical Mechanism
Viscosity-Driven		
Sag/Runs	Ambient Temperature	Viscosity reduction/slumping
Thin Paint	Ambient Temperature	Flash-off kinetics
Thermodynamic		
Popping/Blistering	Humidity	Solvent entrapment/Evaporation
Orange Peel	Airflow/Velocity/Humidity	Coalescence efficiency
Kinetic		
Overspray	Extraction Efficiency	Spray dust redeposition

3.7.1.4 Methodology

To ensure the analytical integrity of this study, three primary methodological options were implemented:

1. **Normalization:** Defect counts were normalized as defect rates (defects per unit) to eliminate bias from fluctuating production volumes.
2. **Data Stratification:** Analysis was restricted to climate-sensitive defect modes (*Sag/Run*, *Orange Peel*, *Thin Paint*, *Popping/Pinhole*, *Overspray* and *Boiling*) to isolate the top-coat application performance from upstream substrate "noise."
3. **Model Selection:** The Laney U' model was selected over the standard u -chart to account for significant overdispersion ($\sigma^2 \gg \mu$), ensuring that control limits reflect actual process variability rather than mathematical artifacts.

3.7.1.5 Environmental Indicators

The selection of environmental indicators was driven by the physical requirements of the top-coat application process, specifically solvent evaporation kinetics, paint rheology, and air stability. The indicators are defined as follows:

Mean Variables (T_{mean} , RH_{mean}): Define baseline conditions affecting the steady-state rate of solvent evaporation and paint viscosity during application and leveling.

Variability Indicators (ΔT , ΔRH): Quantify intra-shift fluctuations, which induce transient process instabilities and localized defects more effectively than steady-state measurements.

Out-of-Specification Share (RH_{OOS}): Acts as a performance metric for the control system, directly correlating process non-compliance with potential defect formation.

This approach ensures that both steady-state performance and transient disturbances are accounted for in the evaluation of coating consistency.

With both of these variables, the data was merged and aligned by month to create the final 12 point series used in the next analysis.

3.7.2 Diagnostic Validation

The defect dataset underwent a statistical audit to ensure its suitability for environmental dependency modelling. The results are summarized in Table 3.12, obtained using Minitab software.

Table 3.12: Diagnostic validation summary of the 2025 defect dataset.

Diagnostic Test	Objective	Outcome
Overdispersion	Evaluate Poisson assumption.	Not confirmed ($\sigma^2 \gg \mu$).
Stationarity	Verify stability of process mean.	Confirmed ($P = 0.790$).
Independence	Ensure uncorrelated observations.	Confirmed.

Although the process mean is stationary ($P = 0.790$), the diagnostic audit revealed significant overdispersion ($\sigma^2 \gg \mu$) in the defect counts. Under these conditions, a standard Poisson-based u -chart would produce excessively narrow control limits, leading to an inflation of Type I errors (false alarms)[58]. To ensure the statistical integrity of the process stability analysis, the Laney U' chart was implemented. This model incorporates an adjustment factor to account for the observed overdispersion, providing control limits that accurately represent the process's inherent variability.

3.7.2.1 Correlation and Independence

Table 3.12 validates the independence of observations.

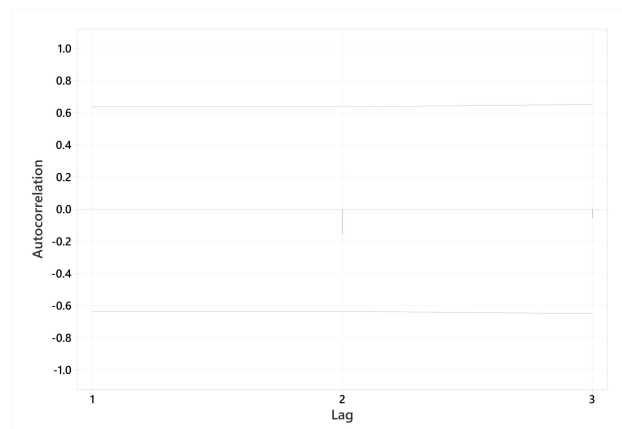


Figure 3.30: Autocorrelation Function plot.

Confirming the independence of defects data, the monthly defect counts were treated as a time series to evaluate the stability of the painting process. The independence of these values was verified via ACF, confirming that the monthly defect rates are not autocorrelated and are therefore suitable for regression analysis against environmental variables.

3.7.3 Process Stability Analysis: Defects

Figure 3.31 presents the Laney U' chart for the 2025 production period, plotting the mean of number of defects recorded against their statistical control limits.

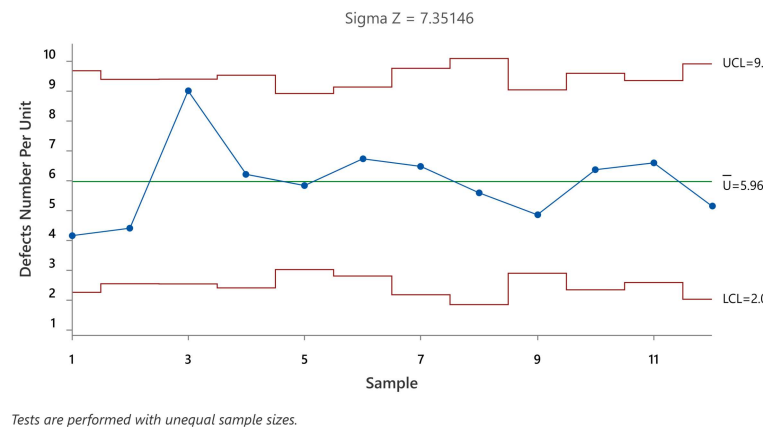


Figure 3.31: Laney U' control chart for climate-sensitive defects.

As illustrated by the Laney U' chart, the process remained within statistical control limits throughout the 2025 period, with an upper threshold of $UCL = 9.91$. The analysis confirms the expected process stability, indicating that the observed excursions (such as the March sample) are characteristic of natural process variation rather than systemic failures. Consistent with the principles of statistical process control established by Shewhart, this chart provides a vital baseline for assessing the booth's performance. However, it is important to note that the statistical robustness of this analysis is constrained by the limited sample size ($N = 12$), which should be considered when interpreting the control limits.

Industrially, this result suggests that while the current booth infrastructure maintains control, it operates with a narrow margin of safety during peak environmental volatility. By establishing this benchmark, future infrastructure enhancements can be objectively evaluated: a successful intervention will be evidenced by a reduction in the mean defect rate ($\bar{U}$) and a narrowing of the control limits, reflecting an improvement in both process performance and statistical stability.

3.7.3.1 Environmental Compliance Analysis

Regarding process compliance with the defined requirements, the bi-daily relative-humidity measurements were used to determine how many readings were outside the specification range for the electrostatic painting process. The monthly relative-humidity out-of-specification share is shown in Figure 3.32.

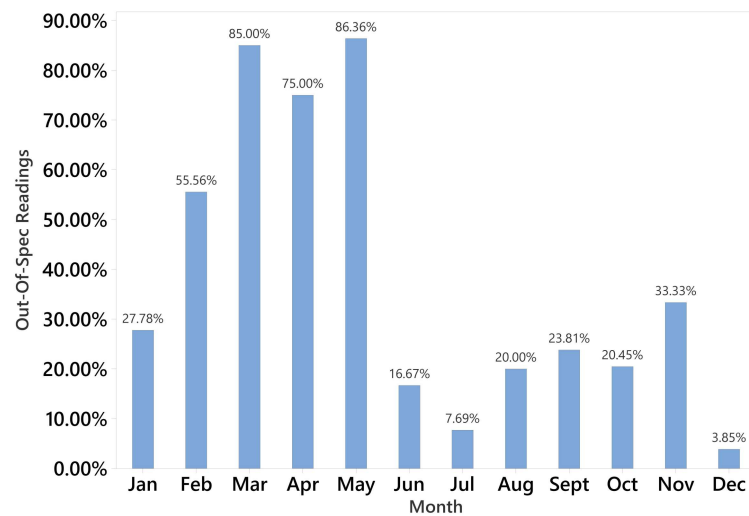


Figure 3.32: Monthly relative humidity out-of-specification share.

March and May registered the highest percentage of relative-humidity readings outside the specification, with values reaching up to 86% of the measurements. It is important to note that in May, there was a reparation made: the cleaning of nozzles and of the humidifier tank that can have an impact on the out-of-spec readings after this month, decreasing their number. This highlights not only the instability of the painting process, but also the high level of non-compliance with the process specification. This supports the need for a humidity-control project to stabilise the process and improve the consistency of coating application.

In contrast, July and December registered low out-of-specification values of 8% and 4%, respectively. The temperature readings presented 0% out-of-specification measurements, indicating that temperature remained within the defined limits. However, being within specification does not necessarily mean that the process is statistically stable or controlled. For this reason, SPC was also used to assess the behaviour of temperature and relative humidity over time.

3.7.3.2 I-MR Chart Selection and Assumptions

Following the on-site *Gemba* observations and the identification of structural limitations in the current process, a statistical analysis of the environmental variables was conducted using Minitab® Software, supported by established methodologies in statistical quality analysis [58].

The objective of this analysis was to assess the stability of the painting process by analysing booth temperature and relative humidity, which are known to influence coating quality and defect formation [27].

Given the structure of the available dataset, an evaluation of the appropriate statistical approach was required. Although two measurements per day were available, these observations correspond to different environmental conditions, as demonstrated in Figures 3.20 and 3.19. Therefore, they do not satisfy the assumptions of rational subgroups.

For this reason, Individual–Moving Range (I–MR) control charts were selected as the most appropriate method for analysing process behaviour. The I chart represents the evolution of individual observations over time, while the MR chart captures the short-term variability between consecutive measurements (inter-shift).

However, the use of I–MR charts requires consideration of normality, independence and sampling frequency. Before interpreting the control charts, diagnostic checks were performed for the main environmental indicators used in the stability analysis. Normality was assessed using normal probability plots, histograms and the Anderson–Darling test. Independence was evaluated using autocorrelation analysis.

3.7.3.3 Normality and independence checks

For RH_{mean} , the Anderson–Darling test resulted in $AD = 0.644$ and $p = 0.070$. For T_{mean} , the corresponding values were $AD = 0.434$ and $p = 0.250$. Since both p -values are above the 5% significance level, normality was not rejected for either variable. The normal probability plots did not show severe deviations from the reference line, although the limited number of observations reduces the strength of this conclusion [28].

The independence assumption was only partially satisfied. The autocorrelation analysis showed positive lag-1 autocorrelation for both variables. For RH_{mean} , the lag-1 autocorrelation was 0.713, with $T = 2.47$. For T_{mean} , the lag-1 autocorrelation was 0.637, with $T = 2.21$. This indicates that consecutive monthly values are not fully independent, which is expected for environmental data affected by seasonal behaviour, external weather conditions and system inertia.

The corresponding normal probability plots, histograms and autocorrelation plots are provided in Appendix A.

Table 3.13: Normality and autocorrelation checks for the main environmental indicators.

Variable	AD	p -value	Lag-1 ACF	Lag-1 T	Diagnostic outcome
RH_{mean}	0.644	0.070	0.713	2.47	Normality not rejected; lag-1 autocorrelation detected.
T_{mean}	0.434	0.250	0.637	2.21	Normality not rejected; lag-1 autocorrelation detected.

Therefore, the control charts were interpreted as exploratory diagnostic tools rather than as formal proof of statistical control. The results remain useful for identifying instability patterns, shifts and abnormal variation, but the presence of lag-1 autocorrelation and the low sampling frequency must be considered when interpreting the control-chart signals. In particular, monthly or AM/PM measurements may not capture short-duration disturbances occurring during production.

3.7.3.4 I-MR Analysis of Environmental Variables

The objective of this analysis was to indicatively assess the stability of the painting process by analysing booth temperature and relative humidity, which are known to influence coating quality and defect formation [27].

The I-MR charts were used to evaluate the stability of booth temperature and relative humidity over the analysed period and identify non-random behaviour, shifts, trends and short-term variability. The I-MR chart for temperature, presented in Figure 3.33, reveals the presence of both special-cause and systematic sources of variation.

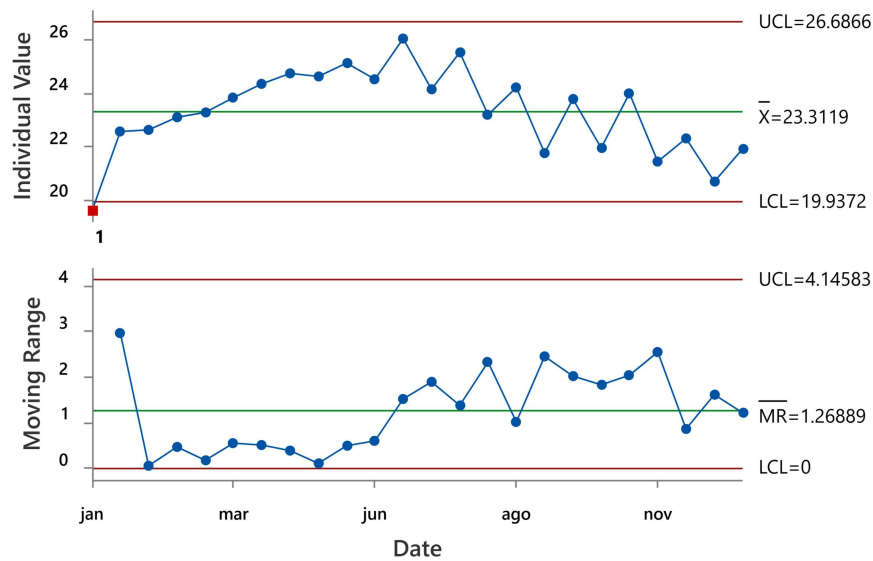


Figure 3.33: I-MR control chart: temperature.

An out-of-control point is observed in January, which demands a special-cause investigation. It was concluded that there were non-standard operating conditions during this period. Since the special cause variation was justified, it was possible to obtain the graph represented in Figure 3.34.

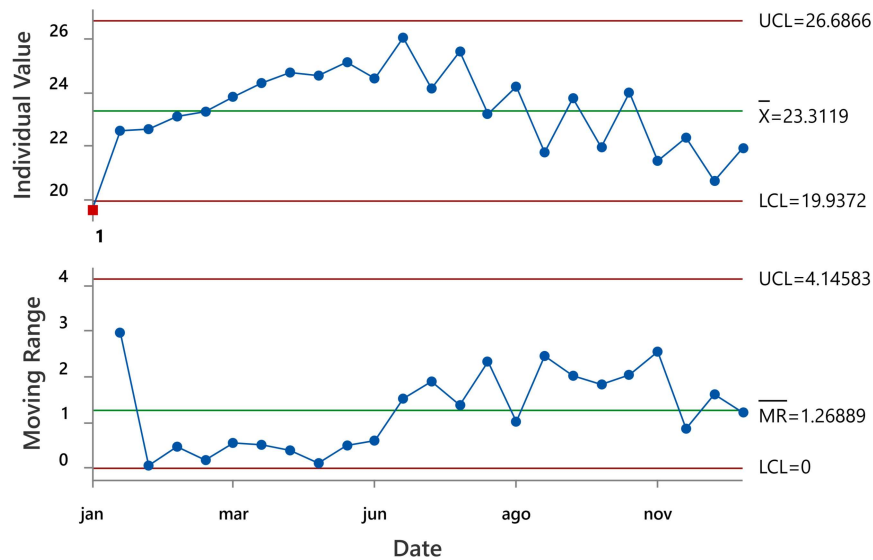


Figure 3.34: I-MR control chart: temperature.

Additionally, a clear temporal trend is identified throughout the year, characterised by an increase in temperature during the summer months followed by a subsequent decrease during the winter months. This non-random behaviour demonstrates that the process is not in statistical control, as the variation is driven by external influences rather than only inherent process variability.

The Moving Range chart indicates relatively low and stable short-term variation during the first half of the year. However, from mid-year onwards, an increase in moving range values is observed, suggesting a rise in intra-day variability that can also be observed in Figure 3.20. Overall, these results indicate that temperature is not maintained at a consistent set point, but rather follows external environmental conditions, highlighting the absence of effective control. The I-MR chart for relative humidity, shown in Figure 3.35, presents a more unstable behaviour than the temperature chart.

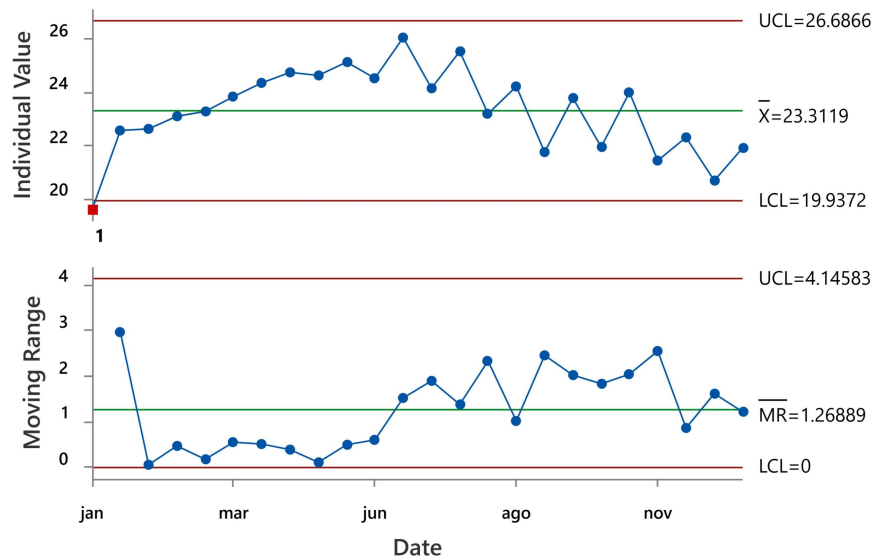


Figure 3.35: I-MR control chart: relative humidity.

During the first months of the year, the Moving Range values remain relatively low. However, from approximately June onwards, the Moving Range values increase, indicating higher short-term variation between consecutive readings.

At the same time, the I-MR chart shows pronounced oscillations and shifts in RH level, confirming that the humidity process is affected by systematic variation rather than only random noise. This behaviour suggests that the current system has limited ability to maintain stable humidity conditions under changing environmental and operating loads.

The combined analysis of temperature and relative humidity indicates that the environmental conditions are not under statistical control. The presence of non-random trends, out-of-control points and systematic variation means that process capability analysis is not appropriate at this stage [58] which highlights the vulnerability of our process to environmental shifts that condition the repeatability of process and standard work.

Capability indices should only be interpreted after the process is stable, otherwise, the calculated capability may not represent the true process behaviour. This instability leads to fluctuating thermal and humidity conditions during coating application, which may affect solvent evaporation, film formation and coating consistency [27, 33].

In this section of process stability analysis, we can conclude that, using the monthly values of temperature and relative humidity measurements and monthly rate defects the electrostatic coating application process environmental variables does not appear to be in control, exhibiting clear patterns and trends. It is also trivial to observe that, despite the reparation made in 2025 that resulting in decreasing of out-of-spec readings, the measurements taken on the painting booth still display values outside of the specification parameter more than 15% of the measured values. That type of out-of-spec readings can mean production stoppage, so it is not acceptable in a painting booth., this can hint at the insufficient capacity of the humidifier system to increase moisture in the air.

A process without being stable is not capable of consistently produce good products [58], which renders the capability analysis not applicable. The focus of this research will first be on stabilizing the process.

3.7.4 Correlation Between Environmental Indicators and Defects

In Chapter 2, we understood that the environmental conditions and the defect rate were linked in the electrostatic coating process. In this subsection the correlation between the defect rate and environmental variables was analysed.

3.7.4.1 Dataset and Analysis Scope

The available dataset consisted of monthly defect records and bi-daily environmental measurements taken in the morning and afternoon. These records were done manually, so it was necessary to clean and treat the 2025 data. Since the number of inspected vehicles varied between months, defect counts were normalised by the number of inspected units before correlation analysis. Therefore, defect rates were used instead of absolute defect counts.

The environmental indicators considered in the analysis were:

- Mean relative humidity, RH_{mean} ;
- Minimum relative humidity, RH_{min} ;
- AM/PM relative-humidity variation, ΔRH ;
- Relative-humidity out-of-specification share, RH_{OOS} ;
- Mean booth temperature, T_{mean} ;
- AM/PM temperature variation, ΔT .

The selected defect categories were those considered more likely to be influenced by booth environmental conditions, film formation, solvent evaporation, atomisation or drying behaviour. A correlation analysis was performed between the selected environmental indicators and the normalised defect rates. Due to the limited number of monthly observations, the results were interpreted cautiously and used only as supporting diagnostic evidence.

Table 3.14 presents a reduced Pearson correlation heat-map between selected environmental indicators and normalised defect rates. Positive correlations are shown in red and negative correlations in blue.

Table 3.14: Full Pearson correlation matrix of process defects and environmental indicators.

Variable	Sagging Rate	Orange Peel	Thin Paint	Boiling Rate	Overspray Rate	Pinhole Rate	Mean Humidity	Mean Temperature	Humidity Variation	Temperature Variation
Sagging Rate	1.00									
Orange Peel Rate	0.348	1.00								
Thin Paint Rate	0.542	-0.007	1.00							
Boiling Rate	0.108	0.144	0.117	1.00						
Overspray Rate	0.341	0.756	-0.256	0.490	1.00					
Pinhole Rate	-0.329	-0.189	-0.125	0.673	-0.011	1.00				
Mean Humidity	-0.407	-0.525	0.440	0.061	-0.654	0.252	1.00			
Mean Temperature	0.788	0.435	0.514	0.051	0.171	-0.159	-0.312	1.00		
Humidity Variation	-0.147	-0.380	0.473	0.460	-0.289	0.431	0.817	-0.243	1.00	
Temperature Variation	-0.322	-0.351	0.072	0.081	-0.389	0.029	0.431	-0.305	0.263	1.00

The correlation analysis of the 2025 production, in Table 3.14 data provides the following objective findings regarding the relationship between environmental booth parameters and surface finish defects:

1. **Environmental Associations:** A strong linear association is observed between Mean Booth Temperature and Sagging Rate ($r = 0.788$). Additionally, a significant inverse association exists between Mean Humidity and Overspray Rate ($r = -0.654$). These parameters demonstrate the most consistent statistical relationship with process variance within the current dataset.
2. **Inter-Defect Dependencies:** Strong positive associations were identified between Orange Peel Rate and Overspray Rate ($r = 0.756$), as well as between Boiling Rate and Pinhole Rate ($r = 0.673$). These relationships suggest that specific defect modes often co-occur, implying shared influence factors during the application and curing stages which was confirmed with quality engineers.
3. **Relative Sensitivity to Environmental Volatility:** Analysis of mean versus delta variables indicates that defect frequencies exhibit a higher sensitivity to absolute mean environmental conditions (T_{mean} and RH_{mean}) than to intra-shift daily fluctuations (ΔT and ΔRH).
4. **Statistical Constraints and Variance:** The calculated r^2 values indicate that environmental parameters account for only a portion of the total observed defect variance. This confirms that the current process is multi-factorial and the influence of climatic factors is limited by

other operational variables. Furthermore, conclusions drawn from associations with $p > 0.05$ must be treated as indicative trends rather than definitive process rules.

Summarized on Table 3.15 are the main findings of the correlation matrix.

Table 3.15: Pearson correlation matrix with statistical significance ($N = 12$).

Primary Variable	Correlated Variable	Pearson (r)	p -value	Inference
Mean Booth Temp.	Sagging Rate	0.788	0.002	Significant ($p < 0.01$)
Orange Peel Rate	Overspray Rate	0.756	0.004	Significant ($p < 0.01$)
Boiling Rate	Pinhole Rate	0.673	0.016	Significant ($p < 0.05$)
Mean Relative Hum.	Overspray Rate	-0.654	0.021	Significant ($p < 0.05$)
Mean Humidity	Humidity Var.	0.817	0.001	Significant ($p < 0.01$)

It was important to note that compared with the pragmatical rule of $N=20-25$ samples [58], with $N=12$, the statistics and correlation analysis could not provide a very narrow confidence intervals. These results are conclusions are merely an indication of possible improvement areas, such as temperature and humidity regulation, and the establishing their relations with defect rate and was interpreted with caution.

3.8 Ishikawa Diagram

Following the most part of the diagnosis chapter, an Ishikawa diagram was used to structure the potential causes associated with booth environmental instability. The objective was to organise the main factors identified during the AS-IS diagnosis and to understand how equipment limitations, measurement gaps, operating practices, environmental variation and maintenance constraints may contribute to unstable temperature and relative humidity conditions.

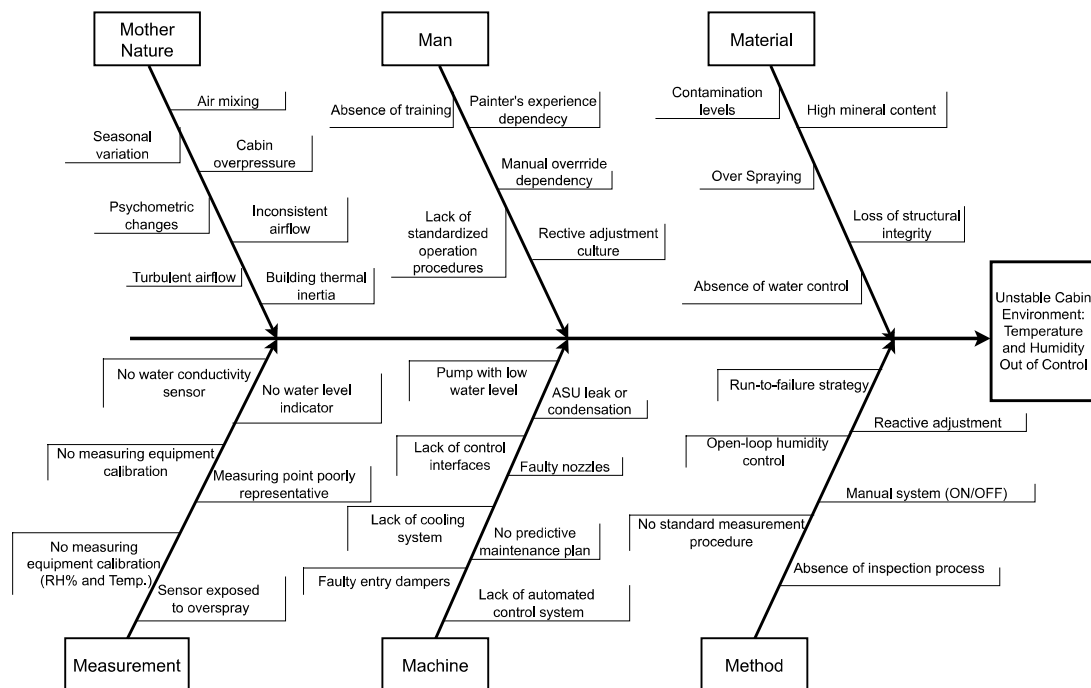


Figure 3.36: Ishikawa diagram analysing root-cause analysis of environmental instability.

The Ishikawa diagram (Figure 3.36) serves as a diagnostic map for this research. By formalizing the root-cause analysis, it reveals that unstable cabin environment is not driven solely by environmental conditions, but by a system where equipment sensitivity, operational technique and material reactivity interact. This diagram bridges the gap between statistical signals and process mechanics, providing the necessary justification for a holistic improvement strategy. Rather than treating only the symptomatic volatility identified in control charts, this approach focuses on the underlying stability of the entire top-coat application process.

3.8.1 Diagnostic Findings-Summary

Table 3.16 summarises the main findings obtained during the AS-IS assessment. The findings were grouped according to the affected process area in order to clarify the main limitations related to environmental stability, equipment condition, measurement capability and operational control.

Table 3.16: Summary of AS-IS diagnostic findings.

Sub-system	Diagnostic finding	Operational effect
I. Spray Environment and Aerodynamics		
Airflow	Downdraft imbalance and audit-identified recirculation.	Reduced overspray evacuation and contamination risk.
Intake Dampers	Fixed/manual intake damper adjustment.	Limited airflow balancing capability.
II. Climate Stability and Humidification Control		
Humidification	Insufficient pump pressure and nozzle fouling.	Poor RH control capability.
Thermal–Humidity	Heating-induced RH reduction.	RH deviations under thermal variation.
Control Logic	Decoupled temperature/RH regulation.	Reactive correction and manual overrides.
Operational Practice	Dependence on operator perception.	Non-standardised reaction logic.
III. Equipment Condition and Water System		
ASU Chimneys	Generalised exhaust-flue corrosion.	Reliability and structural concern.
Humidifiers	Poor atomisation and water leakage.	Reduced humidification effectiveness.
Structure	Ageing booth and ASU infrastructure.	Long-term reliability concern.
Water Quality	High pH and conductivity in recirculating water.	Scaling, fouling and hygiene concern.
Water Renewal	Limited purge and hygiene monitoring.	Potential biological contamination risk.
IV. Monitoring, Measurement and Governance		
Safety / Quality	No automatic Go/No-Go logic.	Production under non-standard conditions.
Data Logging	Manual discrete measurements.	Missed intra-shift environmental drift.
Measurement	Non-standardised measurement protocol.	Reduced data reliability.
Illumination	Low lighting at inspection areas.	Reduced defect detection capability.
Pressure	Adhesive-tape pressure indication.	No quantified booth balance data.

3.9 Failure Modes and Effects Analysis

Although FMEA is traditionally applied as a formal production risk analysis tool, in this dissertation it is used as a diagnostic prioritisation method. The objective is not to certify the painting process through a complete production PFMEA, but to translate the AS-IS diagnostic findings into prioritised improvement requirements. For this reason, the Severity, Occurrence and Detection ratings were based on the AIAG–VDA PFMEA logic, while being adapted to the diagnostic scope of the dissertation [59].

The 1–10 rating scale was preserved. However, the criteria were interpreted using the available AS-IS evidence, namely Ryohin Joken requirements, relative humidity out-of-specification rates,

SPC results, internal audit observations, *Gemba* observations, maintenance feedback, operator feedback and the current level of measurement and control capability.

The analysis includes environmental control, airflow behaviour, equipment condition, water-system condition, measurement capability, reaction logic, pressure visibility and inspection limitations.

3.9.1 FMEA Rating Criteria

Severity, Occurrence and Detection were rated using the criteria shown in Table 3.17. The criteria follow the structure of AIAG–VDA PFMEA evaluation, but are adapted to the context of a legacy painting booth and to the objective of identifying control-system improvement requirements [59].

Table 3.17: Diagnostic FMEA rating criteria adapted from AIAG–VDA PFMEA logic.

Rating	Level	Severity, S	Occurrence, O	Detection, D
10	Very high	Potential acute safety, ATEX or regulatory risk affecting operators, plant compliance or safe process operation.	Failure cause is extremely likely or has no effective prevention control.	Failure mode cannot be detected or no detection method is established.
9	Very high	Potential regulatory non-compliance or severe safety concern.	Failure cause is very likely; existing prevention controls have little effect.	Failure mode is unlikely to be detected by the existing method.
8	High	Major process, quality, safety or production-risk impact; production may continue under clearly non-standard conditions.	Failure cause is recurrent and weakly prevented by the current process.	Detection depends on manual inspection, subjective judgement or delayed reaction.
7	High	High process-stability, reliability or control impact; may cause significant instability or loss of process robustness.	Failure cause is recurrent or inherent to the current system design.	Detection is possible, but not automatic, continuous or sufficiently reliable.
6	Moderate	Moderate effect on process robustness, inspection capability, quality risk or equipment reliability.	Failure cause is occasional or condition-dependent.	Failure can be detected by manual measurement, audit or inspection, but not continuously.
5	Moderate	Moderate local effect requiring rework, correction, additional checking or maintenance follow-up.	Failure cause occurs under specific operating, seasonal or maintenance conditions.	Detection method exists and is generally capable, but is manual or periodic.
4	Low	Low to moderate local effect with limited direct impact on process stability or safety.	Failure cause is relatively uncommon.	Existing checks are likely to detect the condition before major process impact.
3	Low	Low local effect with minor operational disturbance.	Failure cause is uncommon and partly controlled.	Detection is relatively reliable through existing checks.
2	Very low	Minor inconvenience with no relevant effect on process stability, safety or product quality.	Failure cause is rare and mostly prevented by existing controls.	Existing controls are highly likely to detect or prevent the failure.
1	Very low	No discernible effect on the process, product or operator.	Failure cause is extremely rare or physically prevented.	Failure mode is prevented or always detected before impact.

Action Priority was assigned qualitatively from the combined interpretation of Severity, Occurrence and Detection. In this diagnostic application, High Action Priority was assigned to failure modes that directly define TO-BE requirements because they affect environmental stability, safety, monitoring capability or reaction logic and are not reliably detected or prevented by the current system. Medium Action Priority was assigned to relevant supporting issues that require maintenance, inspection, standardisation or future monitoring.

3.9.2 Diagnostic FMEA

Table 3.18 presents the diagnostic FMEA. Each failure mode is linked to one of the AS-IS limitations identified previously through Gemba Walk, technical reports, manual equipments or maintenance reports, allowing the findings to be ranked according to their impact on process stability, monitoring capability, operational reaction and safety. The justification for the rankings can be found on Appendix E, with the respective technical traceability and failure modes.

Table 3.18: Diagnostic FMEA for AS-IS painting booth limitations.

ID	AS-IS diagnostic finding	Failure mode	S	O	D	AP
F01	Downdraft imbalance and audit-identified recirculation	Booth airflow does not provide uniform overspray evacuation	6	6	6	M
F02	Fixed/manual intake damper adjustment	Airflow balance cannot be actively corrected during operation	6	6	7	M
F03	Relative humidity frequently outside the specified operating range	Booth RH not maintained within the required process window	8	8	7	H
F04	Heating-induced RH reduction	Heating lowers RH without sufficient humidification compensation	7	7	7	H
F05	Burner and humidifier are not coordinated	Final supply-air condition is not controlled as an integrated T–RH process	7	7	7	H
F06	Dependence on operator perception and manual adjustment	Environmental correction depends on subjective judgement	7	7	8	H
F07	Generalised exhaust corrosion	ASU chimney degradation may affect reliability and long-term safe operation	6	5	6	M
F08	Poor humidifier atomisation and water leakage	Injected water is not effectively converted into humidity increase	7	6	6	M
F09	Ageing booth and ASU infrastructure	Degraded infrastructure may contribute to instability and contamination risk	6	6	7	M
F10	High pH and conductivity in recirculating water	Water quality may promote fouling, deposits and unstable humidification	6	5	8	M
F11	Limited purge and hygiene monitoring	Water system condition may deteriorate without detection	6	5	8	M
F12	No automatic Go/No-Go logic	Production may continue under non-standard environmental conditions	8	6	8	H
F13	Manual discrete environmental measurements	Short-duration environmental drift may remain undetected	6	8	8	H
F14	Non-standardised measurement protocol	Environmental records may not consistently represent booth conditions	6	8	8	H
F15	Low lighting at inspection areas	Defects may be missed or inconsistently classified during inspection	5	5	6	M
F16	Adhesive-tape pressure indication	Booth pressure balance is not quantified or trended	7	6	8	H

This subjective classification was used as a starting point to understand the priorities to improve on the painting booth system and top coat application.

3.9.3 Prioritised Diagnostic Conclusions

The diagnostic FMEA shows that the highest-priority limitations are concentrated in relative humidity control, heating–humidification coordination, monitoring capability, reaction logic and pressure visibility. These are represented mainly by F03, F04, F05, F06, F12, F13, F14 and F16. These failure modes are directly linked to the absence of continuous monitoring, weak feedback between measured booth conditions and control actions, lack of automatic alarms and lack of standardised reaction logic.

The medium-priority findings remain relevant, but they act mainly as supporting requirements. Airflow imbalance, damper adjustment, humidifier degradation, ageing infrastructure, water-system condition, corrosion and lighting limitations affect process reliability and quality robustness, but they should therefore be addressed through maintenance improvement, inspection routines, restoration actions and monitoring capability.

Overall, the FMEA confirms that the AS-IS limitations are systemic and cannot be solved only through operator adjustment or corrective maintenance. On Table 3.19, it is possible to see the AS-IS diagnosis summary areas and limitations that will be stepping stone for our TO-BE system.

Table 3.19: AS-IS diagnosis summary and TO-BE direction.

Main limitation	AS-IS evidence	TO-BE direction
Unstable RH control	Frequent RH out-of-specification and AM/PM variation.	Improve humidification control and reduce environmental drift.
Temperature not fully stable	Temperature remains within limits but shows non-random seasonal behaviour.	Improve stability, not only specification compliance.
Weak monitoring	Manual measurements, low frequency and no quantified pressure data.	Introduce continuous sensors, data logging and alarms.
Decoupled control	Burner and humidifier operate without coordinated temperature–humidity logic.	Integrate heating and humidification control.
No reaction logic	Out-of-specification values do not trigger formal Go/No-Go actions.	Define alarm, escalation and reaction procedures.
Equipment degradation	Ageing ASUs, humidifier leakage, poor atomisation and water-quality concerns.	Support retrofit with maintenance and component restoration.

3.10 Concurring Process Variables and Boundary Conditions

As discussed in Chapter 2 and established in standard spray coating frameworks [29], coating quality depends on a complex network of variables. To ensure scientific rigor and isolate the impact of the proposed environmental retrofit, these concurring parameters are mapped according to the actual shop-floor reality:

- **Material properties (viscosity, solid content, surface tension):** The facility uses solvent-borne paint consistently supplied by PPG, fixing baseline solid content and surface tension. Viscosity is measured manually before production, and deviations are compensated for by adding solvent using a standardized PPG conversion table (Figure 3.37).

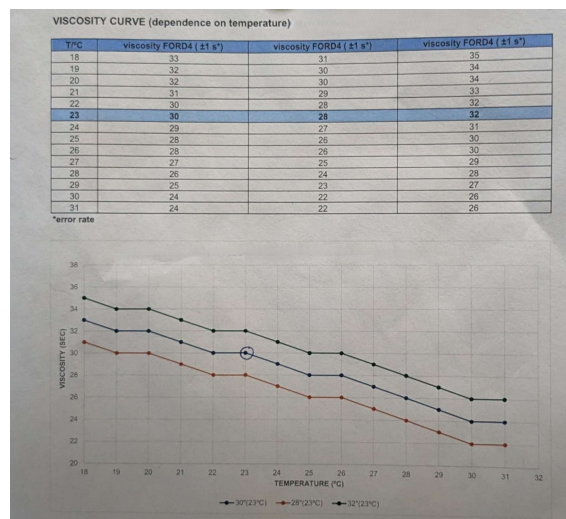


Figure 3.37: Viscosity conversion graph

For the scope of this environmental proposal, fluid properties at the gun inlet are assumed to be managed under these baseline protocols, hence why the future strategy does not pass through these parameters.

- **Gun parameters and atomization (air/paint pressure, particle size):** Gun types, nozzle configurations, atomizing air pressure, and paint pressure dictate particle size and distribution. These parameters are fixed during setup according to standard operating sheets, treating them as constant boundary conditions.
- **Distance and application dynamics (operator, extraction balance):** In this manual line, gun-to-substrate distance introduces human-induced variations, which are treated as intrinsic process noise and mitigated by Toyota Production System (TPS) training. Meanwhile, overspray and solvent evaporation dynamics are supported by downdraft airflow and extraction balance, which are regularly measured and manually adjusted by the maintenance team.
- **Thermodynamic inputs (air and object temperatures):** Ambient air and incoming object temperatures directly govern solvent evaporation during application. While the oven profile handles final curing, booth air temperature and humidity represent the largest unmanaged, dynamically changing sources of variance during the application phase.

By defining these operational boundaries, the proposed retrofit is positioned as a targeted solution to stabilize the critical thermodynamic inputs, relying on existing factory routines to keep the remaining material and mechanical variables within tolerance.

3.11 Evaluation of Improvement Strategies

Before defining the TO-BE solution, different engineering strategies were evaluated to determine the most appropriate approach for improving coating quality and environmental stability. Rather than assuming the optimal solution, several alternatives were compared according to their ability to address the root causes identified during the AS-IS diagnosis.

3.11.1 Maintenance and Equipment Restoration

During the diagnosis, it was noted that much of the variability in several process parameters was rooted in a lack of maintenance or predictive maintenance protocols. For example, the cleaning and replacement of nozzles, as well as the visible corrosion across the entire structure of the painting booth and its air intake system, need to be addressed. Restoring the original capacity of the humidifier chamber is imperative to guarantee the proper functioning of the system, while also being a relatively low-investment action.

However, correcting or minimizing equipment degradation does not eliminate by itself the variations in humidity, as observed in Figure 3.32, and temperature that were observed. Therefore, this strategy was deemed necessary as a supporting action, but not as a sufficient stand-alone strategy to ensure process repeatability inside the painting booth.

3.11.2 Adjustment of Process Parameters

As established in Chapter 2, the electrostatic painting process involves a multitude of variables that need to be controlled, such as viscosity, current, temperature, humidity, paint formulation, gun settings, and flash-off times. Adjusting these parameters could reduce defect occurrence, however, constantly tweaking them to compensate for environmental variability introduces too much dependency on the experience of painters and operators, paint formulation adjustments and shifting production conditions throughout the day, week, or month.

While this strategy is already in place, as the experience of manual painters is an inherent part of the current process adjustment, it serves only as a complementary measure rather than a robust solution for a stable process. The goal is not the constant dependency on the experience of painters, but the exact opposite, to focus on creating a repeatable standardized work environment to allow for the best possible variables for manual electrostatic application of the top coat.

3.11.3 Replacement of the Paint Booth and HVAC System

As illustrated in Chapter 3, there are severe structural problems with the ASU structure, and repeated malfunctions are a clear symptom of an outdated system operating since 1971. The inefficiencies associated with its current state could technically justify replacing the entire painting booth system, which would solve the environmental instability by introducing modern, automated technologies. This could also be a way to automatize the painting process, using automated robot

bells as is the standard in automotive painting booths nowadays, decreasing toxic risk for humans and increasing repeatability [9, 59].

However, the implementation strategies to solve our limitations cannot be observed without looking at the reality of the industrial manufacturing process. Looking at the reality of the plant, it produces around 14 LC70 units per day and operates as a low-volume facility with limited annual budget for such a large capital investment. Furthermore, a project of this dimension requires extensive civil works and mechanical modifications that are not compatible with active production. The extended lead time was also a major constraint, as environmental variability presents an immediate quality and safety risk that cannot be left unattended. For these reasons, this was not chosen as the primary strategy, though it remains a potential long-term future solution.

3.11.4 Automatic Environmental Control Retrofit

An automatic environmental control retrofit presents a direct solution to the root causes, combining continuous monitoring, alarms, and data acquisition that this process could highly benefit from. This solution requires targeted instrumentation, control integration, and localized commissioning, all of which can be implemented while maintaining active production. As a future perspective, this continuous process monitoring also opens up opportunities to better understand process dynamics and implement predictive maintenance protocols.

Consequently, the proposed automatic environmental control retrofit was selected because it directly addresses the highest-priority failure modes identified by the diagnostic analysis while preserving the existing production infrastructure. Taking into account both financial and industrial constraints, this strategy provides the best compromise between technical effectiveness, implementation complexity, production uptime and investment cost.

Chapter 4

Define: TO-BE Proposal Solution

This chapter outlines the TO-BE retrofit strategy for implementing an automatic humidity control system within the existing legacy infrastructure. The proposed architecture integrates continuous environmental monitoring, variable humidification actuation, and PLC/HMI connectivity, all while maintaining strict ATEX safety compliance. To ensure technical alignment across cross-functional teams and international stakeholders, the project utilized a structured management framework, including Kanban workflows and open-item tracking, to coordinate dependencies from diagnostic specification through to the implementation roadmap (detailed in Appendix H).

4.1 Project Roadmap

The project roadmap was divided into short-term, medium-term and long-term actions. This staged approach reflects the retrofit nature of the project, allowing immediate risks to be reduced before the complete automatic humidity-control system is installed.

Table 4.1: Implementation roadmap.

Phase	Main actions	FMEA link
Short-term stabilisation	Correct environmental control-chart limits, verify conductive PPE and grounding, and improve the safety and repeatability of manual measurement practice.	F05, F06, F09
Temporary monitoring	Introduce temporary ATEX/CE-compatible temperature and RH data logging to better characterise intra-shift variation before the permanent system is installed.	F04, F05
Permanent monitoring and control	Install mandatory temperature/RH duct sensors, water-level sensors, remote I/O, PLC, HMI and data-logging infrastructure.	F01, F02, F04, F05, F06
Humidification hardware upgrade	Install one VFD-controlled pump per ASU, replace degraded piping, install new nozzles, clean the humidification section and validate the hydraulic performance with the supplier.	F01, F02, F03, F07
Water-system monitoring	Introduce water-level protection as a mandatory function and consider conductivity monitoring and purge logic as optional diagnostic improvements.	F08
Process optimisation	Use historical data to refine control parameters, evaluate seasonal behaviour, assess energy consumption and support future capability studies after process stabilisation.	F01, F02, F03, F06

The staged roadmap ensures that the most critical risks are addressed first, while allowing advanced diagnostic and optimisation functions to be introduced after the basic monitoring and control architecture has been validated.

4.2 Quick Wins Actions

The first implementation level focuses on short-term stabilisation actions. These actions were selected because they address relevant FMEA items while requiring limited infrastructure modification. They do not replace the full automatic humidity control architecture, but they reduce immediate operational exposure and improve the robustness of the current AS-IS process.

Table 4.2: Short-term stabilisation actions linked to the diagnostic FMEA.

Action item	Technical description	Related FMEA item	Effort
Conductive PPE and grounding verification	Introduce conductive gloves where required and verify the condition of grounding straps, unit transport contacts and floor grills used for charge dissipation.	F09 – Static charge may not be safely dissipated / H	Moderate
Temporary ATEX/CE temperature and RH logger	Install a temporary ATEX/CE-compatible data logger to record temperature and relative humidity continuously during production shifts.	F04 – Short-term deviations may remain undetected / H	Moderate
Standardised manual measurement support	Replace the current improvised manual measurement practice with a safer and repeatable support interface for the measuring device, ensuring fixed positioning during checks.	F05 – Environmental records may not consistently represent real booth condition / H	Moderate
Environmental reaction limits update	Update the visual control chart and reaction limits so that booth temperature and RH are compared directly with the applicable <i>Ryohin Joken</i> process limits.	F06 – Abnormal T/RH values do not trigger a defined reaction procedure / H	Low
ASU2 burner indication verification	Verify and document the wiring fault causing the ASU2 burner malfunction indication to display an incorrect status, reducing ambiguity during troubleshooting.	F02 – Heating and humidification are not coordinated as one control process / H	Low

The conductive PPE and grounding checks were identified as priority actions due to the reported electrostatic shocks during painting operations. These actions are particularly relevant because low relative humidity conditions increase the likelihood of static charge accumulation, while solvent-based painting occurs in a safety-critical environment. The team assigned to this problem reached more improvement actions, such as pistol equipment change that resulted in a decrease of electrostatic shocks, as we can see in the A3 problem solving feedback items in Figure 4.1.

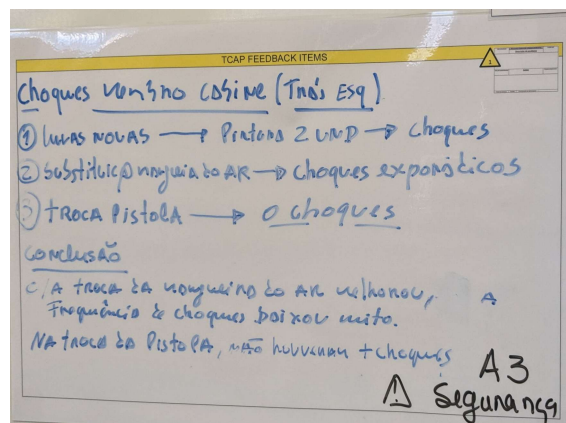


Figure 4.1: A3 feedback: improvement actions

The control chart limit correction addresses a visual management inconsistency identified during the AS-IS diagnosis. Although correcting the limits does not create automatic reaction logic, it reduces the risk of operators using incorrect reference values and improves alignment between the shop-floor recording tool and the defined production standards.

The ASU2 burner indication fault was included as a reliability and maintainability action. Incorrect indication of burner status reduces trust in the existing control panel and can delay reaction during abnormal conditions. Therefore, even though this action is not the main driver of humidity instability, it contributes to restoring the reliability of the local operating interface. It was not possible to implement this measure, due to the lack of availability of maintenance personnel.

As an intermediate improvement to the measurement system, an ATEX/CE-marked data logger was selected as a temporary solution for automatic temperature and relative humidity recording. This solution does not replace the permanent sensor network proposed in the TO-BE architecture, but it improves the frequency and safety of environmental data collection compared with the previous manual method.

4.2.1 ATEX-Compatible Measurements

One of the short-term mitigation actions identified during the diagnostic phase was the replacement of the current mobile, non-ATEX measurement practice used for manual temperature and relative humidity readings inside the painting booth. As discussed in the AS-IS diagnosis, the existing measurement method presents limitations regarding measurement reliability, operator safety and suitability for use in a potentially hazardous painting environment.

The safety of the solution depends on the selected ATEX-certified sensor, the compatibility of the support with the sensor manufacturer requirements, and the final installation and usage procedure. For this, two ATEX/CE marking data-loggers (Figure 4.2) were chosen through a market search and decision matrix..



Figure 4.2: ATEX/CE marking data logger for relative humidity and temperature

When planning the implementation of this sensors, it was clear that the overspray in the cabin presented as a limitation factor, as illustrated in 4.3. Overspray of solvent-based painting could result in malfunctioning of the sensor reduce its accuracy, so it required a new solution for this datalogger implementation.

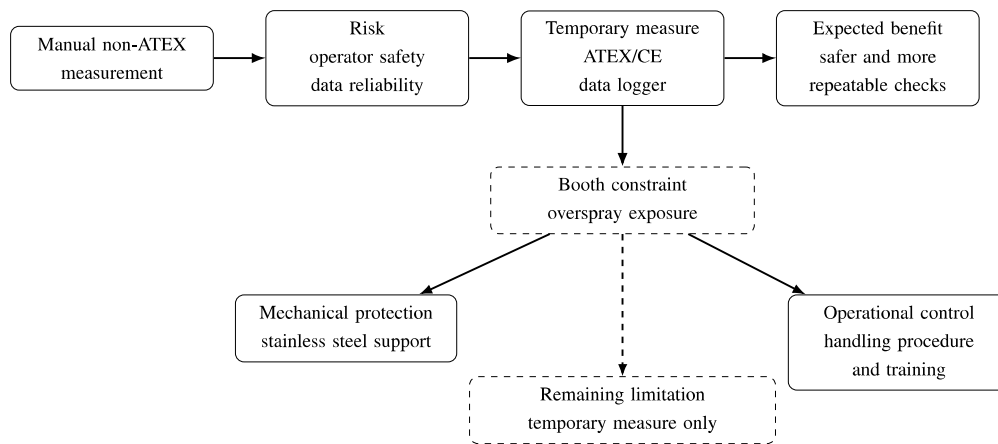


Figure 4.3: Engineering logic of the temporary mitigation for manual environmental measurement.

To solve this problem and to support this mitigation action, a stainless steel sensor support was designed, as shown in Appendix C.1. The support acts as a mechanical protection and mounting interface for the mobile measurement device, reducing the risk of accidental damage during handling and improving repeatability during manual measurements.

The support was designed in stainless steel to improve corrosion resistance and mechanical robustness in the humid and contaminated environment of the painting booth allow for grounding within the painting booth structure. Its geometry was defined to protect the sensor body from overspray, while still allowing exposure of the sensing element to the surrounding air. To ground the sensor and metallic structure, a magnetic was used to ensure that the sensor stays in place. This makes the manual measurement practice more robust than the previous mobile approach.

This action does not correspond to the final instrumentation architecture of the environmental control. Instead, it was designed as a temporary stabilisation measure to reduce operational risk and measurement uncertainty while the full monitoring system is not yet implemented.

4.3 Design Basis and Industrial Constraints

The proposed control architecture was developed as a brownfield retrofit solution for the existing painting booth environmental-control system. Because the baseline asset diagnosis isolated instrumentation and actuation limitations rather than structural air-treatment capacity flaws, the solution preserves the existing booth and Air Supply Unit (ASU) structures. The technical objective was to integrate the instrumentation, actuation, automation, and supervision layers required to establish closed-loop process controllability.

System deployment was bound by the following industrial design constraints:

- Retention of the existing legacy booth and ASU physical structures.
- Minimization of production downtime by executing installation sequences strictly outside operational shifts.

- Full hardware and protocol integration with the existing electrical and control infrastructure.
- Strict compliance with European safety directives, industrial ATEX requirements, and internal Toyota manufacturing standards.
- Maintenance of system maintainability using the existing skills of local technical teams, requiring no external specialized support.
- Provision of specialized training workflows for local operation and maintenance personnel.
- Achievement of a post-commissioning Operational Availability (OPA) target exceeding 99%.

Consequently, the deployment strategy follows a staged execution logic. Initial phases enforce immediate process stabilization to minimize safety exposure. Subsequent phases deploy permanent instrumentation and centralized PLC/HMI integration to achieve data visibility. Final phases upgrade the humidification hardware and hydraulic loop to enable variable actuation, real-time diagnostic capability, and energy optimization.

4.3.1 System Layer Integration

The retrofitted architecture is structured into three functional layers to isolate legacy plant assets from the new automation components, separating physical execution, data acquisition, and process monitoring.

- **Physical Process Layer:** Encompasses the existing legacy Air Supply Unit (ASU) infrastructure, maintaining the original air-treatment configurations.
- **Instrumentation and Control Layer:** Integrates the newly deployed sensors, remote I/O modules, local PLC processing blocks, and variable frequency drive (VFD) water pump assemblies to establish automated closed-loop tracking.
- **Supervision and Interface Layer:** Provides real-time operational visualization, alarm handling, parameter trends, multi-level access controls, and manufacturing data traceability.

This structural design is implemented identically across both *ASU1* and *ASU2*, as it is simplified by Figure 4.4.

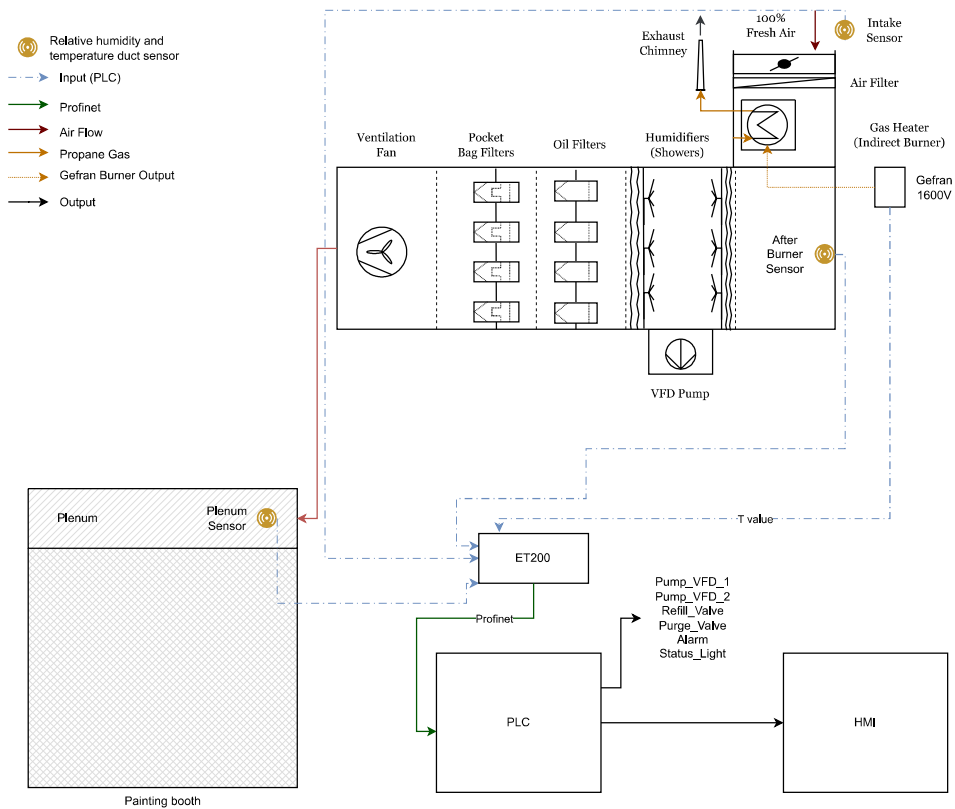


Figure 4.4: Simplified view of proposed solution

This layout ensures complete operational and physical autonomy for each independent climate path while maintaining centralized data aggregation at the PLC and HMI levels, as illustrated in Figure 4.5.

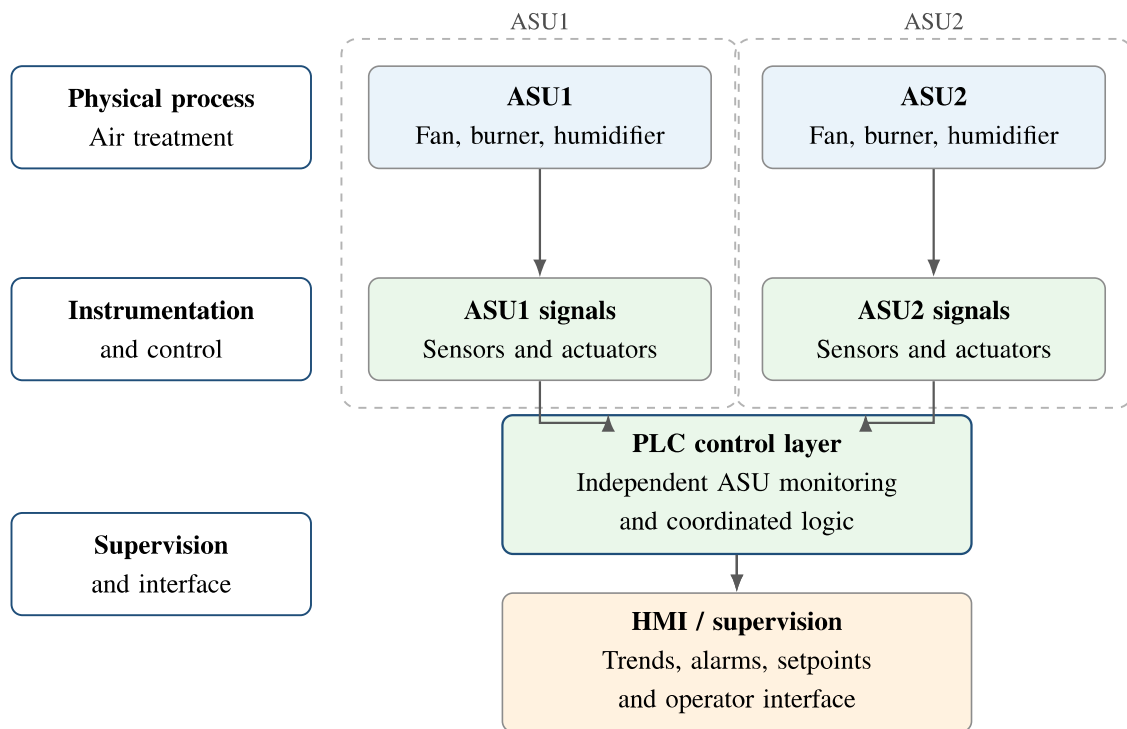


Figure 4.5: Architecture proposed for automatic environmental control.

Figure 4.5 summarises this layered concept, showing how the existing ASU air-treatment process is connected to the proposed sensor network, PLC-based control and HMI supervision.

4.4 Proposed System Architecture

The architecture is structured into three functional layers to isolate legacy plant assets from the new control elements, separating physical execution, data acquisition, and process monitoring. This proposal originated a technical specification for further supplier commissioning that can be seen in Appendix I.

4.4.1 Layered Organisation

1. **Physical Process Layer:** Consists of the existing legacy Air Supply Unit (ASU) infrastructure, retrofitted with variable water-spray actuators to allow modulated moisture delivery.
2. **Instrumentation and Control Layer:** Integrates the combined duct transmitters, local Siemens S7-1200 PLC, and variable frequency drive (VFD) water pump assemblies to execute real-time loop decoupling.
3. **Supervision and Interface Layer:** Provides local operational visualization, real-time alarm handling, and quality data traceability via a dedicated Human-Machine Interface (HMI).

4.4.2 Architecture Rationale

The baseline factory diagnosis exposed a complete operational decoupling between air-heating and humidification loops. The proposed layered architecture resolves this systemic vulnerability through three targeted technical modifications:

- **Psychrometric Tracking:** Establishes localized sensor positions upstream and downstream to dynamically map the air mass enthalpy shifts. Putting the sensor locations away from the painting booth resulted in the elimination of two constraints: overspray, that could damage or require consistent, cleaning and ATEX certified sensors that implies higher investments.
- **Modulated Humidification:** Replaces the legacy binary ON/OFF water spray showers with a continuous VFD pump loop to track dynamic absolute moisture targets.
- **Centralized Supervisory Logic:** Consolidates localized field metrics within a single PLC processing core to execute the cascade calculations and output saturation overrides simultaneously, while allowing easier access for maintenance and supervisor tracking of the system if needed.

4.5 System Sizing and Psychrometric Calculations

The system sizing and psychrometric calculations were based on the psychrometric interactions that the air goes through in the ASU. The effect of the burner and the humidifier as well as the influence of outside parameters, as illustrated in Figure 4.6. To decouple the temperature and the relative humidity parameters, as advised in Chapter 3, the absolute humidity will be the parameter used for dimensioning and psychrometric calculations.

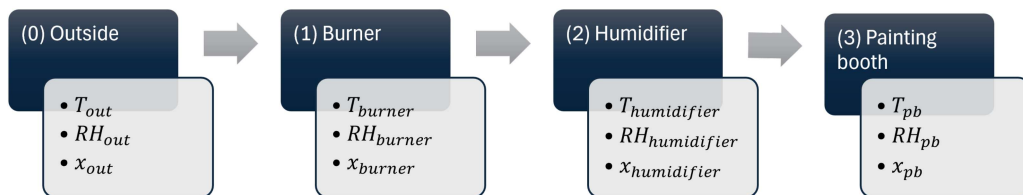


Figure 4.6: ASU psychrometric transformations

This section establishes the quantitative baseline for the *ASU1* and *ASU2* upgrades, defined by worst-case winter boundary conditions (2°C intake, 90% RH). The design parameters were established based on the ASHRAE climatic design conditions for Ovar, Portugal (WMO: 085440), available in Appendix D specifically utilizing the winter heating design criteria (99.6% probability) and extreme annual design values as provided by the ASHRAE Handbook Fundamentals [34].

4.6 Psychrometric Methodology and Mass Balance Framework

The thermodynamic balances of the Air Supply Units (*ASU1* and *ASU2*) are formulated using the absolute humidity ratio (x , kg_{H₂O}/kg_{da}) instead of relative humidity (ϕ) to ensure mathematical stability within the control loops [13, 34]. Relative humidity varies non-linearly with dry-bulb temperature during sensible heating, inducing loop instability. Conversely, the absolute humidity ratio is a conservative mass property that remains invariant across sensible heat exchangers. Shifting the process variable to x decouples mass transfer from energy transfer, eliminating calculation divergence in the PLC.

The psychrometric sequence maps the air stream through four sequential states to meet the required top-coat manufacturing boundaries:

1. **(0) Ambient Air State** (T_{out} , ϕ_{out} , x_{out}): The unregulated meteorological inlet boundary condition.
2. **(1) Pre-Heated State** (T_{burner} , ϕ_{burner} , x_{burner}): The thermal profile post-gas burner but prior to the washer mist chamber ($x_{\text{burner}} = x_{\text{out}}$).
3. **(2) Evaporative Cooling State** ($T_{\text{humidifier}}$, $\phi_{\text{humidifier}}$, $x_{\text{humidifier}}$): The saturated air profile generated within the active water-spray mist zone.
4. **(3) Target Envelope** ($T_{\text{pb}} = 23^\circ\text{C}$, $\phi_{\text{pb}} = 65\%$, x_{pb}): The stabilized climate profile delivered to the painting booth plenum.

4.6.1 Airflow Mass Calculations

Since volumetric airflow ($\dot{V}$) expands and contracts non-linearly with temperature gradients along the air treatment unit, all thermodynamic balances must rely on the invariant dry air mass flow rate ($\dot{m}_{da}$). The mass flow rate is established by evaluating the localized volumetric flow constraints against the standard reference dry air density ($\rho = 1.20 \text{ kg/m}^3$):

$$\dot{m}_{da} = \frac{\dot{V} \cdot \rho}{3600} \quad (4.1)$$

Based on empirical field measurements restricted by the current jammed damper positions, the fixed dry air mass vectors for each independent treatment branch are defined as:

$$\dot{m}_{da,1} = 19.05 \text{ kg/s} \quad (\text{for ASU1}) \quad (4.2)$$

$$\dot{m}_{da,2} = 19.15 \text{ kg/s} \quad (\text{for ASU2}) \quad (4.3)$$

4.6.2 Hydraulic Sizing of the Recirculation Pump and Nozzle Manifold

A critical distinction must be maintained between the thermodynamic evaporation rate ($\dot{m}_w \approx 620 \text{ L/h}$), required for mass balance, and the total volumetric circulation rate (Q), required to ensure kinetic atomization at the nozzles [78].

4.6.2.1 Nozzle Mechanics and Circulation Demand

The legacy air supply unit utilizes a fixed spraying manifold comprising 6 ramps with 10 tangential-flow hollow-cone nozzles each (60 total). Field assessment and PNR catalog cross-referencing identify these as capacity code 2135 units [78]. At a design pressure of 3.0 bar, each nozzle requires a flow rate of 13.5 L/min, establishing the total continuous circulation demand:

$$Q = 60 \text{ nozzles} \times 13.5 \text{ L/min/nozzle} = 810 \text{ L/min} \approx 48.6 \text{ m}^3/\text{h} \approx 0.0135 \text{ m}^3/\text{s} \quad (4.4)$$

4.6.2.2 Hydraulic Power Requirements

To achieve complete atomization, the system requires a nozzle differential pressure of 3.0 bar. Accounting for plumbing losses across risers, manifolds, and control valves, the total manometric design head (H) is established at 35.0 m w.c. ($\approx 3.43 \text{ bar}$). The required hydraulic power (P_h) and subsequent brake shaft power (P_{shaft}), assuming a pump efficiency (η) of 0.70, are calculated as:

$$\Delta P = \rho_w \cdot g \cdot H \approx 343,350 \text{ Pa} \quad (4.5)$$

$$P_h = Q \cdot \Delta P \approx 4.64 \text{ kW} \quad (4.6)$$

$$P_{shaft} = \frac{P_h}{\eta} \approx 6.63 \text{ kW} \quad (4.7)$$

4.6.2.3 Pump Selection

Based on these requirements, a Grundfos NBE end-suction pump with a 7.5 kW motor was selected. This provides a 13.1% mechanical safety buffer above the calculated peak shaft power, ensuring resilience during startup transients and varying sump conditions. This selection aligns with TCAP's standardized procurement policy, facilitating integrated spare parts management and reducing maintenance complexity [78].

4.6.3 Thermodynamic Capacity Validation of Legacy Burners

To scientifically validate the thermal capacity of the existing infrastructure, a steady-state thermodynamic balance of the system was performed for the extreme winter design scenario. The outdoor air boundary condition is defined at $T_{\text{out}} = 2.0^\circ\text{C}$ with a relative humidity $RH_{\text{out}} = 90\%$, corresponding to an absolute moisture ratio of $x_{\text{out}} \approx 0.00395 \text{ kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{dry air}}$ and an enthalpy of $h_{\text{out}} \approx 11.90 \text{ kJ/kg}_{\text{dry air}}$. The target process envelope inside the paint booth requires $T_{\text{booth}} = 23.0^\circ\text{C}$ and $RH_{\text{booth}} = 65\%$, which dictates an absolute moisture ratio of $x_{\text{booth}} \approx 0.01145 \text{ kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{dry air}}$ and a target enthalpy of $h_{\text{booth}} \approx 52.20 \text{ kJ/kg}_{\text{dry air}}$.

The total dry air mass flow rate ($\dot{m}_{\text{air}}$) passing through each Air Handling Unit (AHU) is determined using the operational volumetric airflows and a standard air density ($\rho \approx 1.20 \text{ kg/m}^3$). For ASU1 ($V_{\text{ASU1}} = 19.05 \text{ m}^3/\text{s}$):

$$\dot{m}_{\text{ASU1}} = 19.05 \text{ m}^3/\text{s} \times 1.20 \text{ kg/m}^3 = 22.86 \text{ kg/s} \quad (4.8)$$

For ASU2 ($V_{\text{ASU2}} = 19.15 \text{ m}^3/\text{s}$):

$$\dot{m}_{\text{ASU2}} = 19.15 \text{ m}^3/\text{s} \times 1.20 \text{ kg/m}^3 = 22.98 \text{ kg/s} \quad (4.9)$$

The individual thermal power required by each indirect gas burner loop (Q_{required}) to bridge the combined sensible heating and latent moisture deficit ($\Delta x = 0.00750 \text{ kg/kg}$) is derived from the steady-flow energy equation:

$$Q_{\text{ASU1}} = \dot{m}_{\text{ASU1}} \cdot (h_{\text{booth}} - h_{\text{out}}) = 22.86 \text{ kg/s} \times (52.20 - 11.90) \text{ kJ/kg} \approx 921.26 \text{ kW} \quad (4.10)$$

$$Q_{\text{ASU2}} = \dot{m}_{\text{ASU2}} \cdot (h_{\text{booth}} - h_{\text{out}}) = 22.98 \text{ kg/s} \times (52.20 - 11.90) \text{ kJ/kg} \approx 926.10 \text{ kW} \quad (4.11)$$

The nominal thermal capacity of the indirect gas burners (1000 kW) completely covers the steady-state winter peak demands ($Q_{\text{ASU1}} \approx 921.26 \text{ kW}$ and $Q_{\text{ASU2}} \approx 926.10 \text{ kW}$), ensuring a static thermal safety margin of approximately 8%. Consequently, the physical infrastructure operates without a steady-state deficit, shifting the function of the proposed *evaporative capping* control logic from managing a power shortage to mitigating dynamic transient mismatch, preventing control-loop cross-coupling and burner hunting during severe environmental changes. The combustion dynamics and thermal balance calculations for the indirect gas heating loops follow standard industrial thermal engineering methodologies [36]. This mathematical validation confirms that the hardware capacity of the installed systems complies with the operational boundaries specified by high-tier industrial burner compliance protocols [79].

4.7 Instrumentation, Control, and TO-BE Strategy

This section defines the technical infrastructure required to mitigate the climate-sensitive defect modes identified in Chapter 3. It transitions from the "AS-IS" analytical baseline to the "TO-BE"

architecture, specifying the control requirements necessary to stabilize the top-coat application environment.

4.7.1 Instrumentation and Actuation Requirements

Hardware must fulfil the performance metrics summarised in Table 4.3.

Table 4.3: Hardware specifications and diagnostic sensors.

Component	Parameter	Requirement/Purpose
RH/T Sensors	Pt100 / RH Element	Intake, After-burner, Plenum; $\pm 0.15^{\circ}\text{C}$ / $\pm 2.0\%$ RH.
Conductivity	Sump Probe	0–3000 $\mu\text{S}/\text{cm}$ for mineral concentration limits.
Pressure/Diff. P	Fan/Filter	Optional: Airflow restriction and filter clogging diagnostics.
VFD Loop	Signal/Update	4–20 mA or Profinet; ≤ 500 ms response.

To satisfy design review criteria, the specified instrumentation parameters were validated against industrial norms and standard brownfield constraints:

- **Class A Pt100 and Capacitive RH Transmitters**

- Thermocouples and thermistors exhibit severe signal drift under continuous moisture exposure, while standard commercial hygrometers introduce excessive tracking tolerance errors [26].
- High-accuracy limits ($\pm 0.15^{\circ}\text{C}$, $\pm 2.0\%$ RH) satisfy ISO 9001 requirements and prevent mathematical error propagation during the non-linear psychrometric conversion to absolute Humidity Ratio (HR) inside the local PLC [18].

- **Inductive Water Sump Conductivity Probe**

- Manual water sampling loops or periodic timed bleed-off intervals permit unmonitored Total Dissolved Solids (TDS) peaks and rely entirely on human operational compliance.
- Continuous, automated tracking of mineral accumulation loops directly back to the bleed-off valves to prevent nozzle calcification, preserving droplet atomization consistency [42, 80].

- **Differential Pressure Transducers**

- Calendar-based filter maintenance strategies lead to premature component discards or sudden, unmonitored airflow drops during production hours.

- Real-time differential monitoring enforces predictive clogging tracking compliant with ISO 16890 [53] filtration standards, protecting booth overpressure thresholds and preventing airborne particulate defects[73].

- **Profinet VFD Communication Link**

- Analog 0–10 V signalling remains highly vulnerable to electromagnetic interference generated by surrounding high-power ASU fan motors over long cabling distances.
- A digital Profinet architecture provides a sub-500 ms response window that matches the control system sample time, preventing actuator transport delay and pump VFD loop windup [26].

4.7.2 Actuation Logic

The actuation logic governing the humidification system relies on continuous modulation of the recirculation pump to maintain process stability. Key control parameters include:

- **VFD Frequency Regulation:** The drive is programmed with a lower frequency clamp of 32 Hz (corresponding to a nozzle pressure of approximately 1.3 bar), ensuring the minimum fluid velocity required for effective atomization.
- **Closed-Loop Control:** The VFD operates under a PID control loop, receiving real-time feedback from the plenum humidity sensors. The PLC modulates the pump speed to adjust the water mass flow rate ($\dot{m}_w$) proportionally to the deviation from the humidity setpoint (65 % RH).
- **Dynamic Evaporative Capping:** As a safety interlock, the logic includes a high-priority thermal override. If the upstream burner firing rate exceeds 95 % of its nominal capacity while the plenum temperature remains below 23 °C, the PLC forces a reduction in VFD frequency, effectively capping the evaporative cooling load to prioritize sensible heating stability.
- **Ramp Constraints:** Acceleration and deceleration ramps on the VFD are configured to 5 s to prevent hydraulic shock in the piping network when starting or stopping the recirculation flow.

4.7.3 Implementation Framework (TO-BE Strategy)

The implementation follows a staged roadmap to de-risk the installation, focusing on hardware restoration before automation.

1. **Replace:** Install new, certified nozzles and pressure gauges.
2. **Verify:** Confirm hydraulic coverage across the 3 m washer section.

3. **Measure:** Quantify psychrometric states.
4. **Calculate:** Determine actual evaporation: $\dot{m}_{w,actual} = \dot{m}_{da}(\omega_{out} - \omega_{in})$.
5. **Compare:** Validate against design targets.
6. **Resize:** Execute secondary hydraulic redesign only if restoration fails.

This framework also requires the adjustment of parameters of the control strategy, since their adjustment is most of the times iterative. To ensure the long-term integrity of the automated control loops, a systematic recalibration schedule must be established for the newly deployed temperature and relative humidity transmitter probes. Given the solvent-laden and airborne particulate conditions characteristic of the down-draft paint booth environment, sensor drift poses a significant risk to PID stability. Following industrial metrology guidelines [81, 82], a 6-month recalibration interval is recommended, utilizing portable reference hygrometers for on-site loop validation to maintain absolute drift limits below $\pm 1.5\%$ RH and $\pm 0.3^\circ\text{C}$.

4.8 Water System Strategy

The proposed automation architecture requires an actuation system capable of precise flow modulation, however, the reliability of this system is intrinsically linked to the chemical properties of the water supplied to the spray humidifiers. The AS-IS diagnosis identified uncontrolled water quality as a primary driver of nozzle fouling and structural corrosion [43]. Consequently, defining a robust water management strategy is essential to ensure long-term process stability.

4.8.1 Water Quality Analysis

Diagnostic measurements revealed alkaline conditions ($\text{pH} \approx 8.79$) and elevated conductivity ($\approx 5.47 \text{ mS}$), indicating a high concentration of dissolved minerals. In spray-humidification systems, such conditions typically accelerate scaling, clogging of nozzle orifices and the degradation of metallic components via electrochemical corrosion [43]. These phenomena impair atomisation consistency and necessitate frequent, reactive maintenance, threatening the target operational availability (OPA) of $> 99\%$.

4.8.2 Demineralized Water Trade-off

A transition to demineralized water (DI) was evaluated as a potential mitigation strategy for mineral deposition. A comparative analysis of this transition is presented in Table 4.4.

Table 4.4: Technical comparison: Mineralized vs. Demineralized water.

Criterion	Mineralized Water (Legacy)	Demineralized Water (DI)
Scaling Risk	Higher (High mineral content)	Negligible
CAPEX	Low (Existing infrastructure)	High (Requires RO/DI system)
Compatibility	Proven (Existing materials)	Potential risk (Higher corrosivity)
Operational Strategy	Monitoring/Purge Logic	Water treatment maintenance

The analysis indicates that while DI water offers superior purity, the transition would necessitate extensive repairs and structure compatibility review and significant capital investment for water treatment and coating protection infrastructure. Given the constraints of the existing legacy installation and the objective of maintaining production continuity, the implementation of a full-scale DI water system was deemed unfeasible for the current scope.

Instead, the strategy maintains mineralized water as the operational baseline. To mitigate the associated risks, the TO-BE architecture integrates conductivity-based monitoring and automated purge logic. This approach prioritises maintenance discipline and hygiene control, effectively managing the water quality risk while avoiding the excessive costs and technical complexities of a structural chemical shift.

4.9 Humidification Hardware and Maintenance

This section details the proposed humidification hardware, focusing on its operational specifications and the maintenance protocols required to ensure system reliability. It establishes the technical requirements for integrating these components into the existing booth infrastructure while ensuring long-term performance stability.

4.9.0.1 Piping Replacement and Material Selection

The existing metallic piping exhibited advanced corrosion 3.17, posing a significant risk to the air washer's structural integrity, health and of the workers. To prevent further degradation by galvanic corrosion between stainless steel components and the oxidized iron structure, the piping infrastructure for each Air Handling Unit (ASU) was replaced [43].

The material selection process prioritized chemical inertness and long-term reliability for a water circuit treated, in the future, with biocides. As summarized in Table 4.5, Polypropylene Homopolymer (PP-H) was selected over Stainless Steel 316L due to its superior chemical resistance and dielectric properties that do not allow for pitting or galvanic corrosion.

Table 4.5: Material comparison and selection matrix: SS 316L vs. PP-H [65, 83, 84]

Feature	Stainless Steel 316L	PP-H
Corrosion Resistance	Moderate (Pitting risk)	Excellent (Inert)
Galvanic Potential	High (Risk of corrosion)	None (Dielectric)
Hydraulic Roughness (ϵ)	≈ 0.045 mm	≈ 0.007 mm
Installation Method	TIG Welding / Flanging	Thermal Fusion Welding
Vibration Resilience	Moderate	High
Cost	High	Low

This selection is supported by established industrial standards, as PP-H is recognized for its suitability in aggressive water treatment applications [85]. Furthermore, the use of thermal fusion welding ensures leak-proof joints that are significantly more resilient to vibrations than mechanical flange connections [84]. The mechanical redesign of the humidification piping network utilizes thermoplastic piping systems specified for high-durability industrial applications [85], with structural calculation values verified against standard tank and apparatus guidelines [83, 84]. The atomization pattern relies on high-efficiency tangential flow centrifugal atomizers to ensure a uniform droplet evaporation profile [78].

4.9.0.2 Pump Integration and Vibration Mitigation

To protect both the pump assembly and the piping infrastructure from dynamic loads, flexible expansion bellows have been integrated at the suction and discharge ports. These components provide three primary engineering benefits:

- **Vibration Control:** The bellows act as a mechanical buffer to absorb pump-induced vibrations, preventing transmission to the pipework and protecting thermoplastic fusion welds from fatigue failure [83].
- **Thermal Movement:** Due to the differential thermal expansion coefficients between the metallic pump volute and the PP-H piping, the bellows provide the necessary axial and lateral flexibility to prevent thermal stress-induced leaks or misalignment [83].
- **Load Protection:** Independent spring-hangers and supports are utilized to ensure the pump housing does not bear the structural weight of the piping, which is essential for maintaining precise shaft alignment.

4.9.0.3 Atomization and Nozzle Specification

The atomization system utilizes hollow cone tangential nozzles designed for high-efficiency evaporative cooling. This selection optimizes droplet surface-to-volume ratios at a nominal operating pressure of 2.0 bar. Compared to full cone alternatives, hollow cone nozzles provide superior

evaporation effectiveness at lower flow rates, which is critical for maintaining the target humidity setpoint while capping the latent thermal load.

The total system mass flow requirement of approximately 925 Lh^{-1} is distributed across the nozzle array. Given the individual nozzle capacity of $Q_{nozzle} \approx 15.4\text{ Lmin}^{-1}$ (calculated as $Q_{pump}/60$), the array is configured to ensure uniform coverage across the air washer cross-section.

To mitigate the inherent risk of orifice clogging due to high-conductivity industrial water, the following measures are integrated:

- **Filtration:** A $100\text{ }\mu\text{m}$ upstream filter is mandatory to capture suspended particulates.
- **Conductivity-based blowdown:** The PLC triggers an automated purge when total dissolved solids (TDS) exceed the defined threshold, preventing scale accumulation.
- **Chemical Conditioning:** Biocide and scale-inhibitor dosing prevents bio-fouling and mineral deposition.

4.9.0.4 Operational Maintenance Protocol

To ensure process stability, the previous reactive maintenance approach could be improved by a condition-informed protocol, summarized in Table 4.6.

Table 4.6: Condition-informed maintenance and hygiene protocol.

Focus Area	Routine Action
Hygiene	Periodic tank disinfection, water renewal (purge logic), and stagnation prevention.
Mechanical	Nozzle spray pattern inspection, pump suction/cavitation checks, and leak/corrosion monitoring.
Process	Conductivity-based blowdown, water level tracking, and signal verification.

4.10 Control Logic and Preliminary PLC Algorithm

The control architecture was structured as a multi-loop psychrometric cascade to eliminate transport lag and actuator cross-coupling within the Air Supply Unit (ASU). The tracking variable was shifted from relative humidity (RH) to absolute Humidity Ratio (HR , $\text{g/kg}_{\text{dry air}}$). This variable shift ensures that upstream burner adjustments do not induce downstream humidification loop oscillations.

4.10.1 Evaluation of Control Strategies

The selection of the final control architecture was based on a comparative analysis of three candidate methodologies to manage the cross-coupling between temperature and humidity:

Table 4.7: Control strategy evaluation matrix addressing design selection criteria.

Control Strategy	Technical Disadvantage	Selection Rationale
Decoupled SISO PID	Ignores loop cross-coupling. Thermal adjustments cause moisture overreaction and loop hunting [13, 18].	Rejected: Fails to stabilize the process envelope under seasonal ambient transients.
Discrete Window Control	Causes boundary edge actuator chattering and localized multi-variable instability.	Rejected: Triggers excessive actuator wear and violates ATEX safety boundaries.
Centralized MPC	Demands high computational hardware CAPEX and non-existent legacy plant data [11].	Rejected: Excessive deployment costs; unfeasible for legacy plant architecture limits.
Decoupled Psychrometric Cascade (Proposed)	Requires precise psychrometric sensor calibration and high-resolution PLC execution loops.	Selected Solution: Decouples cross-coupled loops via absolute Humidity Ratio (<i>HR</i>) [86]. Minimizes hardware CAPEX using S7-1200 PLC blocks and mitigates weather shocks via feed-forward paths.

4.10.1.1 Proposed Solution: Decoupled Psychrometric Cascade

The selected strategy employs a Decoupled Psychrometric Cascade to resolve cross-coupled loops by controlling the absolute Humidity Ratio (*HR*) [34]. By decoupling the primary environmental variables, this approach minimizes hardware CAPEX using standard S7-1200 PLC function blocks. Furthermore, it incorporates a feed-forward path to mitigate environmental disturbances ("weather shocks") before they impact the booth state, ensuring stable film formation kinetics.

4.10.2 Selected Architecture and Hardware Implementation

Because the ASU lacks a cooling coil, active condensation-based dehumidification is impossible. When processing hot, dry ambient air, the humidification chamber operates on an adiabatic evaporative cooling principle, trading sensible heat for latent heat to lower duct temperatures.

The physical process was split into two decoupled control loops at the local PLC level:

1. **Thermal Loop:** Tracks the temperature target (T_{setpoint}) by modulating gas burner output, factoring in downstream latent evaporative cooling drops.

2. **Moisture Loop:** Computes absolute *HR* from local *T* and *RH* transmitters. A dedicated PID loop regulates a variable frequency drive (VFD) pump command. Feed-forward control ($u_{FF} = K_{FF} \cdot [HR_{SP} - HR_{in}]$) rejects ambient disturbances, while a plenum sensor provides closed-loop cascade feedback refinement (u_{FB}). A lower threshold of 55% RH was hardcoded into controller saturation limits to ensure rigid ATEX compliance and eliminate electrostatic hazards.

Equipment choices were bound to factory standards, safety mandates, and cost-optimization metrics as detailed in Table 4.8.

Table 4.8: Hardware selection rationale and industrial constraints.

Hardware Element	Selection Constraint	Engineering Rationale
PLC Controller	Must utilize the Siemens ecosystem due to strict factory-wide standardization.	A Siemens S7-1200 was chosen over a high-tier S7-1500. The computational overhead of the multi-loop cascade is easily sustained by the S7-1200. Since user interface tasks are handled independently by a dedicated HMI, opting for the lower-tier controller minimizes hardware CAPEX while meeting all processing targets.
Psychrometric Sensors	Combined Temperature (<i>T</i>) and Relative Humidity (<i>RH</i>) industrial transmitters.	Positioned directly in the inlet duct and plenum. Combined transmitters reduce installation costs, footprint, and wiring complexity while providing synchronized local variables to compute absolute Humidity Ratio (<i>HR</i>).
Sensor Localization	Exclusion from active hazardous zones to comply with cost-sensitive brownfield retrofits.	Sensors were localized upstream in the fresh air intake duct and plenum supply streams rather than inside the spray booth core. This tactical placement follows automotive industry standards, removing instruments from hazardous VOC vapor zones. This choice eliminates the requirement for highly expensive, explosion-proof ATEX-certified instrumentation, reducing procurement CAPEX.

4.11 HMI, Access Control and Audit Trail

The HMI is proposed as the main interface between the automatic humidity control system and the plant users. Its function is not only to display process variables, but also to support controlled decision-making, maintenance diagnosis and process traceability.

The HMI should display real-time temperature and relative humidity values, system status, alarms, historical trends and operating mode. To avoid uncontrolled parameter changes, access should be divided into permission levels, as shown in Table 4.9.

Table 4.9: Proposed HMI access levels and functionalities.

Access Tier	Target User	Main Functionalities
Tier 0	Production operators	View real-time system status, colour-coded dashboard, one-week temperature and relative humidity trends, and basic process variables.
Tier 1	Maintenance technicians	Access Tier 0 functions, adjust humidity set-points, modify alert thresholds, switch between manual and automatic mode, and access alarm logs.
Tier 2	Advanced maintenance	Access Tier 1 functions, tune PID parameters, calibrate sensor offsets and adjust pump scaling.
Tier 3	Process engineering	Access Tier 2 functions, analyse long-term trends, monitor sustainability indicators, evaluate water and energy consumption, and access burner analytics.

This tiered structure is aligned with a human-centric automation approach, according with principles of Industry 5.0 [2]. Operators retain visibility of the process, maintenance teams have controlled access to operational parameters, and engineering teams can use long-term data for process improvement. This is particularly relevant in a manual painting process, where human expertise remains part of the production system and should be supported rather than bypassed.

The system should also include an audit trail. Historical data should be stored in non-volatile memory, with a minimum retention period of 12 months. The stored data should be protected against manual editing or deletion and should be exportable in read-only format, such as protected CSV or PDF. This supports traceability, process audits and future diagnostic studies, while creating the data foundation required for further optimisation.

In alignment with industrial reliability and safety standards, the automated architecture includes a hardware-level manual fallback protocol to isolate the system during critical PLC malfunctions or network communication losses. Through a dedicated bypass switch inside the main electrical enclosure, operators can decouple the VFD-controlled pumps from the automated PID logic and force a static, experience-based baseline modulation via local manual potentiometers. This safety-related control integration ensures that paint shop production continuity is safeguarded against unexpected automation failures, mitigating immediate downtime risks while structural diagnostics are executed.

4.12 Safety and Implementation Requirements

The proposed TO-BE system must comply with the safety requirements applicable to industrial equipment installed in or near a paint shop environment. Since the painting process involves solvent-based coatings and potentially explosive atmospheres, safety cannot be treated as a secondary implementation detail.

The main safety and implementation requirements are summarised in Table 4.10.

Table 4.10: Safety and implementation requirements for the TO-BE system.

Requirement	Purpose
Lock-out Tag-Out system	Ensure safe access during maintenance and prevent unintended energisation.
Emergency stop	Allow immediate shutdown of the humidity control equipment in abnormal or unsafe conditions.
CE marking	Ensure conformity of new equipment with applicable European directives and standards.
Technical file	Provide documentation required for equipment conformity, maintenance and future audits.
Pressure and leak tests	Verify mechanical integrity of piping, humidification circuits and connections.
Material certificates	Confirm suitability of stainless steel and other materials used in the upgraded system.
Earthing and equipotential bonding	Reduce electrical and electrostatic risks, especially in the context of solvent-based painting and ATEX-related safety concerns.
Training	Ensure that operators and maintenance personnel understand operating modes, alarms and maintenance procedures.

These requirements are essential because the proposed solution modifies an existing legacy system. The implementation must therefore guarantee not only improved process control, but also safe operation, maintainability and compliance with industrial standards.

4.13 Project Investment Analysis

The project investment analysis was developed to estimate the investment required for the proposed humidity-control retrofit and to identify the operational mechanisms through which the solution may generate economic value. Since the solution has not yet reached detailed design, installation or post-commissioning validation, the analysis is presented as a preliminary CAPEX/OPEX assessment rather than as a final business case. The objective is not to overstate financial return, but to establish a transparent and conservative investment estimate based on the supplier information currently available.

The available commercial information includes quotations for the main equipment categories: VFD-controlled pump actuation, humidification nozzles and selected instrumentation components. However, several cost blocks remain undefined, particularly installation, PLC/HMI integration, electrical works, complete commissioning, calibration and recurring maintenance. For this reason, the values presented in this section should be interpreted as an equipment-based estimate, not yet as a fully installed project cost.

4.13.1 CAPEX Structure

Capital expenditure, or CAPEX, corresponds to the initial investment required to acquire and implement the proposed humidity-control retrofit. Following the investment structure introduced in Section 2.10, the project-specific CAPEX was divided according to the three-layer architecture of the proposed solution: the physical process layer, the instrumentation and control layer, and the supervision and interface layer.

The preliminary estimate was developed using the commercial information available at this stage. Formal supplier quotations were available for the main process and instrumentation components, namely the pump/VFD actuation, nozzles and selected instrumentation items. Additional market estimates were used for the Siemens PLC, ET 200SP distributed I/O, HMI and auxiliary automation hardware, based on industrial-grade equipment suitable for a Toyota manufacturing environment. Since a complete turnkey quotation was not available, implementation allowances were estimated for mechanical installation, electrical installation, PLC/HMI programming, cabinet components, training, documentation and safety validation.

The total project CAPEX can be expressed as:

$$CAPEX_{project} = C_{phys} + C_{ctrl} + C_{sup} + C_{cont} \quad (4.12)$$

where C_{phys} is the cost of the physical process layer, C_{ctrl} is the cost of the instrumentation and control layer, C_{sup} is the cost of the supervision and interface layer, and C_{cont} is the contingency allowance. All values are presented excluding VAT, since the objective is to estimate the industrial investment cost.

Table 4.11 presents the detailed CAPEX items considered in the expected preliminary estimate. Quoted values were used whenever available. When formal quotations were not available, conservative market estimates or implementation allowances were adopted.

Table 4.11: Preliminary CAPEX items by layer of the proposed solution.

CAPEX item	Basis	Cost [€]
Physical process layer		
Pump/VFD actuation	Two VFD-controlled pumps, one per ASU. Unit cost: 8,428.00 €.	16,856.00
Pump commissioning	Pump start-up commissioning item. Scope limited to pump commissioning.	195.63
Nozzles – expected option	60 stainless-steel nozzles in AISI 316/316L.	5,382.60
Mechanical installation	Pump and nozzle installation, hydraulic adaptation, supports and fittings.	2,500.00
Instrumentation and control layer		
Instrumentation basket	Flow, temperature, air-flow, humidity and IO-Link components included in the IFM quotation.	1,224.35
RH/T duct sensors	Six duct-mounted RH/T sensors. Unit cost: 272.00 €.	1,632.00
Siemens S7-1500 PLC	New S7-1500 PLC required for the retrofit.	2,912.50
PLC memory card	SIMATIC memory card for S7-1500 operation.	75.00
ET 200SP PROFINET interface	Distributed I/O interface for PLC communication over PROFINET.	285.45
ET 200SP analogue input modules	Six 4-channel analogue input modules, providing 24 analogue input channels for 20 sensors plus spare capacity.	1,032.00
ET 200SP BaseUnits	BaseUnits for the distributed I/O assembly.	159.60
24 V DC power supply	Industrial power supply for sensors and ET 200SP station.	150.00
PROFINET and signal accessories	PROFINET cable, connectors, shielding and signal wiring allowance.	350.00
Electrical cabinet components	DIN rail, terminals, fuses, relays, protections, glands and panel accessories.	1,200.00
Electrical installation	Power and signal cabling, cabinet modification and equipment connection.	2,500.00
PLC/HMI programming and integration	PLC logic, HMI screens, alarm handling, signal scaling, PROFINET configuration, I/O testing and functional checks.	2,600.00
Supervision and interface layer		
HMI panel	Siemens KTP700 Basic PN 7-inch PROFINET HMI panel.	822.41
Training and documentation	Operator/maintenance training and technical documentation update.	500.00
Safety validation	Grounding, LOTO, CE/interface verification and installation safety check.	500.00

The automation estimate assumes a new Siemens PLC and an ET 200SP distributed I/O station connected through PROFINET. This architecture was considered appropriate because the retrofit includes 20 sensors distributed around the ASUs while requiring integration into an industrial control platform. The ET 200SP station was sized with 24 analogue input channels, providing capacity for the expected 20 sensor signals and a small reserve for implementation changes.

The corresponding CAPEX distribution by layer is summarised in Table 4.12. The physical process layer represents the largest share of the investment, mainly due to the pump/VFD actuation and nozzle retrofit. However, a significant part of the investment is associated with instrumentation, automation, distributed I/O, wiring and PLC/HMI integration, which reflects the objective of converting a weakly monitored manual process into a controlled and traceable system.

Table 4.12: CAPEX summary by solution layer.

Solution layer	Cost [€]	Share [%]
Physical process layer	24,934.23	61.0
Instrumentation and control layer	14,120.90	34.5
Supervision and interface layer	1,822.41	4.5
Subtotal before contingency	40,877.54	100.0
Contingency, 20%	8,175.51	—
Preliminary expected CAPEX	49,053.05	—

A contingency allowance was included because the project has not yet reached final detailed engineering or complete installation quotation. The contingency is calculated as:

$$C_{cont} = p_{cont} \cdot C_{base} \quad (4.13)$$

where p_{cont} is the contingency percentage and C_{base} is the subtotal before contingency. A value of 20% was adopted to account for uncertainty associated with installation details, integration with existing infrastructure, commissioning effort and minor scope changes, taking into account the level of maturity of installation (Level 3) [66].

Therefore, the preliminary expected CAPEX of the proposed retrofit is:

$$CAPEX_{project} = 40877.54 + 8175.51 = 49053.05 \text{ €} \quad (4.14)$$

This value should be interpreted as a preliminary investment estimate, not as a final approved project cost. It combines formal supplier quotations, industrial-market estimates and conservative allowances for implementation activities. The final value may change after detailed design, final supplier validation, confirmation of installation scope and commissioning planning.

To evaluate the sensitivity of the investment estimate, three CAPEX scenarios were defined. The low case combines the lower nozzle quotation with reduced implementation allowances. The expected case uses the nozzle quotation and standard implementation allowances, as shown in Table 4.13. The high case combines the higher nozzle quotation with increased implementation and integration allowances. This approach reflects the fact that the main uncertainty is not limited to equipment selection, but also includes the maturity of installation and automation-integration costs.

Table 4.13: Preliminary CAPEX sensitivity for the proposed retrofit.

Scenario	Assumption	Subtotal before contingency [€]	20% contingency [€]	CAPEX [€]
Low	Low nozzle option and reduced implementation allowance.	35,600.14	7,120.03	42,720.17
Expected	Expected nozzle option and standard implementation allowance.	40,877.54	8,175.51	49,053.05
High	High nozzle option and increased implementation/integration allowance.	49,176.94	9,835.39	59,012.33

The expected case was selected for the main analysis because it represents the most balanced estimate based on the available supplier quotations, the new PLC architecture and the implementation effort required for industrial deployment. The low and high cases are retained to show the uncertainty range associated with equipment selection and implementation maturity.

At this stage, the remaining uncertainty is mainly related to implementation maturity rather than to the existence of the required equipment. The most relevant items to validate before industrial approval are the final mechanical installation scope, the final electrical installation scope, the approved PLC/HMI architecture, commissioning responsibilities and calibration requirements. These items should be confirmed before the estimate is used as a final investment request.

4.13.2 OPEX Structure

Operating expenditure, or OPEX, corresponds to the recurring annual cost or saving generated after implementation. The proposed retrofit introduces additional recurring costs, mainly due to calibration or verification, sensor replacement, spare parts and maintenance of the new control components. At the same time, it may reduce operational cost through improved pump control, improved fault detection and more stable environmental operation.

The additional annual OPEX is defined as:

$$OPEX_{add} = C_{cal} + C_{rep} + C_{spares} + C_{maint,new} + C_{soft} \quad (4.15)$$

where C_{cal} is the annual calibration or verification cost, C_{rep} is the annualised replacement cost of sensors or probes, C_{spares} is the spare-parts cost, $C_{maint,new}$ is the additional maintenance labour cost, and C_{soft} is any recurring software or licence cost.

Since final supplier maintenance requirements were not available at the time of the analysis, annual OPEX was estimated using preliminary allowances. These values should be validated after final sensor selection, calibration policy definition and maintenance planning.

Calibration requirements were not fully specified in the available supplier quotations. For this reason, calibration was treated as an annual verification/calibration allowance rather than as a confirmed contractual cost. This approach is consistent with metrology guidance, where recalibration intervals should be defined and reviewed according to the measurement equipment, application criticality, operating environment, stability history and required confidence in the measurement results [81, 82].

Table 4.14: Estimated annual OPEX introduced by the proposed retrofit.

OPEX item	Low [€/year]	Expected [€/year]	High [€/year]	Basis
Calibration / verification	400	600	900	Annual verification or calibration of RH/T, flow, pressure and water-quality instrumentation.
Sensor/probe replacement	300	500	800	Annualised replacement allowance based on a five-year replacement or requalification cycle for critical sensors.
Spare parts	200	300	500	Allowance for connectors, nozzles, small fittings, sensor accessories and minor spare components.
Additional maintenance labour	300	400	600	Periodic inspection, cleaning, signal verification and functional checks of the added system.
Software/licence	0	0	0	No recurring software licence was assumed.
Total additional OPEX	1,200	1,800	2,800	Estimated annual recurring cost, excluding VAT.

The expected annual additional OPEX used in the base analysis is therefore:

$$OPEX_{add,exp} = 600 + 500 + 300 + 400 + 0 = 1800 \text{ €/year} \quad (4.16)$$

4.13.3 Annual Savings

The annual net benefit of the retrofit is calculated as the difference between the quantified annual savings and the additional annual OPEX:

$$B_{net} = S_{annual} - OPEX_{add} \quad (4.17)$$

For the economic calculation, the quantified annual saving is divided into two parts:

$$S_{annual} = S_{pump} + S_{gas} \quad (4.18)$$

where S_{pump} is the annual electricity saving from the VFD-controlled humidification pumps and S_{gas} is the scenario-based gas saving associated with improved environmental control. Benefits related to manual adjustment, maintenance response, traceability and quality-risk reduction are not monetised because reliable plant cost data was not available.

Pump electricity impact

The proposed VFD-controlled humidification system may reduce pump electricity consumption if the pumps operate for a significant fraction of the time at reduced speed or remain inactive when humidification is not required[87]. However, the saving is not guaranteed, since the new pumps have a higher rated power than the existing pumps. Therefore, the electricity impact was evaluated through a sensitivity analysis based on different VFD operating profiles.

The annual electricity consumption of the legacy humidification pumps is estimated as:

$$E_{legacy} = n_{ASU} \cdot P_{legacy} \cdot h_{legacy} \quad (4.19)$$

where n_{ASU} is the number of ASUs, P_{legacy} is the installed power of each existing pump and h_{legacy} is the annual operating time of the current system. For two ASUs, one pump per ASU, an existing pump power of 4 kW and an estimated annual operation of 880 h/year:

$$E_{legacy} = 2 \cdot 4 \cdot 880 = 7040 \text{ kWh/year} \quad (4.20)$$

For the proposed VFD-controlled system, annual electricity consumption depends on the operating profile:

$$E_{VFD} = n_{ASU} \cdot P_{new} (h_{full} + \alpha^3 h_{partial}) \quad (4.21)$$

where P_{new} is the rated power of each new pump (7.5 kW), h_{full} is the annual full-speed operating time, $h_{partial}$ is the annual partial-speed operating time and α is the average partial-speed ratio. The cubic term reflects the pump affinity-law approximation, according to which pump power varies approximately with the cube of rotational speed for centrifugal pumps.

The annual electricity impact is then calculated as:

$$S_{pump} = (E_{legacy} - E_{VFD}) C_{elec} \quad (4.22)$$

where C_{elec} is the electricity cost per kWh. A conservative internal electricity cost of 0.05 €/kWh was adopted for this preliminary estimate:

$$C_{elec} = 0.05 \text{ €/kWh} \quad (4.23)$$

The input data used in the estimate are summarised in Table 4.15.

Table 4.15: Data used to estimate pump electricity impact.

Variable	Meaning	Value / status
n_{ASU}	Number of ASUs considered.	2
P_{legacy}	Installed power of each existing pump.	4 kW
P_{new}	Rated power of each new VFD-controlled pump.	7.5 kW
h_{legacy}	Annual operating time of the current pumps.	880 h/year
h_{full}	Annual full-speed operation after VFD control.	Scenario-based
$h_{partial}$	Annual partial-speed operation after VFD control.	Scenario-based
α	Average partial-speed ratio.	Scenario-based
C_{elec}	Electricity cost.	0.05 €/kWh

A sensitivity analysis was then defined for the VFD operating profile, keeping the total annual humidification operating time equal to 880 h/year. The results are presented in Table 4.16.

Table 4.16: Sensitivity analysis for VFD pump electricity impact.

Scenario	VFD operating profile	E_{VFD} [kWh/year]	ΔE [kWh/year]	S_{pump} [€/year]
Conservative	50% full speed; 50% at 80% speed.	6,350.40	689.60	34.48
Expected	30% full speed; 70% at 60% speed.	3,379.20	3,660.80	183.04
Optimistic	20% full speed; 80% at 50% speed.	2,112.00	4,928.00	246.40

In Table 4.16, $\Delta E = E_{legacy} - E_{VFD}$. A positive value indicates an electricity saving, while a negative value indicates an increase in electricity consumption. Thanks to the correct mechanical

specification of the pump at 7.5 kW, even the conservative scenario demonstrates a positive energy saving due to the strong impact of the pump affinity laws under part-load conditions (α^3). Therefore, the electrical benefit of the upgrade is thermodynamically validated.

Gas consumption sensitivity analysis

The financial viability of the retrofit is assessed through a sensitivity analysis based on projected efficiency improvement [62]. Drawing from industrial benchmarks for PID-modulated combustion control and VFD-driven HVAC optimization, the proposed system is estimated to achieve an efficiency gain in the range of 10% to 20% relative to baseline gas consumption [87, 88].

Using the 2023–2024 median baseline of 8.38 kg/unit and an annual production volume of 3014 units, the baseline annual gas consumption is calculated as:

$$m_{\text{gas,baseline}} = 8.38 \cdot 3014 = 25,257.32 \text{ kg/year} \quad (4.24)$$

Based on the gas tariff of 1.43292 €/kg, the total annual baseline cost is 36,192.65 €/year. The sensitivity scenarios are defined by applying the projected efficiency improvement range to this baseline:

- **Pessimistic:** Assumes a 5% efficiency gain;
- **Expected:** Assumes a 12% efficiency gain;
- **Optimistic:** Assumes a 20% efficiency gain.

Table 4.17: Sensitivity analysis of annual gas-cost reduction.

Scenario	Efficiency Gain	Annual Saving [€/year]
Pessimistic	5%	1,809.63
Expected	12%	4,343.12
Optimistic	20%	7,238.53

The annual net benefit is determined by aggregating the electricity savings and gas-cost savings, then subtracting the operational expenditure. Using the expected scenario (12% gas-efficiency gain), the components are:

- Annual Pump Electricity Saving (S_{pump}): 183.04 €/year
- Annual Gas-Cost Saving (S_{gas}): 4,343.12 €/year
- Additional Annual OPEX ($OPEX_{\text{add}}$): 1,800.00 €/year

Substituting these into Eq. 4.17:

$$B_{net} = (183.04 + 4,343.12) - 1,800.00 = 2,726.16 \text{ €/year} \quad (4.25)$$

4.13.4 Economic Indicators

The project's economic viability is assessed using standard engineering economy methodologies, specifically focusing on Simple Payback (PB), Return on Investment (ROI), and Net Present Value (NPV) [62–64]. These metrics provide a structured mathematical framework to evaluate capital allocation efficiency under corporate risk constraints. A seven-year analysis period and an 8% discount rate were adopted for the NPV calculation, aligning both with Toyota's internal hurdle rates and established international guidelines for life-cycle costing in industrial asset management [65, 89].

Table 4.18: Annual net benefit and payback scenarios.

Scenario	S_{pump}	S_{gas}	$OPEX_{add}$	B_{net}	PB [y]
Pessimistic	34.48	0.00	2,800.00	-2,765.52	N/A
Expected	183.04	4,343.12	1,800.00	2,726.16	18.0
Optimistic	246.40	7,238.53	1,200.00	6,284.93	7.8

Table 4.19: ROI and NPV scenarios (7-year period).

Scenario	ROI [%]	NPV [EUR]
Pessimistic	-5.6	-63,456.20
Expected	5.6	-34,863.45
Optimistic	12.8	-15,120.12

The economic metrics reveal a structural contradiction between the project's operational efficiency and its capital recovery timeline. While the expected scenario demonstrates positive efficiency (ROI = 5.6%), the actual annual savings are insufficient to amortize the initial capital expenditure within the mandatory 7-year corporate window. Applying the 8% discount rate to these low annual returns results in a net asset deficit (NPV = -34,863.45 EUR).

Because automotive production lines are typically modified or decommissioned on a 5-to-7-year cycle, the 18.0-year payback period introduces an unacceptable asset-lifespan risk. Consequently, this project cannot be justified to management as a cost-reduction initiative. Its feasibility relies entirely on non-financial operational constraints, where the negative NPV represents the mandatory capital cost required to enforce ATEX safety compliance and eliminate humidity-driven top-coat paint defects.

Conclusion: Project Investment Analysis

The economic evaluation demonstrates that the proposed climate-control retrofit is not self-justifying through energy-cost reduction alone. Under the expected efficiency scenario, the investment yields a seven-year NPV of -35,431.11 EUR and a payback period of 18.7 years, both failing standard automotive capital hurdle rates. Because production line assets are typically modified or decommissioned on a 5-to-7-year cycle, this payback horizon introduces an unacceptable asset-lifespan mismatch.

However, these financial metrics capture only direct utility offsets and do not invalidate the project's feasibility. The primary justification relies on transitioning the QCT1 painting line from a manual, weakly monitored process to a high-fidelity, automated system. The investment is justified by three non-financial operational pillars:

- **Risk Mitigation and ATEX Compliance:** The system maintains relative humidity within strict boundaries to eliminate electrostatic discharge ignition hazards in solvent-laden atmospheres, securing compliance with EN 16985 facility safety standards.
- **Operational Stability and Quality Assurance:** Replacing manual adjustments with PID-modulated control eliminates the thermal and moisture excursions that drive rework spikes, establishing a direct path to process repeatability and paint defect reduction.
- **Process Traceability and Diagnostics:** The integrated PLC-HMI architecture provides real-time visibility and digital data logging. This baseline eliminates sporadic, human-dependent checks while accelerating root-cause analysis and maintenance diagnostics.

Consequently, this retrofit serves as a risk-management asset that isolates the QCT1 booth from environmental volatility. While energy savings provide a modest operational offset, the strategic value lies in safety compliance, quality assurance, and digital readiness. Future optimization phases should focus on quantifying the financial impact of rework prevention and quality-claim mitigation, as these variables represent the true drivers for long-term capital return.

4.14 Next Steps

This chapter developed the TO-BE strategy for the painting booth environmental control system, using the AS-IS diagnosis and diagnostic FMEA as the technical basis. The proposed solution was defined as a retrofit, rather than a full replacement, due to the constraints of the existing legacy infrastructure, production continuity and limited intervention windows.

Table 4.20: Summary of the proposed TO-BE strategy.

Area	Main proposal	Expected contribution
Short-term stabilisation	Safer measurement practices, visual management, grounding/PPE verification, maintenance standardisation and correction of known reliability issues.	Immediate reduction of operational risk and improved process discipline without major infrastructure changes.
Instrumentation	Permanent RH/T, pressure, flow and water-quality monitoring in relevant ASU/booth locations.	Continuous process visibility and earlier detection of out-of-specification conditions.
Control architecture	PLC-based control with ET 200SP remote I/O, PROFINET communication and VFD-controlled humidification pumps.	Structured reaction logic and improved coordination between measurement, actuation and supervision.
Supervision and reaction	HMI screens, alarm logic, Go/No-Go criteria, audit trail and operator/maintenance information.	Faster response, improved traceability and reduced dependence on manual checks.
Industrial implementation	Supplier validation, installation planning, commissioning, calibration strategy and post-implementation monitoring.	Required steps before the proposed benefits can be confirmed in production.

Overall, the TO-BE strategy directly addresses the main weaknesses identified in the AS-IS system: insufficient environmental monitoring, weak coordination between humidity and temperature regulation, absence of structured reaction logic, limited maintenance visibility and safety-related concerns. Its main expected contribution is an increase in process robustness, traceability and reaction capability. However, the proposal remains an engineering roadmap at this stage; quantitative reductions in coating defects, gas consumption or maintenance losses can only be confirmed after supplier validation, commissioning and post-implementation monitoring.

Chapter 5

Simulation-Based Assessment

This chapter represents the Check phase of the adopted PDCA cycle. Following the AS-IS diagnosis and TO-BE proposal, a simplified Simscape Moist Air model was developed to validate the physical feasibility of the retrofit architecture. Rather than building a fully calibrated industrial digital twin, the objective was to verify whether the proposed sensing, actuation, and control concepts generate physically plausible temperature and humidity responses under representative conditions.

As a simulation-based validation tool, the model checks the coherence of key physical mechanisms: air supply, heating, humidification, latent cooling, duct transport, booth mixing, and exhaust balance. Furthermore, it served to structure the control architecture into clear functional layers: command generation, safety interlocks, actuator dynamics, and moist-air physical response.

5.1 Validation Objective and Scope

The primary objective of the simulation was to verify the physical plausibility of the proposed TO-BE control architecture before industrial implementation. Rather than reproducing every geometric detail, leakage path, or transient procedure of the real paint booth, the model addresses a specific engineering question: whether the proposed architecture produces coherent temperature and humidity responses under heating and humidification inputs.

The validation scope is thus focused on control-relevant behavior. The model evaluates whether burner actuation raises supply temperature, whether humidification increases the humidity ratio, whether evaporative actions capture latent cooling effects, and whether the booth responds with realistic physical delays under balanced supply and exhaust flows.

Conversely, detailed CFD airflow distribution, calibrated defect prediction, full start-up/shutdown sequences, micro-level component physics (e.g. nozzle evaporation, combustion dynamics), and exact legacy equipment calibration were outside the scope. These boundaries align with the model's purpose: to provide a conceptual validation of the control strategy rather than to replace detailed industrial commissioning.

5.2 Model Assumptions and Limitations

The model was developed as a control-oriented simulation model. Its main assumptions and limitations are summarised in Table 5.1.

Table 5.1: Main assumptions and limitations of the simulation model.

Area	Assumption / simplification	Implication
Model purpose	Control-oriented physical consistency model, not a calibrated industrial digital twin.	Results validate trends and architecture feasibility, not exact booth prediction.
Industrial data	No high-frequency booth data were available for calibration.	Validation is qualitative and based on expected physical behaviour.
Geometry	Booth, ducts and ASUs were represented by equivalent volumes and flow paths.	Local airflow non-uniformity, vortices and detailed duct losses were not assessed.
Airflow balance	Nominal supply and equivalent exhaust flows were used.	Mass balance could be checked, but detailed fan/scrubber behaviour was not modelled.
Burner	Burner action was represented by imposed heat input and simple actuator dynamics.	Sensible heating was assessed without detailed combustion or staging logic.
Humidifier	Humidification was represented by effective evaporation and latent cooling.	Moisture addition was assessed without nozzle, droplet or water-loop dynamics.
Interlocks	Safety logic was validated at command level.	Full physical start-up and shutdown transients were outside the main validation scope.

5.2.1 Psychrometric State-Point Definition

The humidification requirement was defined using a state-point psychrometric balance along the ASU air-treatment path. The air is first drawn from the outdoor environment, then heated by the burner, humidified by the spray humidifier and finally delivered through the duct and plenum to the painting booth. Therefore, the relevant air states can be represented as:

$$(T_{out}, RH_{out}, w_{out}) \rightarrow (T_{AB}, RH_{AB}, w_{AB}) \rightarrow (T_{hum}, RH_{hum}, w_{hum}) \rightarrow (T_{booth}, RH_{plenum}, w_{plenum}) \quad (5.1)$$

where T is the dry-bulb temperature, RH is the relative humidity and W is the humidity ratio. The subscripts *out*, *AB*, *hum* and *plenum* refer respectively to the outdoor air, after-burner condition, after-humidifier condition and plenum condition. In the Simscape model, it was also possible

to collect the data in the booth to ensure proper diagnostics and calibrations of psychrometric assumptions. Across the burner, the air temperature increases, but no water vapour is added to the air stream. Therefore, the humidity ratio can be assumed approximately constant:

$$w_{AB} \approx w_{out} \quad (5.2)$$

Although W remains approximately unchanged, the increase in dry-bulb temperature reduces the relative humidity. This explains why burner operation can create a humidity-control demand even when the absolute moisture content of the intake air has not changed.

Across the humidifier, water evaporates into the air stream and increases the humidity ratio:

$$W_{hum} = W_{AB} + \Delta W_{evap} \quad (5.3)$$

The required water evaporation rate is therefore given by:

$$\dot{m}_{evap} = \dot{m}_{da} (W_{target} - W_{AB}) \quad (5.4)$$

where $\dot{m}_{da}$ is the dry-air mass flow rate and W_{target} is the humidity ratio corresponding to the required booth condition. If $W_{AB} \geq W_{target}$, no humidification is required.

The booth target condition is defined by the required temperature and relative humidity:

$$T_{set} = 23 \text{ }^{\circ}\text{C} \quad RH_{set} = 65\% \quad (5.5)$$

At 101.325 kPa, this condition corresponds to:

$$w_{set} \approx 0.01073 \text{ kg}_{water}/\text{kg}_{dryair} \quad (5.6)$$

The after-humidifier condition should therefore be selected so that, after duct and plenum transport, the booth air condition remains close to T_{set} , RH_{set} and W_{set} . In a preliminary sizing calculation, duct and plenum losses may be neglected and the after-humidifier condition can be approximated as the booth supply condition. In a detailed implementation, this assumption should be validated using duct/plenum sensors and commissioning data.

5.3 Conceptual Modelling Strategy

The model was developed in the Simscape Moist Air domain to represent the coupled pressure, temperature and humidity behaviour of the booth environmental-control system. Its architecture

followed the main functional elements of the process: outdoor air boundary conditions, air supply units, heating, humidification, duct transport, painting booth volume and equivalent exhaust extraction.

A staged modelling approach was adopted. A simplified one-ASU model was first developed to verify the basic physical mechanisms of heating, humidification, latent cooling and booth response. After this behaviour was confirmed, the model was extended to the two-ASU architecture, with ASU1 and ASU2 represented as parallel supply branches feeding a common painting booth volume. This enabled the assessment of symmetry, mixing and mass-balance behaviour at system level.

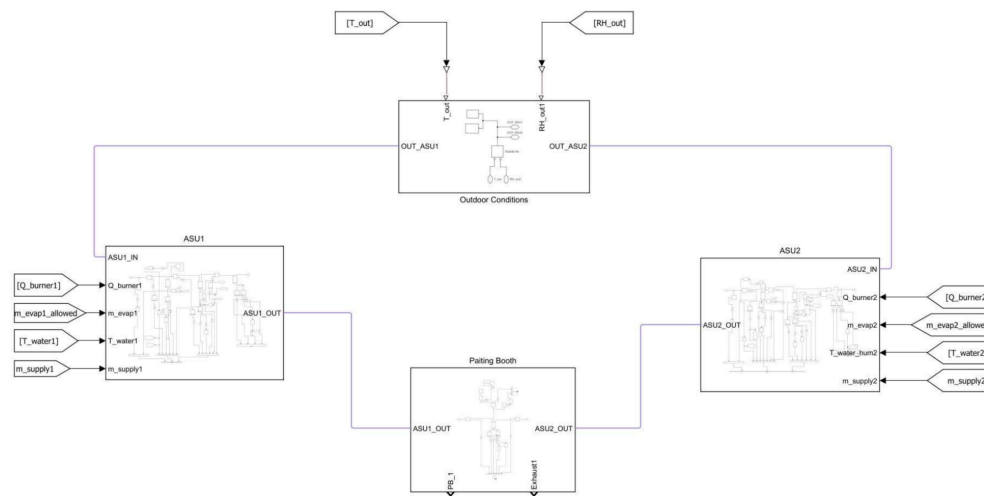


Figure 5.1: Simscape model overview

The control logic was modelled separately from the moist-air physical system. Raw commands were processed by a safety-interlock layer, which determined whether supply flow, humidification and burner actuation were permitted, as illustrated by Figure 5.2. The permitted commands were then passed through simple first-order actuator dynamics before being applied to the physical model. This separation clarified the distinction between command signals, permitted actuator outputs and the resulting physical booth response.

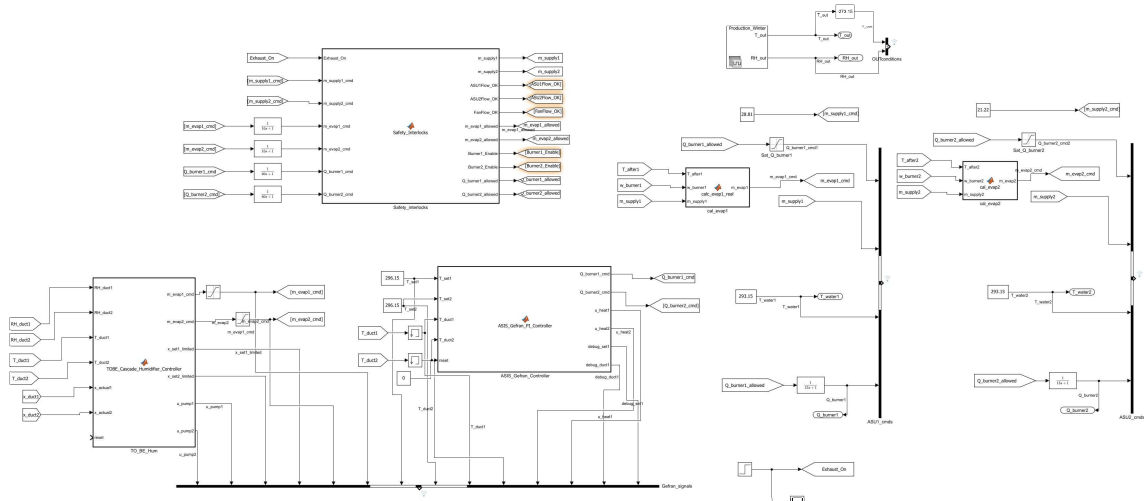


Figure 5.2: Control system subsystem: Example with model 2

5.4 Physical Consistency Validation of the Simplified One-ASU Model

The first validation stage focused on a simplified one-ASU configuration. This stage was used to confirm that the individual physical mechanisms, shown in Figure 5.3, were represented with the correct qualitative behaviour before adding the complexity of two parallel air supply units.

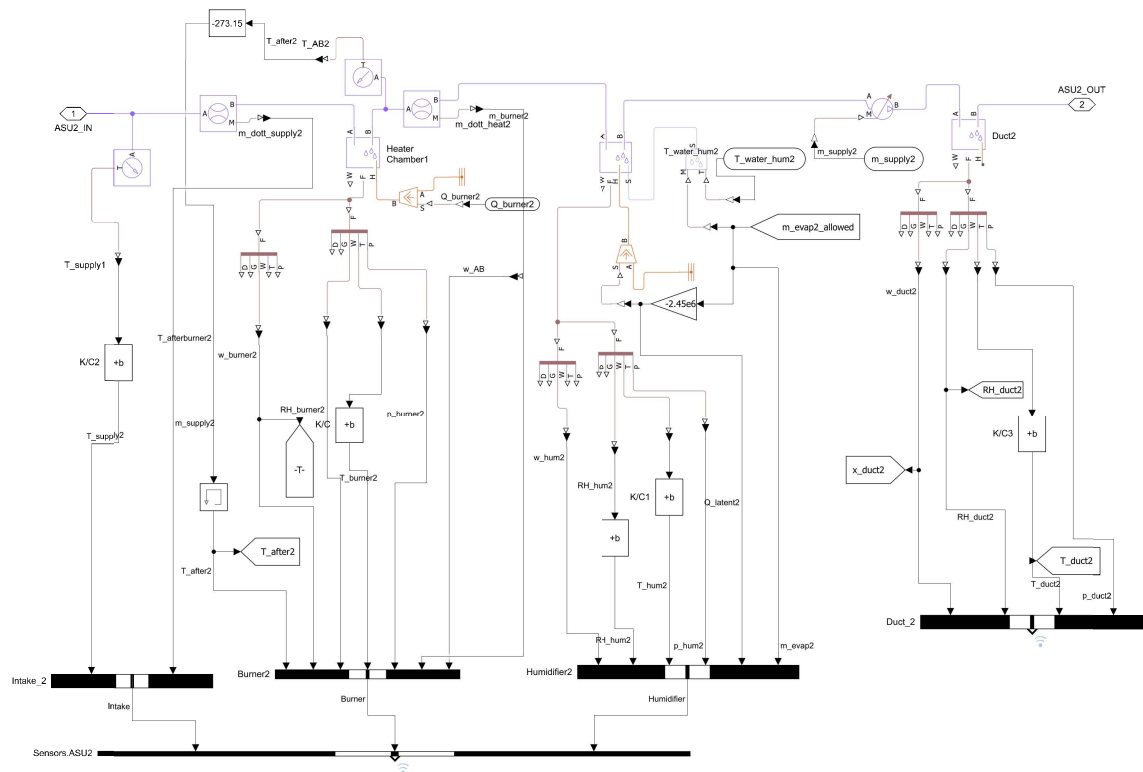


Figure 5.3: ASU 2 Simscape physical model

The expected physical behaviour was defined before analysing the simulation results. Burner actuation was expected to increase the air temperature downstream of the heater, while reducing relative humidity if no additional moisture was added. Humidifier actuation was expected to increase the humidity ratio and relative humidity downstream of the humidifier. Since water evaporation requires latent heat, humidification was also expected to reduce the air temperature downstream of the humidifier. Finally, the painting booth response was expected to be delayed and smoother than the local ASU outlet response due to the booth volume and mixing behaviour.

5.4.1 Validation Matrix: Physics

The validation matrix was built around simple open-loop actuation tests. Each test was designed to isolate one physical mechanism or one system-level behaviour. Figure 5.4 summarises the validation logic.

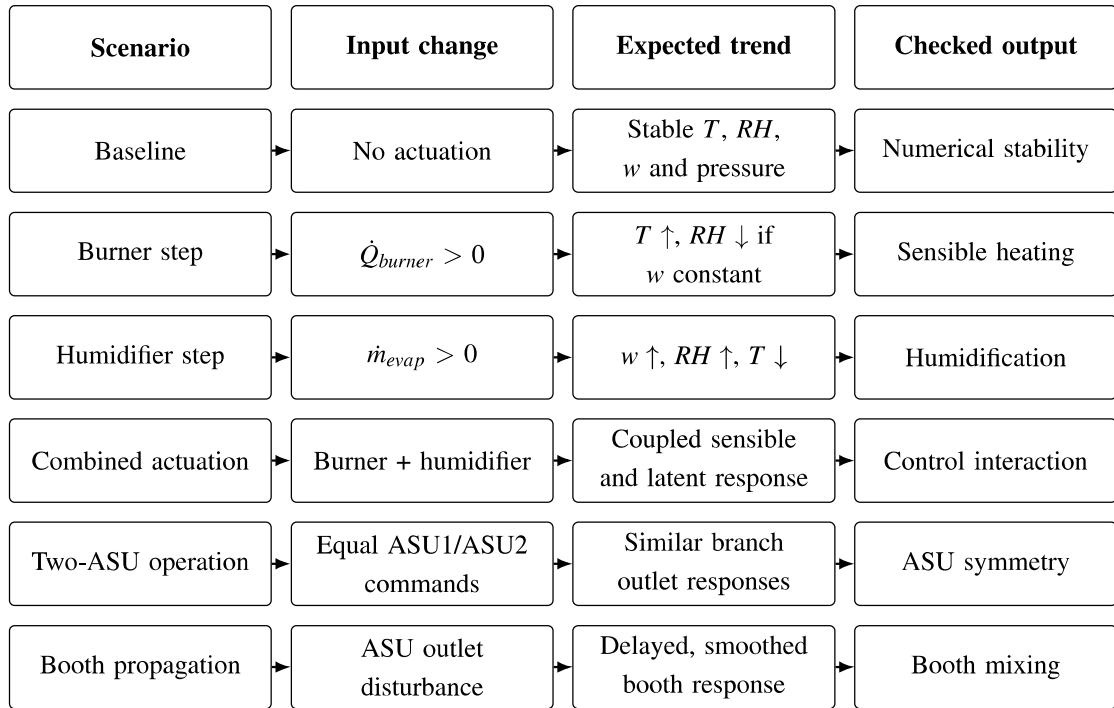


Figure 5.4: Simulation validation logic for physical-consistency assessment.

5.4.2 Mass Balance and Exhaust Stability

Mass-balance consistency was assessed by comparing the total supply flow from the ASU branches with the equivalent exhaust flow. In the simplified validation model, the exhaust was represented as an equivalent extraction flow coupled to the total permitted ASU supply flow. This modelling choice was adopted to avoid artificial mass accumulation in the painting booth and to focus the simulation on control-relevant temperature and humidity propagation.

The expected condition for stable operation was:

$$\dot{m}_{exhaust} \approx \dot{m}_{ASU1} + \dot{m}_{ASU2}$$

where $\dot{m}_{ASU1}$ and $\dot{m}_{ASU2}$ are the permitted supply mass flow rates of each air supply unit. This relationship was not intended to represent a detailed exhaust fan curve or scrubber pressure-drop model. Instead, it provided a physically consistent boundary condition for validating the heating and humidification response under nominal ventilation operation, as illustrated in Figure 5.5.

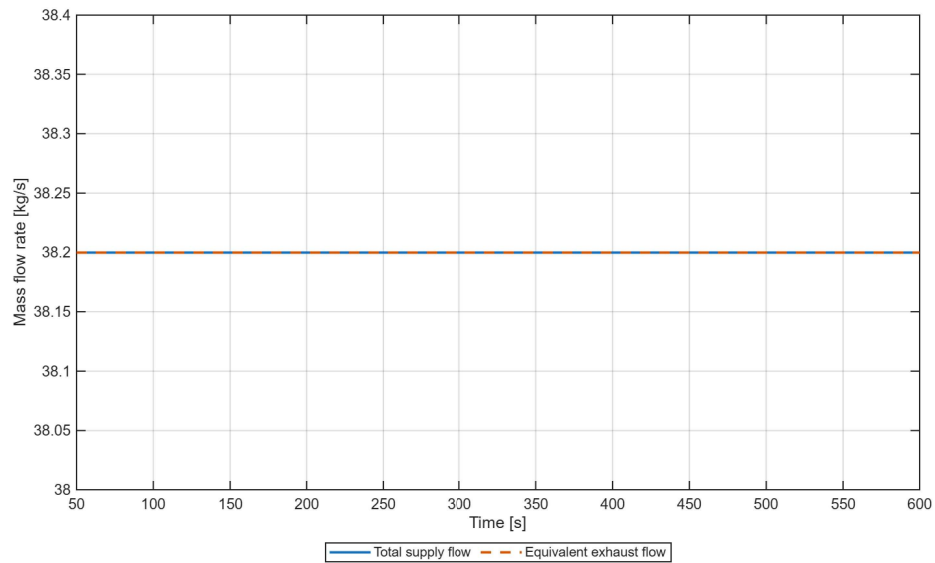


Figure 5.5: Mass balance validation

5.4.3 Burner Thermal Response Validation

A symmetric burner-step scenario was used to validate the sensible-heating behaviour of the two-ASU moist-air model. In this scenario, the burner command of both ASU branches was increased from 0 to 80 kW at $t = 100$ s, while humidification remained inactive. The objective was to isolate the thermal effect of burner actuation and verify whether the model produced the expected temperature and humidity response.

The resulting temperature response is shown in Figure 5.6. After burner actuation, both ASU duct temperatures increased with similar dynamics, confirming the consistency of the two parallel ASU branches. The painting booth temperature also increased, with a slightly smoother response due to the booth-equivalent volume and mixing effect.

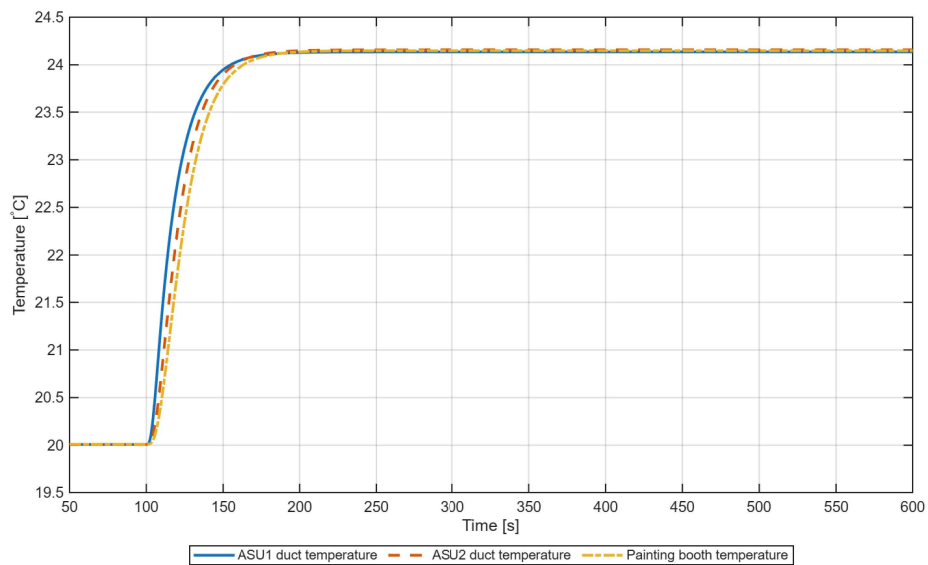


Figure 5.6: Thermal response of the two-ASU model under symmetric burner actuation.

The humidity response during the same scenario is presented in Figure 5.7. Since no moisture was added, the painting booth humidity ratio remained approximately constant. However, relative humidity decreased as temperature increased. This behaviour is consistent with sensible heating at nearly constant moisture content, and confirms the expected psychrometric response of the model.

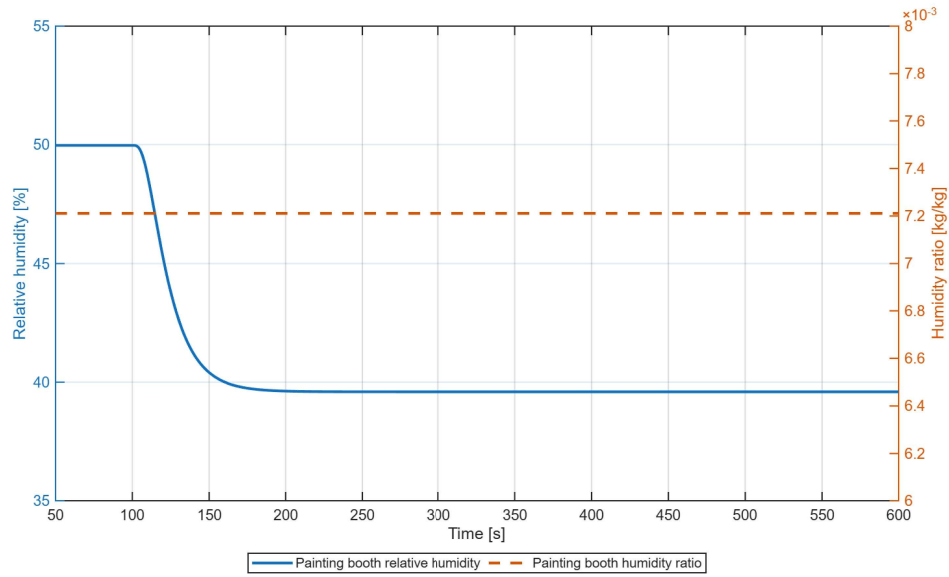


Figure 5.7: Painting-booth humidity response during sensible heating validation.

Overall, this scenario confirms that burner actuation produces a physically coherent thermal response in the two-ASU model. The results show symmetric heating behaviour in both ASU branches, propagation of the temperature increase to the booth volume, and the expected decrease in relative humidity under approximately constant humidity ratio.

5.4.4 Humidity Response Validation

Humidity response validation was performed using a symmetric humidifier-step scenario. In this test, the evaporated water flow applied to both ASU branches was increased to 0.010 kg/s, while burner actuation remained inactive. The objective was to verify whether the model reproduced the expected moisture-addition behaviour.

The humidity ratio W was used as the main indicator of water vapour addition, since it directly represents the moisture content of the air. Relative humidity, RH , was also analysed because it corresponds to the operational variable used in the paint booth specification, although it is affected by both moisture content and temperature.

As shown in Figure 5.8, the humidity ratio increased after humidifier actuation in both ASU branches and in the painting booth. The duct responses were similar, confirming the consistency of the two ASU branches, while the painting booth response was slightly delayed due to the booth-equivalent volume and mixing effect.

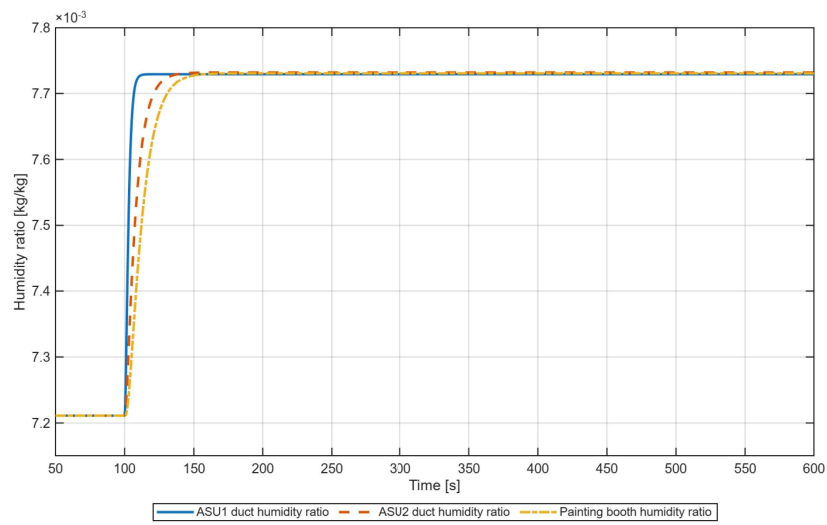


Figure 5.8: Humidity-ratio response of the two-ASU model under symmetric humidifier actuation.

The corresponding booth response is shown in Figure 5.9. The relative humidity increased after humidification, while the booth temperature decreased. This behaviour is physically consistent with evaporative humidification, where water vapour is added to the air stream and latent heat is removed from the air.

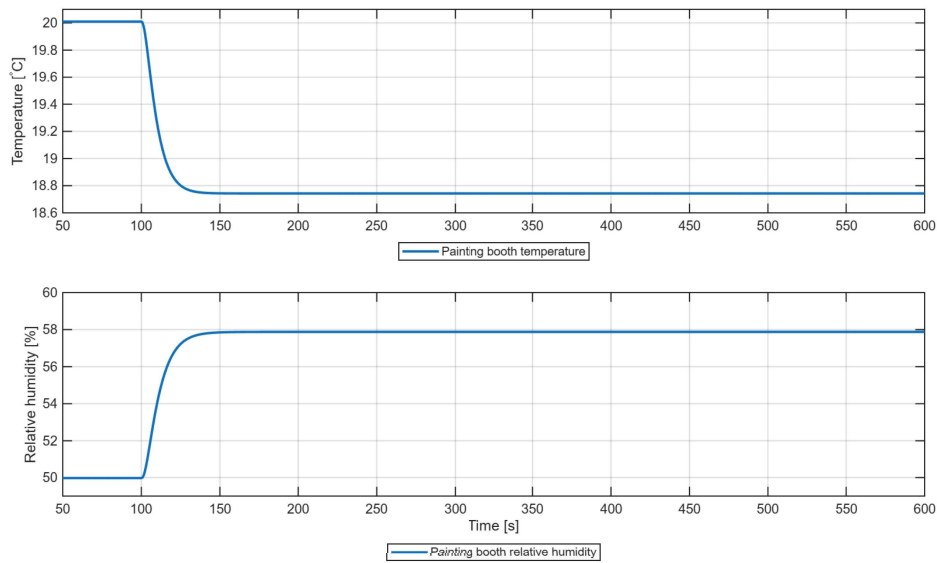


Figure 5.9: Painting-booth temperature and relative-humidity response during humidification validation.

Overall, this scenario confirms that the humidification model produces the expected physical response: W increases, RH increases and air temperature decreases due to latent cooling.

5.4.5 Combined Heating and Humidification Response Validation

A combined actuation scenario was used to validate the interaction between sensible heating and evaporative humidification in the two-ASU moist-air model. In this scenario, the burner command of both ASU branches was increased from 0 to 80 kW at $t = 100$ s. The humidifier command was then increased to 0.010 kg/s at $t = 160$ s. This staggered sequence was selected to make the separate effects of heating and humidification visible before analysing their combined impact on the painting booth conditions.

The applied actuator inputs are shown in Figure 5.10. The same burner and humidifier commands were applied to both ASU branches, allowing the coupled response of the duplicated ASU architecture to be evaluated under symmetric actuation.

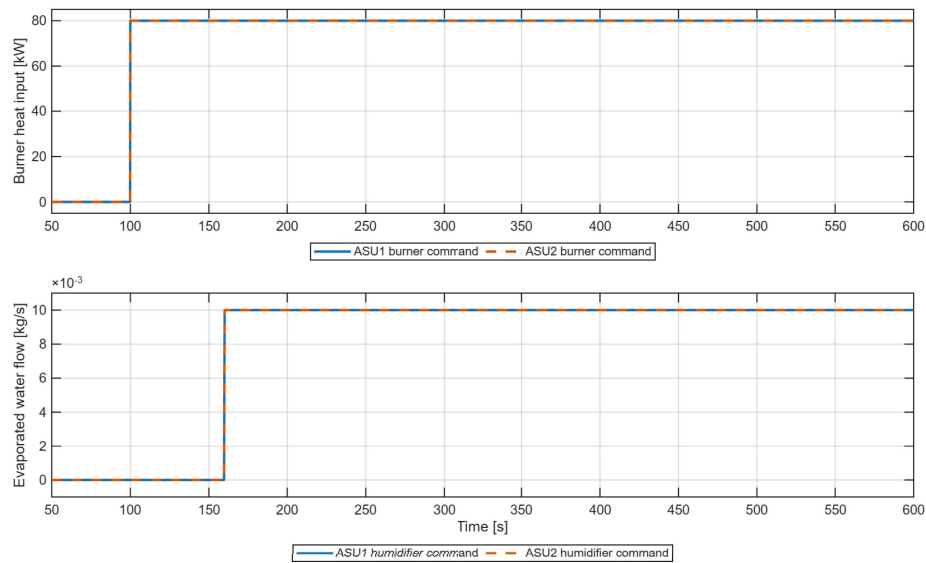


Figure 5.10: Combined burner and humidifier inputs applied to both ASU branches.

The temperature response is presented in Figure 5.11. After burner actuation, the ASU duct temperatures and painting booth temperature increased, confirming the sensible-heating effect. After humidifier actuation, the temperature response was moderated due to evaporative cooling. The painting booth response remained smoother than the duct responses, which is consistent with the booth-equivalent volume and mixing effect.

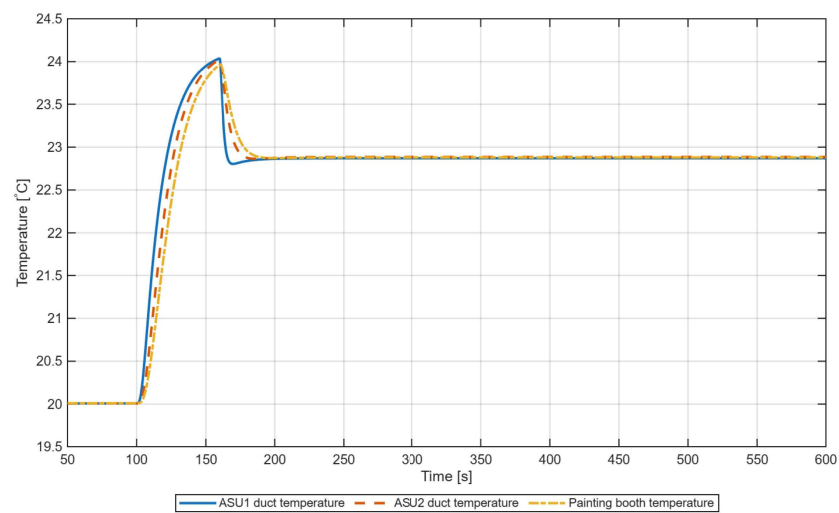


Figure 5.11: Temperature response of the two-ASU model under combined heating and humidification.

The humidity-ratio response is shown in Figure 5.12. During the initial burner-only period, the humidity ratio remained approximately constant, as no moisture was added to the air stream. After humidifier actuation, the humidity ratio increased in both ASU branches and in the painting booth, confirming the moisture-addition behaviour of the humidification model.

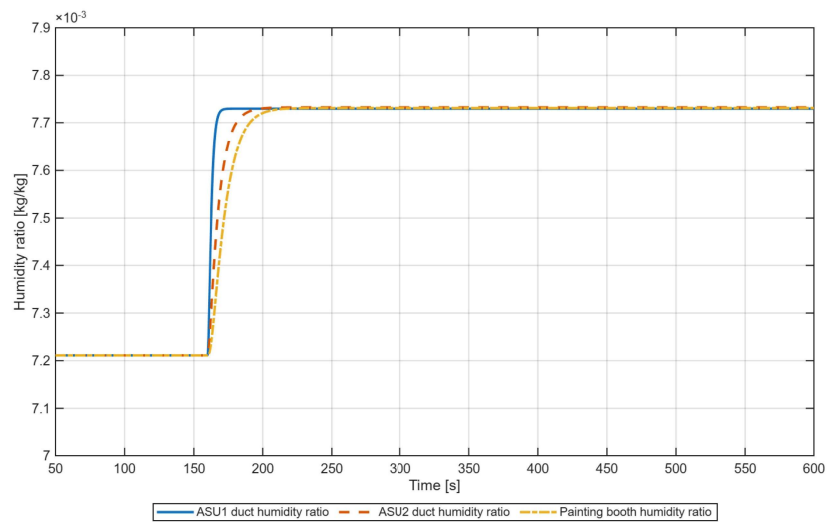


Figure 5.12: Humidity-ratio response of the two-ASU model under combined heating and humidification.

The combined booth response is summarised in Figure 5.13. The burner step caused the booth temperature to increase and the relative humidity to decrease. After humidifier actuation, the humidity ratio increased and the relative humidity recovered, while the booth temperature was reduced by the latent cooling effect. This confirms that the model is able to reproduce the expected interaction between sensible heating and evaporative humidification.

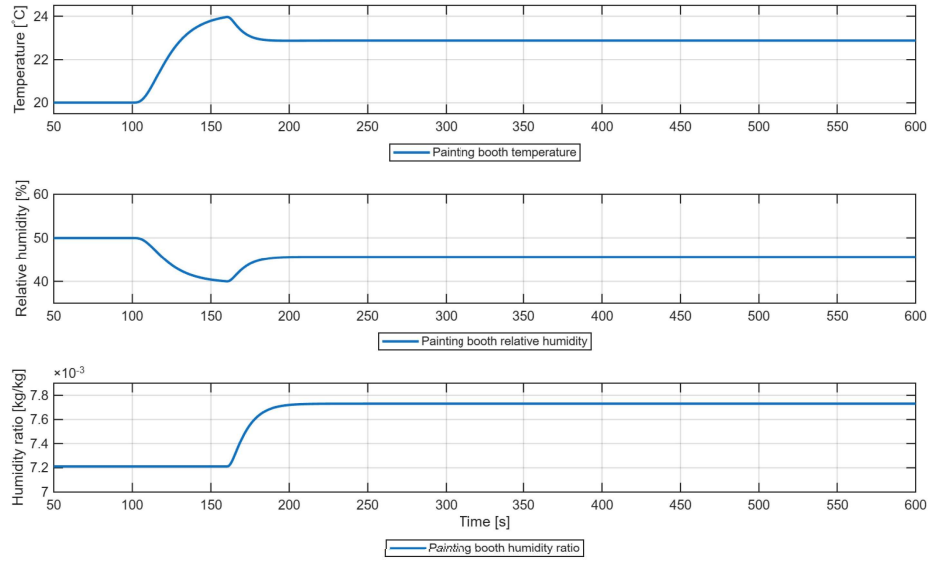


Figure 5.13: Painting-booth temperature, relative-humidity and humidity-ratio response under combined heating and humidification.

Overall, this scenario confirms that the simplified two-ASU model can represent the main coupled psychrometric effects relevant to the proposed environmental-control architecture. Burner actuation increased temperature and reduced relative humidity at nearly constant humidity ratio, while humidifier actuation increased moisture content, increased relative humidity and introduced latent cooling. This provides a physically consistent basis for the subsequent comparison between the AS-IS and TO-BE control strategies.

5.5 Extension Towards the Two-ASU Control Architecture

After validating the simplified one-ASU model, the architecture was extended to two parallel air supply units. This extension was required because the real paint booth is supplied by two ASUs, each contributing to the booth inlet conditions. The two-ASU model allowed the proposed control architecture to be assessed at system level, including duplicated actuation, parallel supply paths and booth mixing.

The two-ASU model included separate actuation commands for each branch:

$$\dot{m}_{supply,1}, \quad \dot{m}_{supply,2}, \quad \dot{m}_{evap,1}, \quad \dot{m}_{evap,2}, \quad \dot{Q}_{burner,1}, \quad \dot{Q}_{burner,2}$$

A safety-interlock layer was introduced to distinguish raw commands from permitted actuator outputs. The exhaust status was represented as an operational Boolean signal. When the exhaust

signal was disabled, the permitted ASU supply flows, humidification commands and burner commands were forced to zero at command level. When the exhaust signal was enabled and both ASU supply flows were above the minimum threshold, humidification was permitted. Burner actuation was only permitted when valid fan flow was available and the corresponding humidifier was confirmed to be active.

For the physical moist-air validation, simulations were performed under nominal ventilation conditions to avoid introducing artificial numerical stiffness associated with switching ideal flow sources in a compressible moist-air network. The interlock logic was therefore validated at command level, while the physical model was used to assess temperature and humidity (Figure 5.3) propagation under operating conditions. This separation is consistent with the objective of the chapter, which is to validate the proposed control architecture and physical response trends, not to reproduce complete HVAC start-up or shutdown transients.

5.6 Model Limitations

The main limitations of the simulation model are summarised in Table 5.2.

Table 5.2: Main limitations of the simulation model.

Limitation	Implication
No industrial calibration	The model validates physical trends, not exact booth conditions.
Simplified geometry	Ducts, ASUs and booth volumes were represented by equivalent components: local airflow non-uniformity and vortices were not modelled.
Simplified burner model	The burner was represented by an imposed heat input, detailed combustion and staging behaviour were not reproduced.
Simplified humidifier model	Humidification was represented by effective evaporation and latent cooling. Nozzle, droplet and recirculating-water dynamics were not modelled.
Equivalent exhaust	The exhaust was simplified as an equivalent extraction boundary: fan curves, scrubbers, leakage and damper behaviour were not included.
Interlocks validated at command level	Full physical start-up and shutdown transients were not the focus, the physical model was assessed under nominal ventilation conditions.

Despite these limitations, the model is sufficient to verify the physical consistency of the proposed control architecture and its main temperature and humidity response trends.

5.7 Engineering Assessment of Control Strategies

As it was summarized in Chapter 4, the control solution for the environmental control of the coating application process was defined to be a supervisory multi-variable adaptive control system. The framework uses a two-stage approach: first, a supervisory calculation tracks shifting outdoor weather conditions to determine the most energy-efficient temperature and humidity targets within

the safe operating window. Second, the primary heating and humidification units adjust their outputs to stabilize the chamber environment and prevent rapid fluctuations that could disrupt the paint application process.

5.7.1 Comparison of control strategies

To ensure structural film uniformity and controlled solvent evaporation rates during the coating curing phase, the conditioning system must maintain the chamber air within a strict psychrometric operating envelope. The AS-IS system (Model 1: Gefran controller of temperature) imposes rigid, static boundary states that induce thermodynamic unfeasibility and actuator saturation under extreme ambient conditions. The proposed framework (Model 2) implements a constrained real-time boundary optimization layer that adapts to ambient enthalpy variations while preserving the structural integrity of the process envelope.

5.7.2 Psychrometric Envelope

The properties of the moist air inside the spray booth are defined by its temperature (T) and relative humidity (RH). To maintain paint quality and ensure proper drying, these properties must stay within a specific operating window, designated as Ω :

$$\Omega = \{(T, RH) \in \mathbb{R}^2 \mid 18.0^\circ\text{C} \leq T \leq 28.0^\circ\text{C}, 55.0\% \leq RH \leq 80.0\%\} \quad (5.7)$$

The environmental conditions inside this window determine the vapor pressure difference between the wet paint film and the surrounding air, which directly controls how fast the water and solvents evaporate from the coating.

5.7.3 Actuator Dynamic Constraints and Simulation Sizing

The mechanical bottlenecks, time constants, and saturation boundaries hardcoded into the Simulink actuator subsystems are outlined in Table 5.3.

Table 5.3: Simulink actuator dynamic parameters and physical modeling justifications.

Actuator Block	Hardcoded Lag	Delay /	Saturation Limits	Physical / Modeling Justification
Gas Burner (Q_{burner})	First-order function ($\tau_{\text{burner}} = 60$ s)	transfer	Min: 0 kW Max: 900 kW	Represents the thermal inertia of the heat exchanger and burner staging lag. The maximum cap matches the physical utility rating of the factory's air handling unit.
Humidifier Pump ($\dot{m}_{\text{evap}}$)	First-order function ($\tau_{\text{humidifier}} = 10$ s)	transfer	Min: 0 kg/s Max: 0.10 kg/s (Model 1) Max: 0.50 kg/s (Model 2)	Models the hydraulic delay of the spray manifold and water pressure build-up. The 0.10 kg/s limit in Model 1 represents the baseline pump saturation ceiling causing the winter control breakdowns.
Air Supply Fan ($\dot{m}_{\text{air}}$)	Rate Limiter block (± 2 kg/s ²)		ASU1: 19.05 kg/s ASU2: 19.15 kg/s	Prevents instantaneous, unphysical flow steps in the Simscape Moist Air network. Simulates the mechanical ramp-up/ramp-down window of the industrial fan motor.

The simulation time chosen was $t=2000$ s since this time frame allows the system to stabilize in all scenarios and proved to be a compromise between computational low and the real 8h simulation of the production day.

5.7.3.1 Hardcoded Safety Constraints for ATEX Compliance

To guarantee operational safety under all optimization pathways, the lower relative humidity boundary of 55% is enforced as a hardcoded inequality constraint within the optimization algorithm of Model 2. While the supervisory layer is permitted to dynamically relax the dry-bulb temperature target to reduce overall burner loading, the relative humidity optimization domain is strictly bounded such that:

$$RH_{\text{sp}}(t) \geq 55.0\% \quad (5.8)$$

By embedding this ATEX safety threshold directly into the optimization core, Model 2 mathematically prevents the controller from selecting energy-efficient operational states that would otherwise induce static charge accumulation risks. This hardcoded priority ensures that process compliance and explosion mitigation take absolute precedence over fuel economy during extreme weather transients, as can be observed in Appendix G.

5.7.4 Basis of control systems

The baseline system (Model 1) forces a rigid target inside the booth ($T_{sp} = 23^\circ\text{C}$) being blind to the relative humidity control. In freezing winter weather (Cold_Dry), the incoming air brings almost no heat or moisture (h_{in} drops severely). Since in the present state, the pump speed is fixed, it was modulated as always evaporating ($\dot{m}_{\text{evap}1} \rightarrow \dot{m}_{\text{max}}$) and the water evaporation absorbed a large amount of heat. This forces the burner ($Q_{\text{burner}1}$) to stabilize at 450 kW to compensate.

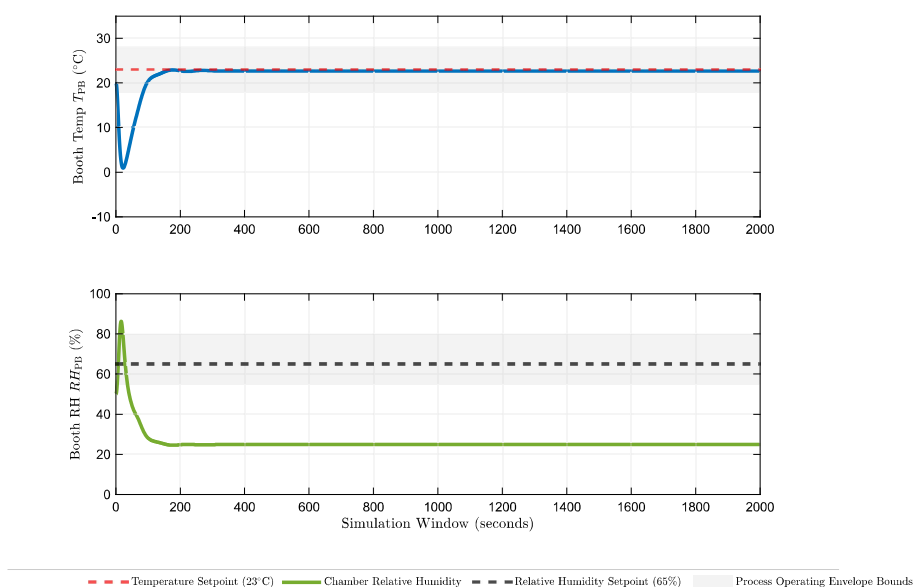


Figure 5.14: Booth environmental control under the Cold_Dry scenario (Model 1).

In contrast, with the flexible set point of the Model 2 (Figure 5.15), it is possible to be within the process window even on extreme cold and dry conditions. This multi-variable flexible control allows for less downtime and production stoppage due to temperature or humidity parameters outside the process window.

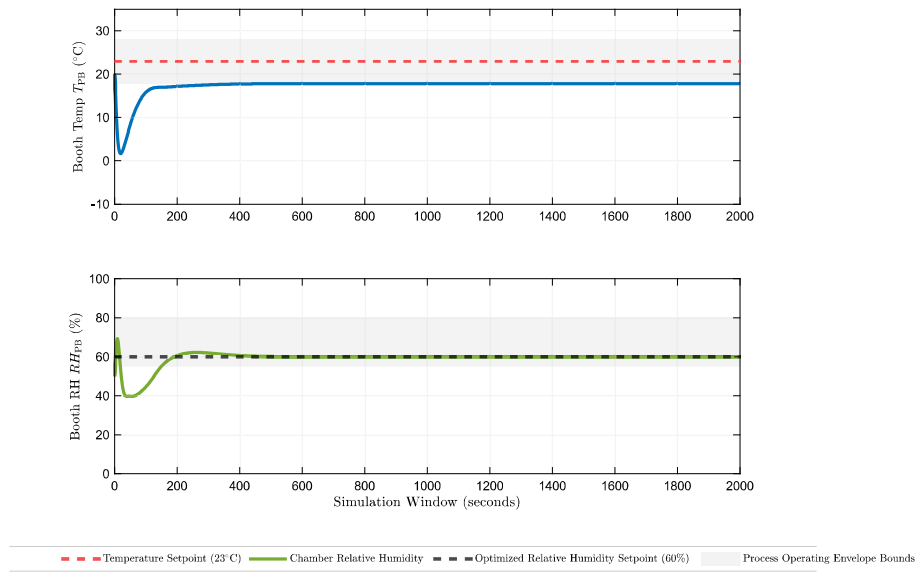


Figure 5.15: Booth environmental control under the Cold_Dry scenario (Model 2).

While the temperature window it is possible to achieve, the fixed speed and capacity of the current humidifier system could not achieve the required quality window Ω .

5.7.5 Performance Analysis Under Winter Production Conditions (Prod_Winter)

In a perspective to understand the transient environmental states and corresponding actuator outputs under the winter production scenario (Prod_Winter) are analyzed across both control frameworks.

The baseline environmental performance regarding core chamber conditions is captured in Figure 5.16, which tracks the resulting deviations when tracking rigid targets.

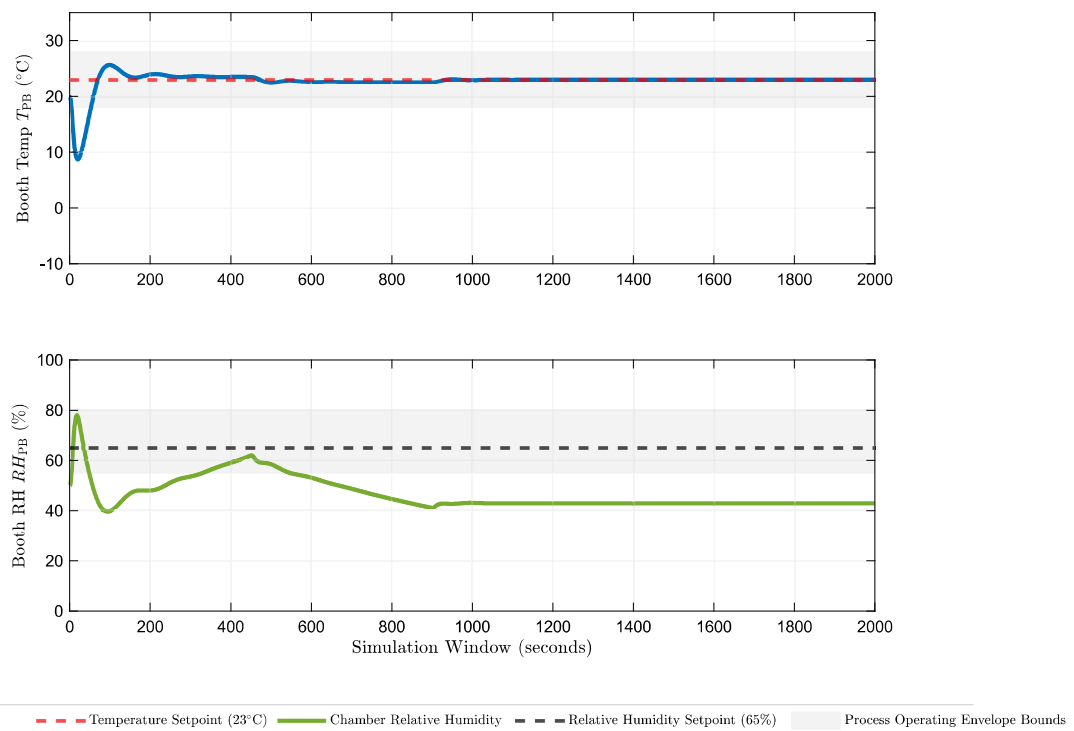


Figure 5.16: Booth environmental condition under the Prod_Winter scenario s (Model 1).

The underlying physical bottleneck causing this environmental deviation is illustrated in Figure 5.17, exposing the strict mechanical limits encountered by the baseline actuators. This condition represents an imminent safety risk, due to ATEX atmospheres below 55% in the painting booth which justifies the need to a pump that has a higher recirculated water flow. This higher recirculated water flow will translate into higher water mass absorbed by the air, which consequently will increase the relative humidity of the painting booth.

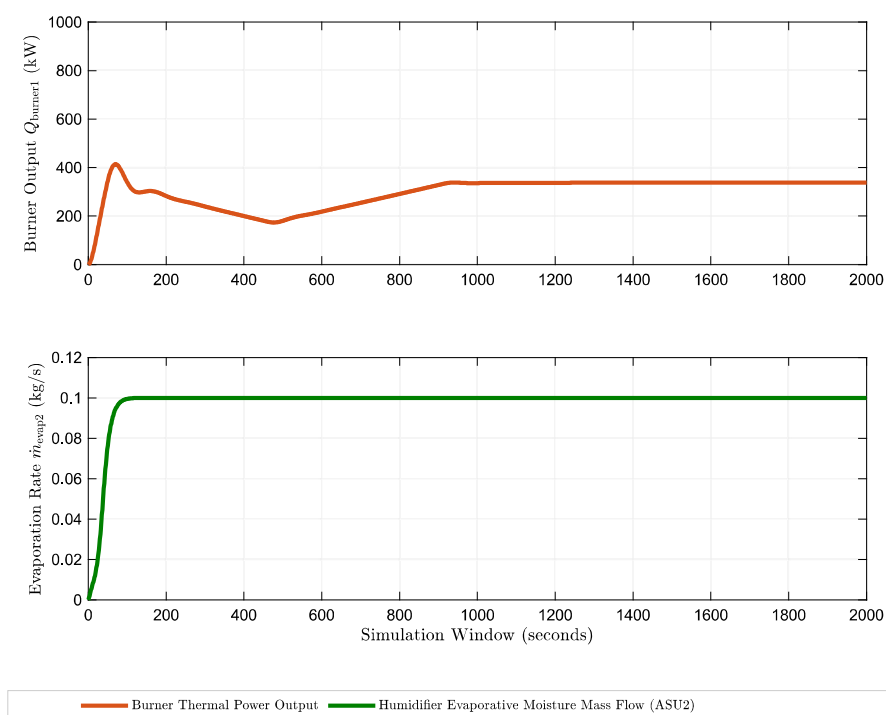


Figure 5.17: Burner thermal output and humidifier mass flow saturation at 0.10 kg/s (Model 1).

To contrast this behavior, the optimized environmental regulation achieved via dynamic target relaxation is presented in Figure 5.18.

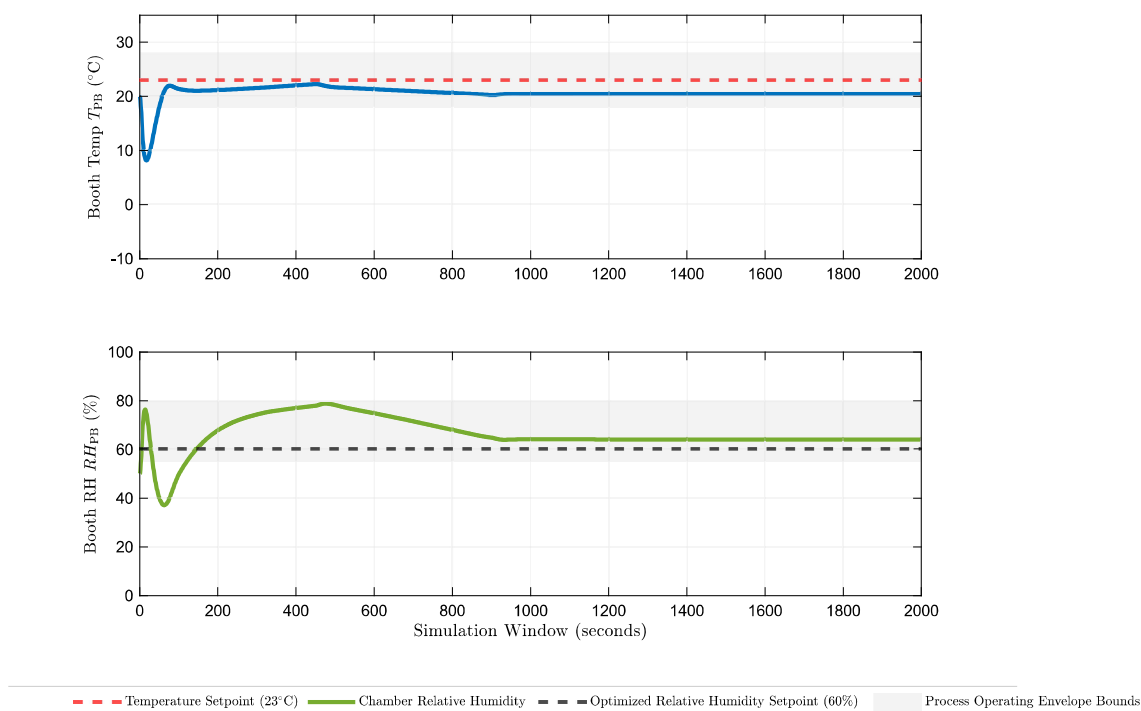


Figure 5.18: Booth environmental regulation under the `Prod_Winter` scenario using adaptive optimization (Model 2).

The corresponding unconstrained actuator efforts, for evaporation of water and burner power, that prevent loop windup and match the true demand are shown in Figure 5.19.

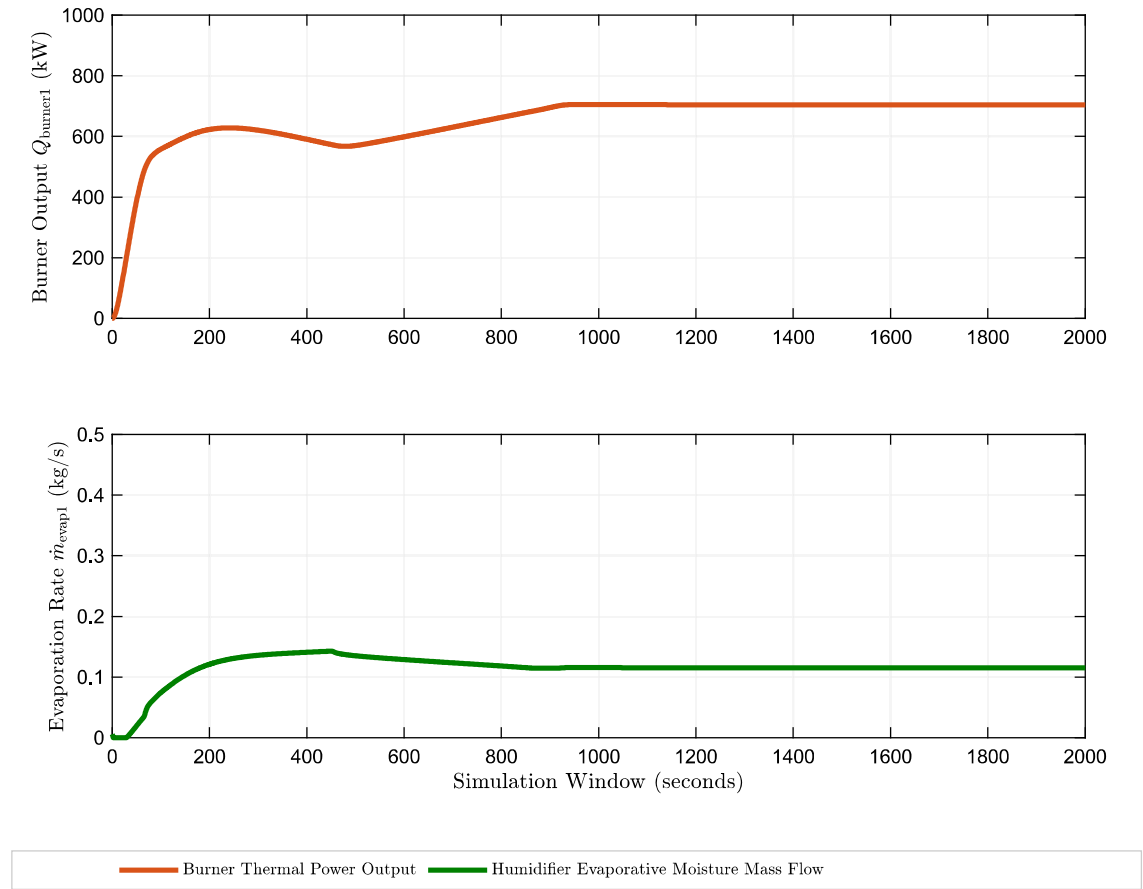


Figure 5.19: Dynamic burner power and humidifier mass flow matching process demand (Model 2).

5.7.6 Performance Analysis under Hot and Humid Conditions (Hot_Hum)

The environmental states of the booth chamber under the hot, humid summer scenario (Hot_Hum) are evaluated for both model configurations. Figure 5.20 illustrates the baseline regulation response, while Figure 5.21 captures the response under shifting target boundaries.

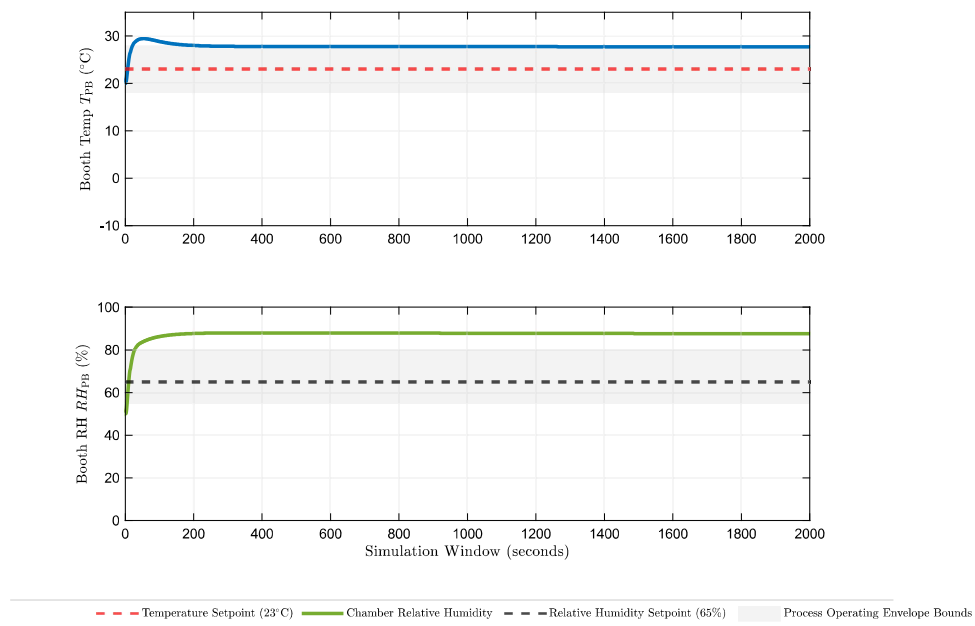


Figure 5.20: Booth environmental regulation failure under the Hot_Hum scenario with Model 1.

Under the baseline configuration (Model 1), the chamber temperature (T_{PB}) flatlines right at the absolute upper limit of the process window (30°C), while the relative humidity (RH_{PB}) saturates outside compliance boundaries at approximately 90%. Operating at this elevated humidity level would trigger an immediate production stoppage due to process parameter non-compliance. This failure mode aligns with established automotive coating literature; as documented by the literature [29], paint transfer efficiency between the application gun and the substrate decreases drastically under high ambient moisture concentrations, leading to surface defects.

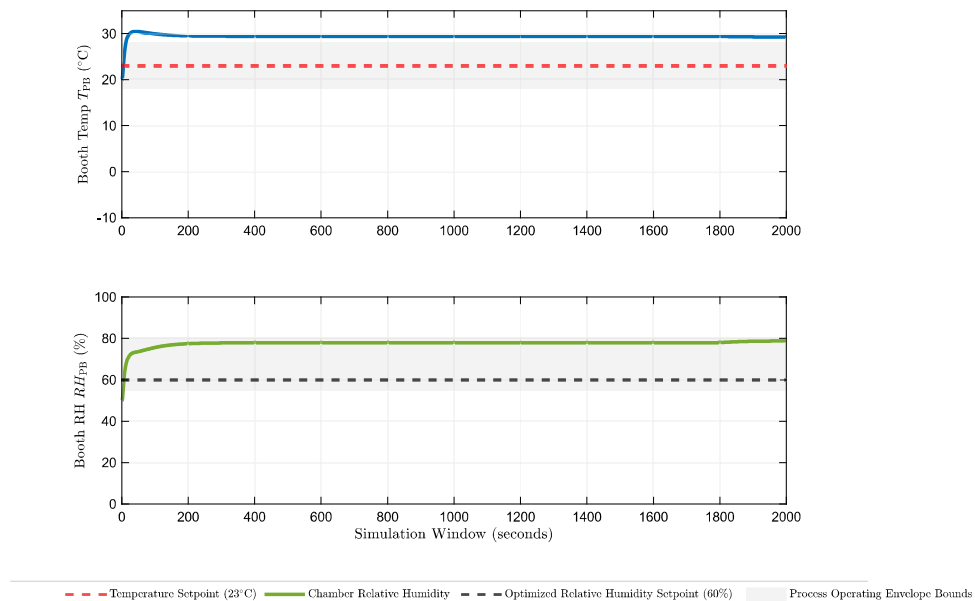


Figure 5.21: Booth environmental regulation failure under the Hot_Hum scenario with shifted setpoint criteria (Model 2).

Under the adaptive framework (Model 2), Figure 5.20 demonstrates that software optimization alone cannot overcome fundamental physical hardware omissions. When subjected to the *Hot_Hum* scenario, the optimizer recognizes the extreme incoming moisture load and commands zero actuator effort from the burner and humidifier loops. Despite this intervention, the booth temperature (T_{PB}) escapes the 23.0°C set point to stall at 29.0°C, while the relative humidity (RH_{PB}) flatlines outside compliance boundaries at approximately 79%. While this represents a marginal relative humidity improvement over the baseline system, operating in this region remains unfeasible. As supported by Goldschmidt and Streitberger [29], such elevated moisture profiles drastically reduce paint gun transfer efficiency, which would ultimately require an immediate industrial process shutdown to avoid widespread coating failures.

The fact that none of the control models can comply with process standards reveals a hardware limitation of this system in hot and humid environments. There was no hardware capable of decreasing the temperature of the air, such as a chiller. This control could also be aided if the dampers were not fixed and the air flow was not a boundary due to lack of predictive maintenance. In light of future perspectives of climate change and hotter temperatures in the next few years, analysing the implementation of a chiller could be a good investment to guarantee the process parameters in the most extreme conditions.

5.7.7 Synthesis of Results and Comparative Discussion

Table 5.4 consolidates the control outcomes and actuator states across all seasonal stress tests.

Table 5.4: Global performance summary and control outcomes across seasonal extremes.

Scenario	Baseline Framework (Model 1)	Adaptive Framework (Model 2)
Cold_Dry	Rigid T_{PB} (23.0°C); RH_{PB} collapses to 25% due to fixed humidifier limits. Quality failure.	Drops T_{PB} to 18.0°C; stabilizes RH_{PB} at 60% inside the process envelope (Ω). Compliant.
Prod_Winter	RH_{PB} drops to 43% due to humidifier saturation at its 0.10 kg/s hydraulic limit. ATEX safety risk.	Maintains RH_{PB} at 64% by relaxing T_{PB} to 20.5°C. Unconstrained linear control, 110% burner fuel penalty.
Hot_Hum	T_{PB} stalls at 28.5°C (marginal compliance); RH_{PB} saturates outside spec at 90%. Line shutdown required.	T_{PB} stalls at 29.0°C; suppresses RH_{PB} to 79% via path optimization. Hardware-limited failure.

5.7.7.1 Core Research Takeaways

1. **Set point flexibility vs. rigidity:** Model 1 fails because enforcing a strict temperature target during cold weather forces an unnatural moisture capacity expansion in the air stream. Model 2 proves that trading off minor temperature tracking deviations preserves relative humidity bounds and prevents plant downtime.

2. **Thermodynamic cost of compliance:** Overcoming actuator saturation under winter transients demands a steep energetic premium. Model 2 avoids loop windup but doubles steady-state burner output to ≈ 710 kW to compensate for the massive endothermic load of water vaporization.
3. **Physical limits of software optimization:** The `Hot_Hum` failures establish the boundary of software capability. When ambient disturbances require cooling and dehumidification, a heating-only architecture hits a physical wall. Both models command zero actuator output, but without an active chiller or dehumidifier, the booth tracks the unconditioned ambient air. The resulting high humidity (79%–90%) drops paint transfer efficiency [29] and forces an immediate line stoppage, serving as empirical justification for a possible capital expenditure (CapEx) hardware retrofit.

5.8 Project Maturity and Implementation Readiness

Based on the readiness-level principles discussed in Section 2.10.1, a simplified five-level maturity model was adopted to evaluate the implementation readiness of the proposed retrofit, as illustrated in Figure 5.22.

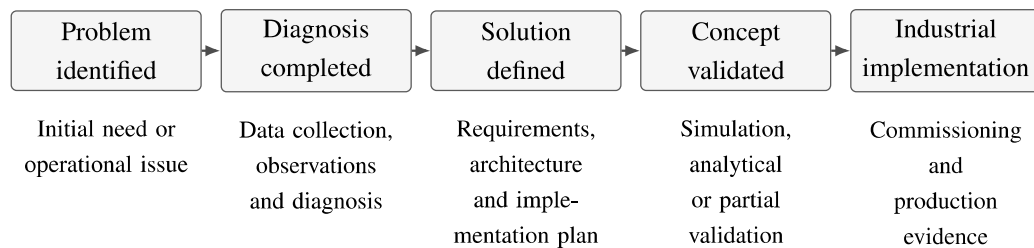


Figure 5.22: Technology Readiness Level and Manufacturing Readiness Level frameworks for industrial engineering projects [67–69].

This readiness logic provides the theoretical basis for evaluating implementation maturity later in the thesis. In particular, it avoids treating conceptual validation, such as simulation or analytical verification, as equivalent to industrial validation. A solution can therefore be technically defined and partially validated while still requiring procurement, installation, commissioning, training and post-implementation monitoring before it can be considered fully implemented in the manufacturing floor.

Since this project concerns the retrofit of an existing manufacturing process, the original readiness-level logic was simplified into five levels, shown in Table 5.5. This avoids overstating the maturity of a solution that has been technically defined and conceptually validated, but not yet fully deployed in production.

Table 5.5: Maturity levels adopted for the proposed retrofit.

Level	Definition
1 – Problem identified	The problem is recognised, but no structured diagnosis has been completed.
2 – Diagnosis completed	The current condition is characterised through data, observations, audits or analytical tools.
3 – Solution defined	A coherent TO-BE solution is specified, including requirements, architecture, risks, costs or implementation actions.
4 – Concept validated	The concept is validated through simulation, analytical verification, prototype testing or partial technical validation.
5 – Industrially implemented	The solution is installed, commissioned and validated using post-implementation production data.

The resulting maturity assessment is summarised in Table 5.6. The classification was based on the evidence produced during the project, including the AS-IS diagnosis, FMEA, technical specification, supplier comparison, control architecture, simulation model, preliminary CAPEX/OPEX analysis and implementation roadmap.

Table 5.6: Maturity assessment of the main project workstreams.

Workstream	Level	Justification
AS-IS diagnosis	2	The current condition was characterised using environmental records, defect data, process observations and airflow assessment.
Root cause analysis	2	Main causes were identified through Ishikawa analysis, shop-floor observations and process constraints. Quantitative confirmation remains limited by manual data collection.
Risk assessment	3	The diagnostic FMEA prioritised the main failure modes and supported the selection of improvement actions.
Technical specification	3	Monitoring requirements, sensor needs, PLC/HMI functions, alarms and reaction logic were defined.
Supplier selection	3	Alternative suppliers were compared using technical and implementation criteria, supporting the selection of a preferred solution.
Control architecture	3	The proposed architecture defines monitoring, control loops, HMI levels and alarm-based decision support.
Simulation model	4	The Simulink/Simscape model validated the physical plausibility of the heating and humidification control concept.
Economic assessment	3	A preliminary CAPEX/OPEX structure was developed to identify investment areas, operational cost drivers and expected value mechanisms.
Implementation roadmap	3	A staged implementation strategy was defined, separating immediate stabilisation actions from automation and structural upgrades.
Industrial deployment	2–3	Deployment requirements and constraints were identified, but the solution has not yet been installed or commissioned.

Overall, the project is classified as Level 3 – Solution Defined, with preliminary evidence of Level 4 – Concept Validated maturity for the simulation-supported control concept.

This classification is intentionally conservative. The project progressed beyond diagnosis by defining a structured TO-BE solution, including risk prioritisation, technical requirements, supplier evaluation, control architecture, preliminary economic assessment and implementation planning. In addition, the simulation model provided preliminary conceptual assessment of the proposed environmental control strategy.

However, the project cannot be classified as Level 5 – Industrially Implemented. The retrofit has not yet been fully installed, commissioned or validated under continuous production conditions. Therefore, the simulation results should be interpreted as concept assessment, not industrial validation.

The project is consequently mature enough to support decision-making and future procurement, but not yet mature enough to claim realised operational benefits. Reaching Level 5 would require final supplier quotation, detailed engineering, installation of calibrated instrumentation, PLC/HMI integration, commissioning, operator and maintenance training, and post-implementation

monitoring of environmental stability, out-of-specification events, energy consumption, maintenance interventions and quality-related indicators.

Chapter 6

Conclusions, Limitations, and Future Work

This chapter concludes the dissertation by consolidating the research outcomes against industrial safety and quality criteria, outlining the legacy and administrative constraints that bounded field deployment, and establishing the execution path for subsequent implementation phases.

6.1 Core Research Conclusions

The engineering assessment successfully validated the thermodynamic and operational feasibility of the proposed supervisor-level control strategy, yielding the following core takeaways:

1. **Methodological framework for industrial retrofits:** A structured engineering methodology was established to formulate technical specifications under strict brownfield constraints. The framework integrates cross-departmental requirements spanning engineering, safety, and production utilities.
2. **Simulation as an architectural assessment tool:** The Matlab/Simscape simulation framework proved highly effective as an engineering assessment tool. It successfully exposed the cross-coupled vulnerabilities of rigid, single-variable architectures (Model 1) while demonstrating the capabilities of flexible, multivariable adaptive control (Model 2) under seasonal weather extremes.
3. **Mitigation of physical electrostatic hazards:** The engineering assessment diagnosed and resolved a critical, active shop-floor safety hazard regarding operational electroshocks experienced by personnel on the production line. By identifying that baseline actuator constraints allowed relative humidity to collapse far below the ATEX safety envelope, this work proved that the shocks were a direct symptom of hazardous electrostatic charge accumulation. The integration of the hardcoded 55% RH constraint within Model 2 mathematically eliminates this ignition risk, transforming the control strategy into an active, validated solution for plant-wide ATEX atmospheric compliance and workforce hazard mitigation.

4. **Process and environmental stability:** Physical deployment limitations prevented the direct empirical calculation of defect reduction rates, but the simulation demonstrates that the adaptive system guarantees superior environmental stability within the cabin. However, it also isolated a critical hardware bottleneck: the existing plant completely lacks a chiller or thermal sink mechanism, rendering it physically impossible to suppress high-temperature, high-humidity ambient summer loads.
5. **Environmental defect correlation:** Historical data analysis confirmed a clear correlation between ambient environmental variability, specifically elevated dry-bulb temperatures, and prominent coating defects, including paint sags/runs, orange peel, thin paint, and surface pores/holes.
6. **Prioritization in brownfield retrofits:** The deployment of Failure Mode and Effects Analysis (FMEA) within this work proved to be an invaluable decision-support tool to objectively rank deployment actions and prioritize physical improvement pathways.

6.2 Implementation Roadblocks and Field Deployment Limitations

While the physical viability and safety integrity of the supervisor-level control strategy were assessed through simulation, full factory deployment was restricted by intense administrative, organizational, and data-driven constraints. These factors define the operational context of this research:

- **Cross-Departmental Approval Cycles:** Project validation required formal sign-offs across multiple departments through a sequential and manual paperwork process. Given the high volume of concurrent industrial projects at TCAP, this administrative loop (Figure 6.1) frequently extended lead times to over two months before procurement could even begin.

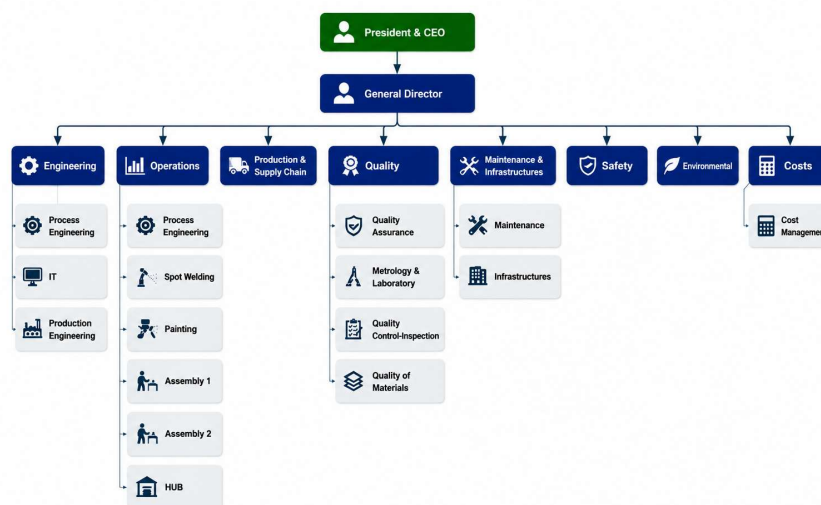


Figure 6.1: TCAP internal organization chart.

Full deployment depended on securing parallel authorizations from both local TCAP management and Toyota Motor Europe (TME) regional stakeholders and Figure 6.2).

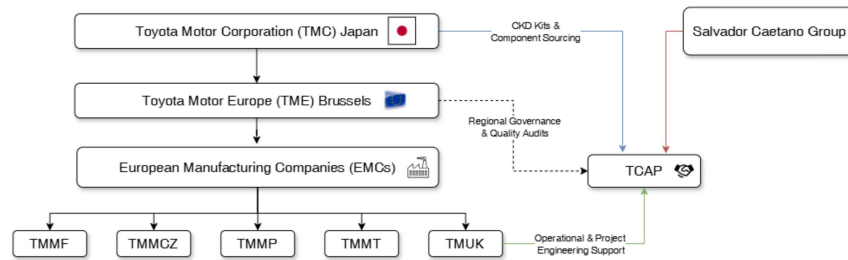


Figure 6.2: TCAP and TME international stakeholder organization chart.

- **Technical Liaison Delays:** Aligning the technical architecture and support protocols with TME added a 4-week window to the schedule. Nevertheless, this period proved essential to refine engineering specifications and guarantee compliance with corporate safety constraints before closing the procurement phase.
- **Pending Procurement and Operational Tracks:** The project currently stands at the pre-execution phase. Completing the on-site deployment remains subject to finalizing commercial quotations, structuring formal commissioning protocols, securing final budget approvals, concluding supplier negotiations, and scheduling installation windows exclusively during non-production hours.
- **Resource Conflict and Concurrent Projects:** The thesis timeline overlapped with major facility upgrades on the shop floor. Due to these competing priorities and shared resource constraints, it was impossible to safely carve out dedicated installation windows within the available time frame.
- **Data Fragmentation and Legacy Knowledge Loss:** Assessing the baseline was heavily challenged by fragmented, manual, and sometimes conflicting legacy records, which required extensive data-cleaning and historical archiving audits to reconstruct the technical specifications needed for modelling. Crucially, because the plant's HVAC infrastructure had been managed for years by a single specialist who recently retired, relying on unrecorded experiential knowledge created a significant diagnostic barrier.
- **Operational Communication and Instrumentation Gaps:** Coordination between departments was constrained by tight personnel availability and missing historical files, requiring considerable time for staff interviews and manual document retrieval. Furthermore, field testing was limited by a lack of calibrated, high-fidelity monitoring instruments available on the shop floor.

6.3 Retrospective: Methodological Modifications

If this research project were initiated anew, specific execution strategies would be altered to accelerate deployment:

- **Targeted Communication Chains:** Early identification of key stakeholders and specialized data owners would be prioritized to bypass fragmented legacy communication chains.
- **Accelerated Technical Support Requests:** While the initial Gemba walks were highly effective at establishing immediate diagnostic context, formal requests for TME specialized technical support would be executed significantly earlier to reduce technical alignment loops.
- **Organizational and Project Management Proactivity:** Deep structural mapping of internal company approval workflows and project validation protocols would be conducted in week one. Advanced project management tracking tools would be embedded immediately to optimize time management and data aggregation.

Ultimately, this project provided a comprehensive immersion into the complexities of an active automotive manufacturing environment. Bridging the gap between theoretical process control and the physical constraints of a legacy painting line proved to be an invaluable professional experience. By successfully navigating the technical, organizational and safety-critical demands of the Toyota Caetano Portugal facility, this research not only developed a robust retrofit strategy for environmental stability but also highlighted the critical necessity of proactive, cross-functional communication in industrial engineering.

6.4 Future Work

The baseline established in this dissertation provides a foundation for both short-term operational improvements and long-term digital transformation. As the project moves from virtual simulation into physical shop-floor execution, the continuation of this work could naturally adopt an Action Research approach. This will allow for iterative cycles of real-world implementation, continuous performance monitoring, and systematic reflection on the operational impacts. Within this framework, the following research and development paths are proposed to mature the painting process control:

- **Standardization and measurement systems analysis of shop-floor diagnostics:** Investigating methodologies to transition visual management frameworks into formalized, live diagnostic benchmarks. This path should include rigorous Measurement Systems Analysis (MSA), which could be conducted through external metrology audits or specialized internal protocols, to evaluate sensor reliability and repeatability, ensuring that the data driving future Go/No-Go protocols is statistically validated and free from instrumentation error.

- **Transition to structured malfunctioning reports and failure modelling:** Researching systematic data-capture architectures to eliminate maintenance log fragmentation. This involves investigating how mandatory, coded HMI/PLC fields mapped directly to FMEA failure modes can be processed via automated root-cause analysis algorithms rather than ad-hoc troubleshooting.
- **Digital twin convergence and predictive energy management:** Investigating model convergence, parameter identification, and real-time data assimilation techniques to elevate the Simscape physical model into a live digital twin. Research should focus on closed-loop, simulation-driven setpoint optimization algorithms for high-capacity burners during rapid external climate shifts.
- **Predictive quality and psychrometric-defect correlation algorithms:** Investigating advanced statistical regression or machine learning models to correlate high-frequency psychrometric process variables with downstream quality audit trails. The core research objective is to develop predictive algorithms capable of forecasting coating defects, such as orange peel or popping, prior to visual manifestation on the vehicle body.
- **Institutional asset knowledge and robust automation architectures:** Researching scalable deployment frameworks that decouple legacy factory operations from human dependency. Future academic and technical work must investigate resilient control architectures that guarantee permanent ATEX safety compliance and process stability regardless of shop-floor staff turnover.

In conclusion, this dissertation successfully establishes a balanced, data-driven methodology for modernizing legacy brownfield manufacturing assets. By linking systematic factory diagnostics with robust control logic and physical simulation validation, this work addresses immediate quality variations and critical ATEX safety hazards on the top-coat painting line. Ultimately, this research decouples shop-floor stability from human dependency and unrecorded practices, providing a scalable and reproducible automation framework for future industrial deployment within constrained production environments.

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Appendix A

Statistical Diagnostic Checks

This appendix presents the statistical diagnostic plots used to support the interpretation of the process-stability and exploratory defect analyses. The results are included as supporting evidence and should be interpreted together with the limitations discussed in the main text.

A.1 Normality Assessment

Normal probability plots and histograms were used to assess the distribution of the main environmental indicators.

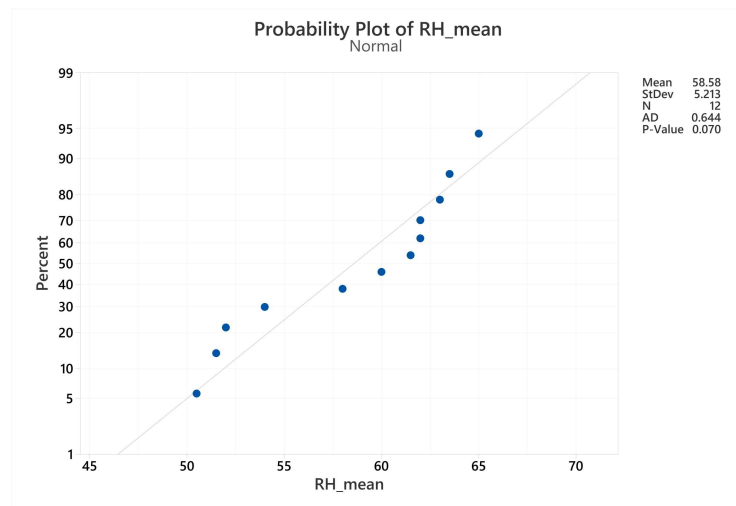


Figure A.1: Normal probability plot for RH_{mean} .

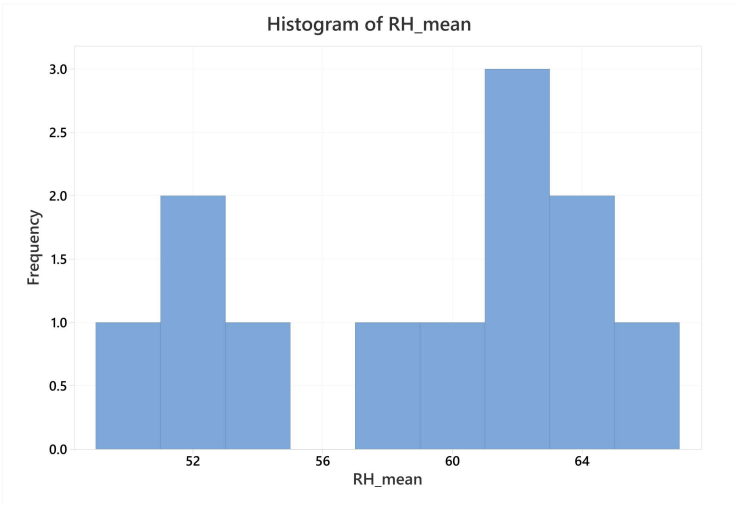


Figure A.2: Histogram of RH_{mean} .

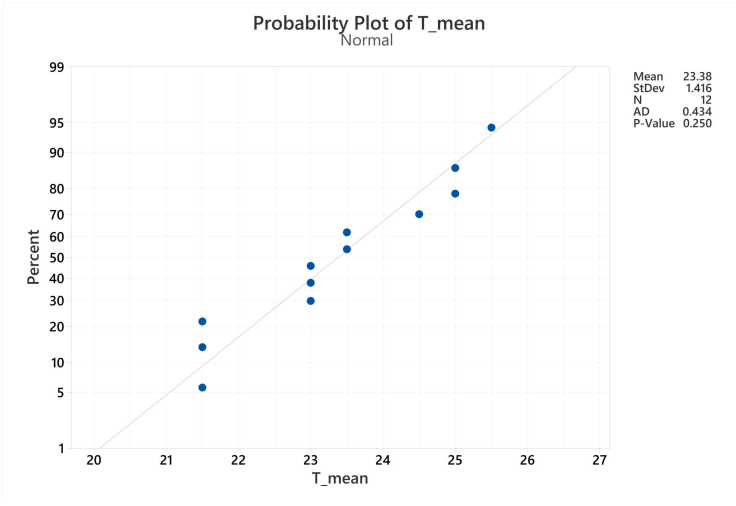
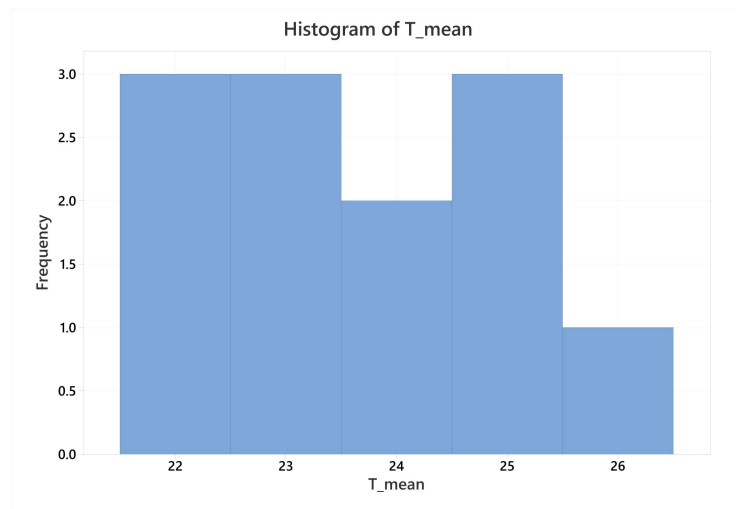
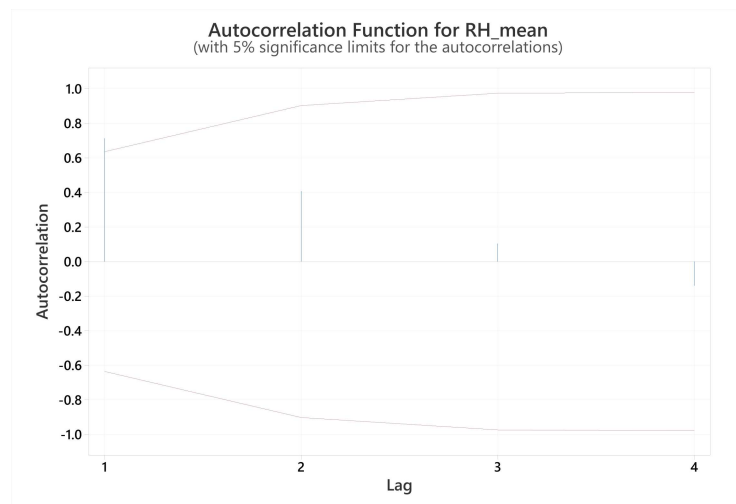


Figure A.3: Normal probability plot for T_{mean} .

Figure A.4: Histogram of T_{mean} .

A.2 Autocorrelation Assessment

Autocorrelation plots were used to evaluate time dependence between consecutive observations.

Figure A.5: Autocorrelation plot for RH_{mean} .

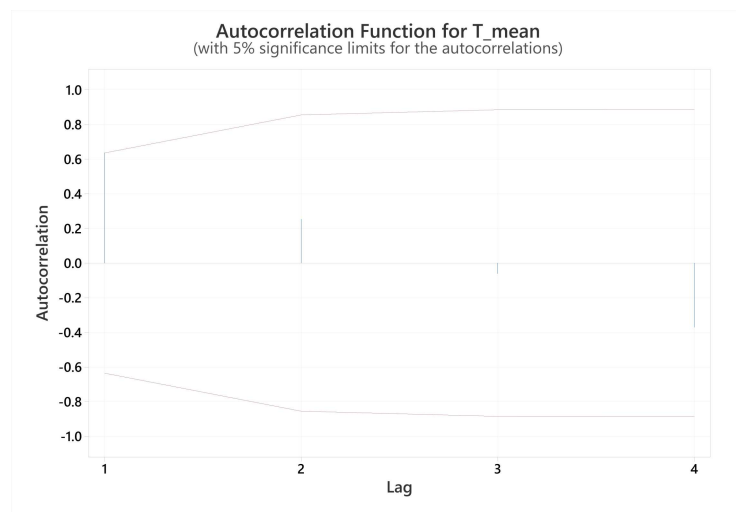


Figure A.6: Autocorrelation plot for T_{mean} .

Appendix B

Energy Consumption

Since the painting process can be over 60% of the energy costs in the automotive manufacturing process and the continuous EU compromise for green manufacturing processes, it is natural to observe and analyse this process through a costs and energy consumption lenses, as electricity, gas and water costs. It was not possible to get the data either of the water consumption or the electricity consumption, due to the facilities layout presently in the plant and the placement of electric boards. Analysing the 2025 data, compiled in the table B.1, we have an average consumption per unit of 10,40 Kg/unit.

Table B.1: Gas Consumption Data - 2025

2025	J	F	M	A	M	J	J	A	S	O	N	D	Total
Gas (Kg)	4436	5240	6544	2083	3269	353	7	20	710	1317	3407	3956	31342
Units	241	251	249	222	330	289	208	169	307	304	252	192	3014
Cons/Unit	18,41	20,88	26,28	9,38	9,91	1,22	0,03	0,12	2,31	4,33	13,52	20,60	10,40

Comparing this gas consumption with the average of gas consumption per unit observed in years before, as shown in table B.2 and table B.3, we can observe significant increase in the months of January, February and March in 2025.

Table B.2: Gas Consumption Data - 2023

2023	J	F	M	A	M	J	J	A	S	O	N	D	Total
Gas (kg)	2162	1765	4230	1544	897	456	348	245	40	623	2073	2187	16570
Units	145	107	313	134	197	235	173	101	81	50	182	147	1865
Cons/Unit	14.91	16.49	13.52	11.52	4.55	1.94	2.01	2.43	0.49	12.46	11.39	14.88	8.88

Table B.3: Gas Consumption Data - 2024

2024	J	F	M	A	M	J	J	A	S	O	N	D	Total
Gas (kg)	2872	2633	1078	437	1083	226	627	245	1706	2647	3127	1402	18083
Units	236	223	103	99	170	46	195	85	209	417	349	166	2298
Cons/Unit	12.17	11.81	10.47	4.41	6.37	4.91	3.22	2.88	8.16	6.35	8.96	8.45	7.87

This increase in gas consumption can be attributed to a significant volume of manufacturing process testing due to an alteration in the production process, during these months. Because of this abnormal consumption, for energy consumption analysis of the process, we will use the average of the 2023 and 2024: 8,38 kg/unit. As far as gas consumption, the painting process represents 78% of the gas costs (Figure B.1) associated with this plant, which represents an exceptional opportunity to improve costs and efficiency when associated with this project.

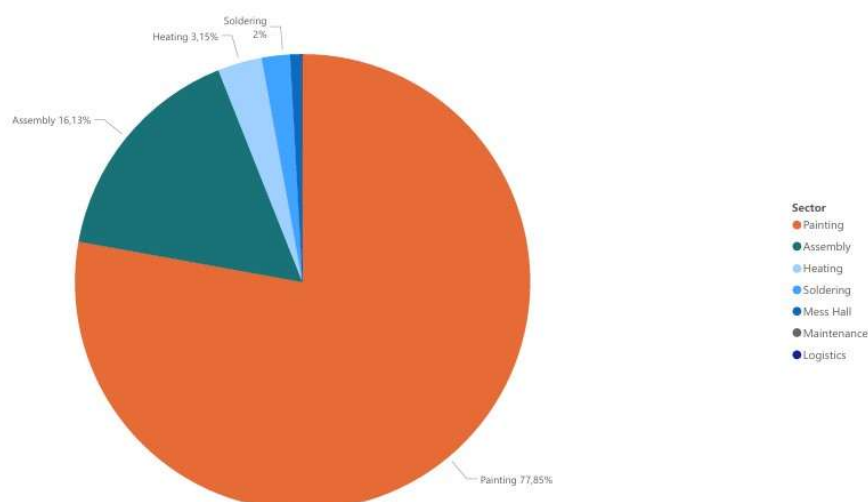


Figure B.1: Gas Consumption by sector

Being such an energy heavy sector in the manufacturing process, it was important to analyse the consumptions of gas to understand how and where the consumption could be improved. The gas consumption data on the painting sector, in the burners of the painting booth was used to calculate potential savings and used as a base line for sensitivity scenarios.

Sensor Protection

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Appendix D

Climatic Design Conditions - Ovar, Portugal

The following climatic design conditions for Ovar, Portugal (WMO: 085440), are derived from the 2025 ASHRAE Handbook of Fundamentals [90]. These values provide the boundary conditions for the environmental simulation and system retrofit design.

Table D.1: ASHRAE Climatic Design Conditions (2025 Fundamentals)

Category	Condition	Value	Unit
Site Information	Latitude	40.9158	N
	Longitude	8.6411	W
	Elevation	22	m
Heating (99.6%)	Dry Bulb (DB)	-0.4	°C
Cooling (0.4%)	Dry Bulb (DB)	29.4	°C
	Mean Coincident WB	19.3	°C
Dehumidification	0.4% Dew Point (DP)	19.6	°C
	HR at 0.4% DP	14.4	g/kg

Note: The 99.6% heating design condition indicates the temperature likely to be exceeded 99.6% of the time during the coldest month. The 0.4% cooling design condition represents the conditions likely to be exceeded only 0.4% of the time, providing a robust threshold for HVAC system sizing.

Appendix E

Diagnostic FMEA and Traceability

E.1 Technical Traceability

To support the Table 3.18, Table E.1 details the traceability of each failure mode. It clarifies the potential effect, the likely factors and the existing controls associated with each diagnostic finding.

Table E.1: Technical traceability of the diagnostic FMEA.

ID	Potential effect	Likely cause or contributing factor	Existing control
F01	Increased overspray, local turbulence and increased contamination risk.	Airflow distribution imbalance, damper position, duct/plenum condition and extraction balance.	Internal downdraft audit and visual process observation.
F02	Limited ability to rebalance air flow when conditions change.	Fixed/manual damper settings and absence of active airflow-control feedback.	Manual damper adjustment based on audit or maintenance intervention.
F03	Production may occur outside the required RH process window, increasing quality and electrostatic-safety risk.	Outdoor-air variation, heating demand, insufficient humidification response and limited automatic correction.	Manual AM/PM temperature and RH records.
F04	Relative humidity may drop during heating periods, reducing environmental stability during application.	Sensible heating increases air temperature without coordinated moisture addition.	Local burner control and manual RH observation.
F05	Final booth air condition may vary because temperature and humidity are not controlled as one coupled process.	Independent burner and humidifier operation with no integrated temperature-humidity control logic.	Separate local controls for heating and humidification.
F06	Environmental corrections may be delayed, excessive or inconsistent between operators or shifts.	Limited continuous feedback and dependence on operator perception or experience.	Manual set-point adjustment and informal operator reaction.
F07	Reduced ASU reliability and possible long-term safety or maintenance.	Condensation, acidic corrosion and ageing exhaust-flue components.	Visual inspection and corrective maintenance during intervention periods.
F08	Poor RH response, water accumulation or uneven humidification.	Nozzle fouling, poor atomisation, leakage, low delivery pressure or incomplete evaporation.	Visual inspection and corrective maintenance after visible symptoms.
F09	Higher probability of contamination, leakage, thermal losses and unstable equipment behaviour.	Ageing booth structure, ASU degradation, corrosion and limited condition monitoring.	Annual shutdown activities and corrective maintenance.
F10	Nozzle fouling, scaling, deposits and unstable humidifier performance.	Industrial water use, high conductivity, high pH and lack of routine water-quality control.	Occasional water checks and visual observation.
F11	Progressive water-system degradation may remain undetected, with fouling or hygiene risk.	Limited purge, refill and hygiene-monitoring routine.	Visual observation of water condition.
F12	Production may continue under non-standard environmental conditions without consistent escalation.	No automatic alarm, Go/No-Go rule, interlock or formal stop/release decision logic.	Manual recording without automatic reaction logic.
F13	Short-duration environmental disturbances may be missed between measurements.	Low sampling frequency and absence of continuous data acquisition.	Bi-daily manual measurements.
F14	Historical environmental records may have reduced reliability and weak comparability.	Non-standardised measurement location, time, equipment condition and calibration status.	Informal measurement routine and manual recording.
F15	Defects may be missed or inconsistently classified before downstream stages.	Insufficient lighting at the in-production inspection position.	Manual visual inspection by operators or quality personnel.
F16	Pressure imbalance may remain undetected, reducing confidence in airflow direction and control.	Absence of differential pressure instrumentation and no continuous booth-pressure trend.	Qualitative adhesive-tape observation.

E.2 Rating Justification

Table E.2 summarises the rationale used to assign the Severity, Occurrence and Detection values. This supports the defensibility of the diagnostic FMEA and avoids interpreting the ratings as arbitrary numerical values.

Table E.2: Justification of diagnostic FMEA ratings.

ID	Severity rationale	Occurrence rationale	Detection rationale
F01	S=6: moderate process robustness and contamination impact.	O=6: confirmed by audit, but not continuously quantified.	D=6: detectable by audit, not by continuous monitoring.
F02	S=6: limited airflow-control robustness.	O=6: fixed damper condition is restrictive. .	D=7: no automatic airflow-balance feedback, detected by external audit.
F03	S=8: RH outside specification affects quality and electrostatic safety.	O=8: repeated RH non-compliance observed in records.	D=7: manual detection without automatic reaction.
F04	S=7: heating-induced RH drop affects environmental stability.	O=7: expected whenever heating demand is relevant, as seen in statistical process control analysis.	D=7: interaction is not directly monitored or controlled.
F05	S=7: decoupled control affects final supply-air condition.	O=7: inherent limitation of current architecture.	D=7: no integrated T–RH control feedback, inferred by technical judgement on ambient variables control charts.
F06	S=7: subjective correction can create inconsistent control.	O=7: manual intervention observed as operating practice.	D=8: detected by Gemba Walk and interviews.
F07	S=6: reliability and long-term safe-operation concern.	O=5: degradation is condition-dependent and progressive.	D=6: visible by inspection, but not continuously monitored.
F08	S=7: poor atomisation directly affects RH-control capability.	O=6: leakage/fouling/poor atomisation observed as recurrent concerns.	D=6: visible symptoms can be detected, by inspection, but performance loss is not monitored in real time.
F09	S=6: degradation affects reliability, contamination and thermal robustness.	O=6: ageing is present in several parts of the legacy installation.	D=7: mostly detected by inspection or failure, recurrent maintenance reports, not by condition monitoring.
F10	S=6: water quality affects fouling and humidifier stability.	O=5: condition-dependent and linked to water renewal/maintenance.	D=8: no continuous conductivity, pH or water-quality monitoring.
F11	S=6: water-system degradation may affect reliability and hygiene.	O=5: progressive and condition-dependent.	D=8: no routine automated monitoring or alarm, detected by maintenance reports and Gemba Walk.
F12	S=8: production may continue under non-standard environmental conditions.	O=6: out-of-spec events occur but are not continuous all year, as seen through production relative humidity manual logs (Gemba Walk).	D=8: no automatic Go/No-Go alarm, interlock or escalation rule.
F13	S=6: missed short-term deviations affect diagnostic and reaction capability.	O=8: discrete manual measurement is the normal operating method, checked by Gemba Walk and Genshi Gembutsu.	D=8: intra-shift drift cannot be detected between manual checks.
F14	S=6: non-standard measurement reduces data reliability.	O=8: informal measurement routine is recurrent.	D=8: no automatic validation of method, timing, location or calibration.
F15	S=5: lighting affects defect detection but is not a primary environmental-control failure.	O=5: issue identified by feedback, not quantified as continuous.	D=6: limitation is observable in Gemba, but missed defects may not be detected.
F16	S=7: pressure imbalance can affect airflow direction, containment and contamination control.	O=6: pressure condition may vary with airflow and extraction balance, observed by Gemba Walk and external audit.	D=8: adhesive tape is qualitative and does not quantify or trend pressure differential.

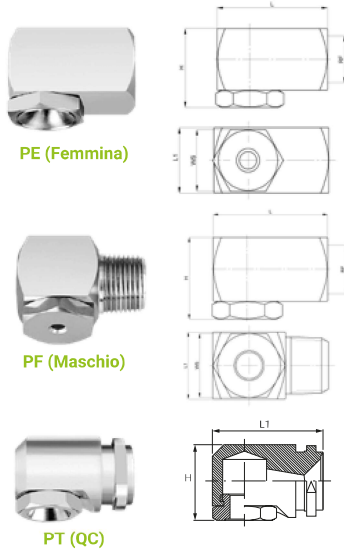
Appendix F

Nozzles Data Catalogue

For the preliminary sizing of the nozzle tree structure, the following values in the Figure F.1 were used from [78]. The actual choosing and requirements of implementation required commissioning and installing on Toyota Caetano plant which was not possible in the timeline of this dissertation.

HOLLOW CONE NOZZLES

PE / PF / PT (HOLLOW CONE NOZZLES)



STANDARD ANGLE SPRAY NOZZLES

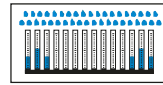
PE/PF hollow cone nozzles generate a ring-shaped spray pattern with finely atomized droplets and work on the tangential flow principle. Inside these nozzles there is an axial groove that injects the liquid tangentially into the vortex chamber where the strong centrifugal force produces a high rotational velocity and generates a finely atomized liquid flow. As these nozzles have a large inside free passage and no swirl insert, they offer the maximum resistance to clogging. PE/PF nozzles are widely used in many production processes and their variety of spray angles and capacities make them suitable for all kinds of working environments.

THREAD SPECIFICATION

PE: Female (BSP, NPT)

PF: Male (BSPT, NPT)

PT: Quick connection



STANDARD ANGLE SPRAY NOZZLES

	PEx	PFx	PTx	CODE	RF RG	Capacity (lpm) at different pressure values(bar)								H	L	L1	WS
						inch	0,5	0,7	1,0	2,0	3,0	5,0	7,0				
50° (xxN)	*	*	*	2180	3/8"	7,35	8,69	10,4	14,7	18,0	23,2	27,5	32,9	24,5	35,0	20,0	19,0
	*	*	*	2220		8,98	10,6	12,7	18,0	22,0	28,4	33,6	40,2				
	*	*	*	2390		15,9	18,8	22,5	31,8	39,0	50,3	59,6	71,2				
70° (xxS)	*	*	*	0390	1/8"	0,16	0,19	0,23	0,32	0,39	0,50	0,60	0,71	18,5	28,0	15,0	13,0
	*	*	*	0780		0,32	0,38	0,45	0,64	0,78	1,01	1,19	1,42				
	*	*	*	1160		0,65	0,77	0,92	1,31	1,60	2,07	2,44	2,92				
	*	*	*	1230		0,94	1,11	1,33	1,88	2,30	2,97	3,51	4,20				
	*	*	*	1390		1,59	1,88	2,25	3,18	3,90	5,03	5,96	7,12				
	*	*	*	1630		2,57	3,04	3,64	5,14	6,30	8,13	9,62	11,5				
	*	*	*	1780	3,18	3,77	4,50	6,37	7,80	10,1	11,9	14,2	23,0	32,0	18,0	17,0	
	*	*	*	0781	0,32	0,38	0,45	0,64	0,78	1,01	1,19	1,42					
	*	*	*	1161	0,65	0,77	0,92	1,31	1,60	2,07	2,44	2,92					
	*	*	*	1231	0,94	1,11	1,33	1,88	2,30	2,97	3,51	4,20					
	*	*	*	1391	1,59	1,88	2,25	3,18	3,90	5,03	5,96	7,12					
	*	*	*	1631	2,57	3,04	3,64	5,14	6,30	8,13	9,62	11,5					
	*	*	*	1781	3,18	3,77	4,50	6,37	7,80	10,1	11,9	14,2	24,5	35,0	20,0	19,0	
	*	*	*	2117	4,78	5,65	6,75	9,55	11,7	15,1	17,9	21,4					
	*	*	*	1392	1,59	1,88	2,25	3,18	3,90	5,03	5,96	7,12					
	*	*	*	1632	2,57	3,04	3,64	5,14	6,30	8,13	9,62	11,5					
	*	*	*	1782	3,18	3,77	4,50	6,37	7,80	10,1	11,9	14,2					
	*	*	*	2118	4,78	5,65	6,75	9,55	11,7	15,1	17,9	21,4					
	*	*	*	2157	6,41	7,58	9,06	12,8	15,7	20,3	24,0	28,7	31,0	50,0	25,0	24,0	
	*	*	*	2196	8,00	9,47	11,3	16,0	19,6	25,3	29,9	35,8					
	*	*	*	2230	9,39	11,10	13,3	18,8	23,0	29,7	35,1	42,0					
	*	*	*	2390	15,90	18,8	22,5	31,8	39,0	50,3	59,6	71,2					
	*	*	*	2197	8,00	9,47	11,3	16,0	19,6	25,3	29,9	35,8					
	*	*	*	2231	9,39	11,1	13,3	18,8	23,0	29,7	35,1	42,0					
	*	*	*	2310	1/2"	12,7	15,0	17,9	25,3	31,0	40,0	47,4	56,6	39,0	58,0	32,0	32,0
	*	*	*	2391		15,9	18,8	22,5	31,8	39,0	50,3	59,6	71,2				
	*	*	*	2470		19,2	22,7	27,1	38,4	47,0	60,7	71,8	85,8				
*	*	*	2311	3/4"	12,7	15,0	17,9	25,3	31,0	40,0	47,4	56,6	39,0	58,0	32,0	32,0	
*	*	*	2392		15,9	18,8	22,5	31,8	39,0	50,3	59,6	71,2					
*	*	*	2471		19,2	22,7	27,1	38,4	47,0	60,7	71,8	85,8					
*	*	*	2550		22,5	26,6	31,8	44,9	55,0	71,0	84,0	100					
*	*	*	2630		25,7	30,4	36,4	51,4	63,0	81,3	96,2	115					
*	*	*	2700		28,6	33,8	40,4	57,2	70,0	90,4	107	128					
*	*	*	2780		31,8	37,7	45,0	63,7	78,0	101	119	142					
*	*	*	2860		35,1	41,5	49,7	70,2	86,0	111	131	157					
*	*	*	2940	38,4	45,4	54,3	76,8	94,0	121	144	172						

Figure F.1: Nozzle values for preliminary sizing

Appendix G

Simulation Assessment of Control Logic

This chapter provides the comprehensive mathematical constants, hardware parameters, boundary conditions, and raw data profiles utilized to construct and execute the Matlab/Simscape models.

Appendix H

Project Management and Coordination

This appendix provides a summary of the project management tools and methodologies employed to coordinate the retrofit strategy across departments. These visual documents the scheduling, task dependency management, and communication workflows established between maintenance, quality, automation and facilities teams (Figures H.1,H.2, H.3 and H.6).

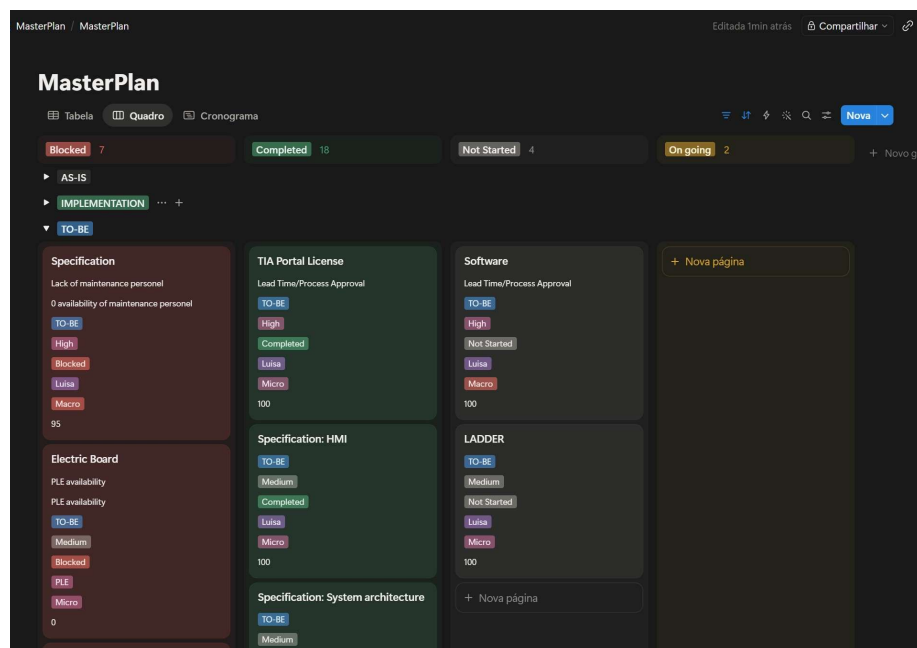


Figure H.1: Implementation Kanban cards exported from project management software 1.

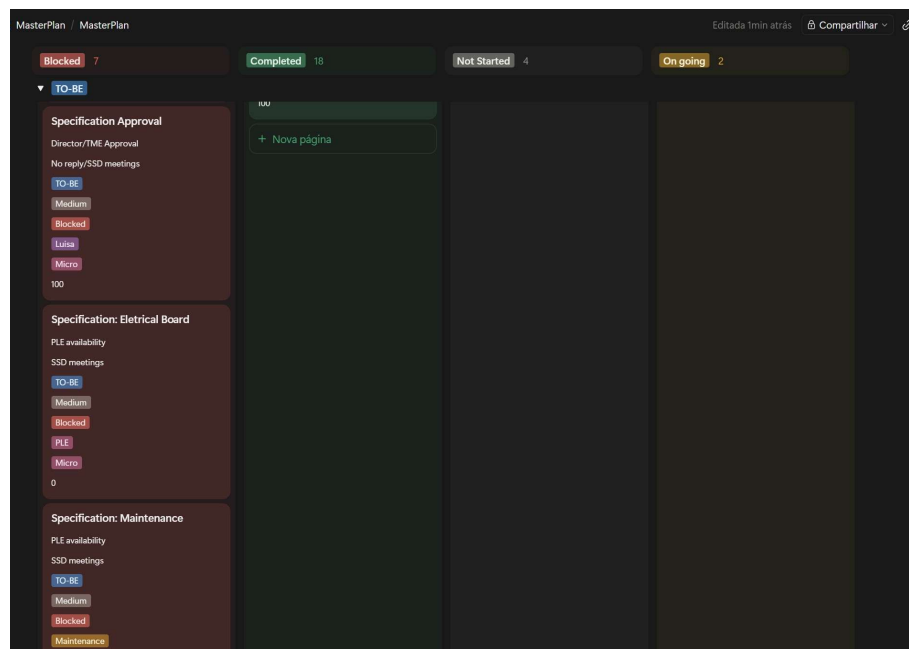


Figure H.2: Implementation Kanban cards exported from project management software 2.

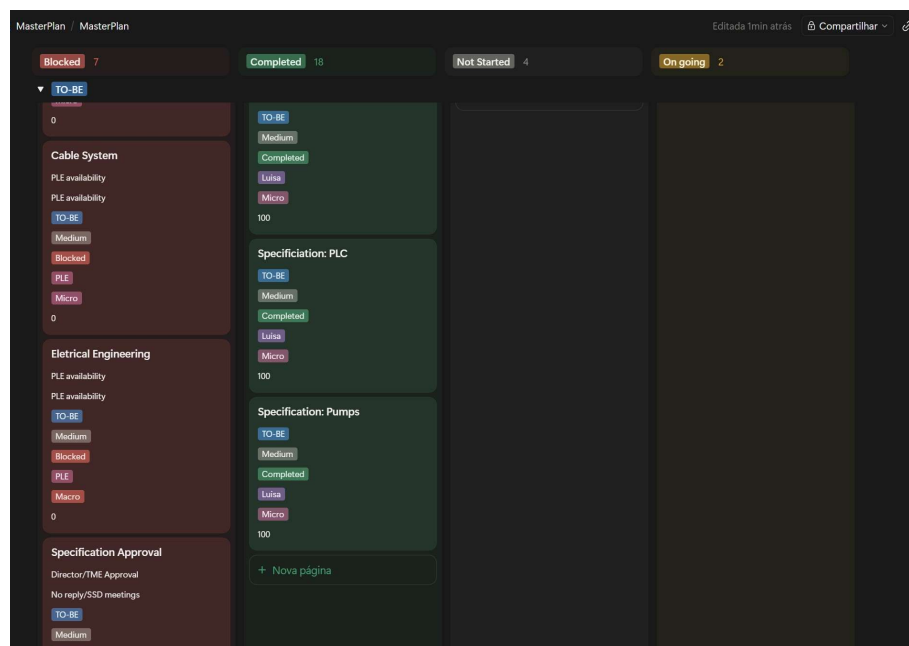


Figure H.3: Implementation Kanban cards exported from project management software 3.

Note: The tools utilized included Notion for documentation and integrated project management modules to ensure synchronization of project milestones and department action items.

The Gantt chart was a tool used to ensure the timing plan and to be able to track the tasks, as it can be observed in Figures H.4 and H.5.

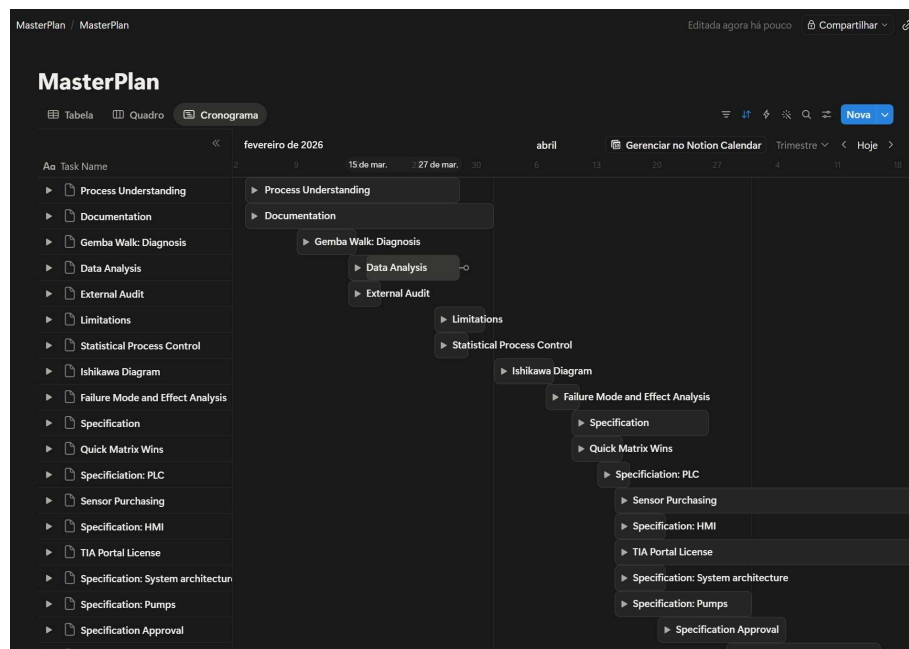


Figure H.4: Implementation Gantt charts exported from project management software 1.

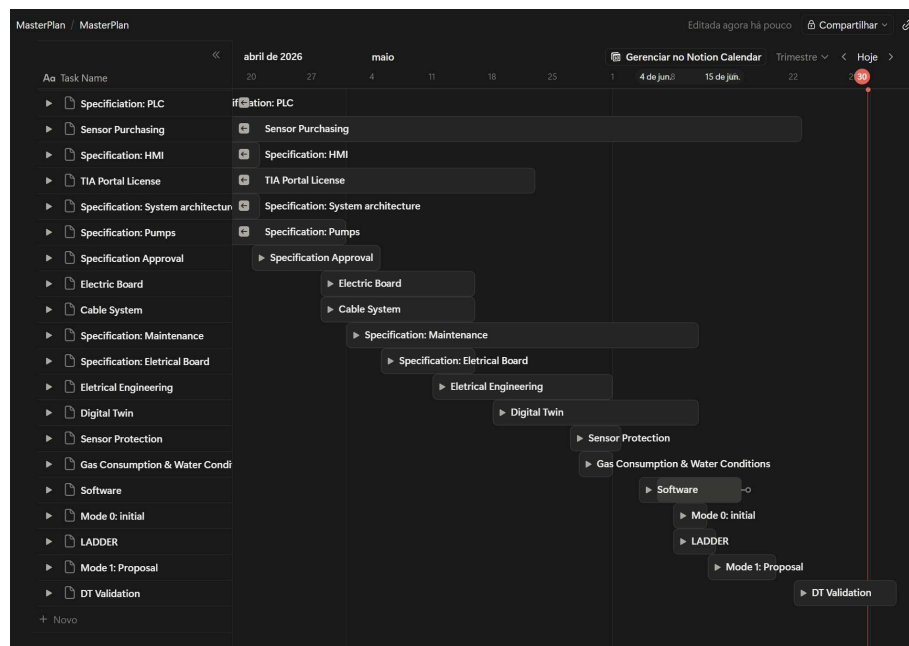


Figure H.5: Implementation Gantt charts exported from project management software 2.

05/07/2026 **Project: Automatic Humidity Control** **Q & A Sheet / To Do List**

Category	Date	Description	Comments	By	Resp.	Co.	Target	Status
Soft.	19/03/2026	Siemens Licensing (auto PLC)	Floating/1-pc license?	LM	ENG	TCAP	24-Mar	CLOSED
Dim.	19/03/2026	Painting booth interior meas.	Measured	LM	LM	TCAP	24-Mar	CLOSED
Gemba	19/03/2026	Intake Visit	-	-	-	TCAP	19-Mar	CLOSED
Tech.	19/03/2026	EMC solutions	Showers TMCZ, TMTT	LM	LM	TME	24-Mar	CLOSED
Tech.	25/03/2026	Sensor Placement	-	-	-	TME	01-Apr	CLOSED
THESIS	20/03/2026	Analysis: cost, env, safety	-	-	-	TCAP	05-Jun	CLOSED
OPER.	20/03/2026	Operator questionnaire	-	LM	LM	TCAP	29-Mar	CLOSED
AS-IS	25/03/2026	Pump analysis	No variable pressure	-	-	TCAP	30-Mar	CLOSED
AS-IS	26/03/2026	Burner behavior	vs temperature	LM	LM	TME	31-Mar	CLOSED
Tech.	26/03/2026	EMC solutions: cooler?	-	LM	LM	TME	31-Mar	CLOSED
Tech.	27/03/2026	Controller type/Manual paint?	Human variations	LM	LM	TCAP	31-Mar	CLOSED
AS-IS	30/03/2026	Sensor location	-	LM	-	TME	01-Apr	CLOSED
AS-IS	30/03/2026	Plenum vs Cabin variation	-	-	-	TME	05-Jun	OPEN
AS-IS	30/03/2026	Bag filter function	Water collection?	-	-	-	29-Mar	CLOSED
HVAC	02/05/2026	Burner functioning	Fixed setpoint or modulating?	LM	LM	TME	15-May	CLOSED
HVAC	04/05/2026	Pressure gauge calibration	Accuracy check for airflow	LM	Maint.	TCAP	20-May	OPEN
PROCESS	04/05/2026	Pump flow/head check	Cavitation risk at high load?	LM	Maint.	TCAP	20-May	CLOSED
MAINT.	05/05/2026	Cleaning Tank protocol	-	LM	Maint.	TCAP	15-May	CLOSED
SAFETY	06/05/2026	PPE update (Chemicals)	Review gloves/mask specs	LM	Safety	TCAP	25-May	CLOSED
TO-BE	05/05/2026	Subcontractor electric board	-	LM	CA	TCAP	10-May	OPEN
TO-BE	05/05/2026	Cleaning Tank + Intake	5 days estimate	LM	Maint.	TCAP	15-May	CLOSED
TO-BE	05/05/2026	Skimmer requirement	Renting?	LM	LM	TCAP	10-May	CLOSED
TO-BE	05/05/2026	Specification Approval	-	LM	AG	TCAP	10-May	CLOSED
MAINT.	07/05/2026	Log: Burner heat exchange	Clean efficiency cycle	LM	Maint.	TCAP	25-May	CLOSED

Figure H.6: Open issues list.

This author had no previous experience with this software and had training in project management tools, through Toyota On-Boarding training and online resources of Notion.

H.1 Psychrometric and Thermodynamic Constants

Table H.1 outlines the fixed thermodynamic properties utilized across the fluid domain models for mass and energy balance calculations.

Table H.1: Thermodynamic and physical constants at standard atmospheric pressure.

Constant Description	Symbol	Value	Unit
Standard Atmospheric Pressure	P_{atm}	101325	Pa
Specific Heat Capacity of Dry Air	$c_{p,\text{da}}$	1005	J/(kg · K)
Specific Heat Capacity of Water Vapor	$c_{p,\text{v}}$	1860	J/(kg · K)
Specific Heat Capacity of Liquid Water	$c_{p,\text{w}}$	4184	J/(kg · K)
Latent Heat of Vaporization (at 0°C)	$h_{\text{fg}0}$	2.501×10^6	J/kg
Universal Gas Constant for Air	R_{da}	287.05	J/(kg · K)
Universal Gas Constant for Water Vapor	R_{v}	461.5	J/(kg · K)

H.2 Seasonal Simulation Boundary Profiles

The model validation sequences executed in Chapter 5 utilized the discrete environmental input matrices outlined in Table H.2.

Table H.2: Boundary condition input sets for summer and winter stress tests.

Scenario Matrix	Parameter	Minimum	Peak Target	Mean Value	Variance Profile
Extreme Winter Set (Moisture Deficit Focus)	T_{out}	−2.0°C	7.0°C	3.5°C	Sinusoidal Diurnal Cycle
	RH_{out}	40%	65%	52.5%	Inverse Thermal Tracking
	x_{out}	0.0016	0.0040	0.0028	Calculated Conservative Input
Extreme Summer Set (Thermal Overload Focus)	T_{out}	26.0°C	38.0°C	32.0°C	Peak Summer Load Matrix
	RH_{out}	25%	45%	35.0%	Extreme sensible load phase
	x_{out}	0.0065	0.0125	0.0095	Hot-dry operational envelope

H.3 Coding program for Model 2

In Figure H.7, we can see the hard coding of the layers of master and slave, to comply with ATEX regulations, while allowing for a flexible set point.

```

function [m_evap1_cmd, m_evap2_cmd, x_set1_limited, x_set2_limited, u_pump1, u_pump2] = TOBE_Cascade_Humidifier_Controller( ...
    RH_duct1, RH_duct2, T_duct1, T_duct2, x_actua11, x_actua12, reset)
%#codegen

% --- FIXED DISCRETE TIMESTEP ---
Ts = 1.0;

% --- MASTER LOOP PARAMETERS (Outer RH Loop) ---
Kp_master = 0.018;
Ti_master = 45.0;
Ki_master = Kp_master / Ti_master;

% --- SLAVE LOOP PARAMETERS (Inner Absolute Humidity Loop) ---
Kp_slave = 2500.0;
Ti_slave = 30.0;
Ki_slave = Kp_slave / Ti_slave;

% --- ACTUATOR CONFIGURATION ---
m_evap_max = 0.3; % Max pump mass flow (kg/s)

% --- PERSISTENT INTEGRATORS ---
persistent I_master1 I_master2 I_slave1 I_slave2
if isempty(I_master1), I_master1 = 0.0; end
if isempty(I_master2), I_master2 = 0.0; end
if isempty(I_slave1), I_slave1 = 0.0; end
if isempty(I_slave2), I_slave2 = 0.0; end

if reset >= 0.5
    I_master1 = 0.0; I_master2 = 0.0;
    I_slave1 = 0.0; I_slave2 = 0.0;
end

% =====
% PIPELINE 1 EXECUTION (ASU1)
% =====
% Dynamic target floating logic for Pipeline 1 based on localized thermal state
if T_duct1 < 20.0
    RH_target1 = 0.60;
elseif T_duct1 > 22.0
    RH_target1 = 0.80;
else
    % Linear interpolation across the 20-22°C boundary to scale RH target between 60% and 80%
    RH_target1 = 0.60 + 0.20 * (T_duct1 - 20.0) / (22.0 - 20.0);
end

e_RH1 = RH_target1 - RH_duct1;
u_master1_unsat = (Kp_master * e_RH1) + I_master1;

P_sat1 = 610.78 * exp((17.27 * T_duct1) / (T_duct1 + 237.3));
P_v_floor1 = 0.55 * P_sat1;
x_floor1 = 0.622 * P_v_floor1 / (101325.0 - P_v_floor1);

x_limit_min1 = x_floor1;
x_limit_max1 = 0.0350;
x_set1_limited = min(max(u_master1_unsat, x_limit_min1), x_limit_max1);

if (u_master1_unsat > x_limit_min1 && u_master1_unsat < x_limit_max1) || ...
    (u_master1_unsat <= x_limit_min1 && e_RH1 > 0) || ...
    (u_master1_unsat >= x_limit_max1 && e_RH1 < 0)
    I_master1 = I_master1 + Ki_master * e_RH1 * Ts;
end

```

Figure H.7: Coding program for model 2

Appendix I

Toyota Technical Specification

The official industrial specification framework, standard requirements and brownfield design boundaries mandated by Toyota for the automatic humidity control system are attached below, to follow with external suppliers in the implementation phase.

TOYOTA

Paint Shop Equipment Upgrade

Technical Specifications

Section 2.0

AUTOMATIC HUMIDITY CONTROL

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1 DOCUMENT ISSUE

Revision Number	Name	Date of Modification	Ver.	Comments
0	Luísa Mendes	12/05/2026	00	
1	Luisa Mendes	30/06/2026	01	
2				
3				
4				
5				

Originator	Coordinator	Manager			TME Manager
Luísa Mendes	Rui Mané	António Gomes			Martin Bell

2 Introduction

This tender document is for a Design & Build contract (TCAP-Ovar Plant) for the automatic humidity control for the painting booth at TCAP Paint Shop.

The factory is in Ovar, Portugal.

Address:

Toyota Caetano Portugal – Fabrica de Ovar
Rua Olho Marinho, 1427
3885-113 Arada, Ovar

3 Scope of Works

Detailed scope of work will be explained in the scope of work matrix below.

Toyota will supply all primary services (within 5m of usage point).

Where the location of the services is not convenient to the contractor, they must identify during the tender process. Unless otherwise agreed, the relocation of services or obstacles after the award of the contract is the responsibility of the contractor.

PROJECT SCOPE OF SUPPLY MATRIX TCAP					
Humidity Control Paint Booth					
					● = Lead ○ = Support Date 13/05/2026
	Supply Item - Humidity Control Paint Booth	Contractor	Other	TCAP	Comment
1.0	Site Preparation & Building Infrastructure				
1.1	Construction safety & site management	●			
1.4	Utilities Supply				
1.5	Power (including Tape-off box)	●			TCAP will provide primary utility only
1.6	Compressed Air	●			TCAP will provide primary utility only
1.7	Electrical Maintenance Boards for construction	●			
1.8	DI Water			○	TCAP will provide primary utility only
Global Humidity Control Paint Booth					
2.0	Humidity Control Paint Booth				
2.1	Basic Layout			●	
2.2	Detailed Design	●			
2.3	ESHSR Documentation, Design Risk & CE	●			
2.4	Fabrication, Delivery, Off Loading, Storage	●			
2.5	Installation, Testing, Commissioning	●			
2.7	Cleaning acceptance / Crater tests	○	○	●	
2.9	All pumps, sensors, gauges and other components	●			
2.13	Spares	●			To be quoted as option to TCAP
3.0	Technical				
3.1	Training (operation and maintenance)	●	○		TCAP
3.2	Commissioning	●		○	
3.4	As Built Drawings	●			
3.5	CE Marking of all equipment	●			
3.6	Technical file as required in EU	●			
3.7	All calculation notes (detailed)	●			
3.8	Material certificates (for stainless steel and other)	●			
3.9	Degreased and silicon free certificates for pipes/components	●			
3.10	Pressure and leak tests (incl. reports)	●			
3.11	Production Trial Support	●		○	
3.12	12 month warranty starting at M4 kanban sign-off	●			
4.0	Ancillary Equipment				
4.1	Piping and Required Identification	●			Appendix 4
4.2	Primary Power Supply			●	Only primary (busbar) supplied by TCAP
4.3	Secondary Power Supply & Utilities	●			
4.4	Nitrogen supply station (hardener inerting)	●			Bottle connection and valve arrangement
4.5	Hoist and handling devices (incl. calculation notes)				Notified body
4.6	Lead test for hoist				
4.7	Pail storage racks and structures		●		
4.8	Tote storage racks and structures		●		
4.9	DIW buffer tank system	●			
4.12	Dry air piping to booth (robots and take off points)	●			
5.0	Electrical Works				
5.1	Electrical Works	●			
5.2	Control Panels	●			
5.3	Cable runs / trunking	●			
5.4	Earthing and equipotential bonding	●			
5.5	Earthing and equipotential bonding check		●		Notified body
5.6	PLC Software /Modifications/Interlocks	●			
5.7	Local Network	●			
5.8	Site Network			●	
5.9	UPS				Not Required
5.10	Electrical Drawing	●			
6.0	Other Works				
7.0	Construction Safety & Site Management				
7.1	H&S Manual	○		●	
7.2	Method Statement & Risks Analysis	●		○	
7.3	Detail Daily Work Plans	●			
7.4	Project Control Board	●		○	
7.5	Site Work Permits			●	
7.6	Contractor Inductions	○		●	
7.7	Transportation	●			
7.8	Lifting and access Equipment	●			
7.9	Cleanliness/Tidyness of worksite (4S)	●			
7.10	Waste sorting	●		○	
7.11	Disposal of Waste	○		●	

4 Equipment & Process Description

The scope of this tender includes for the design, manufacturing, installation and commissioning of updating the humidifier system and installing an automatic humidity control.

The contractor must design the equipment and select to achieve the quality of the existing production and parameters mentioned in this specification.

The system must be installed within the existing structure and air supply. The installing phase is to be completed during a limited time after production hours.

5 Deliverables

The requirements of the following conditions must be met:

- The most economical running cost solution available
- Minimum Impact to production during installation (or agreed timing to minimize the impact)
- Design and built to applicable EU Directives and Standards/Norms
- Reliability of operation and ease of Maintenance (Include TCAP members training)
- Equipment OPA (Overall Process Availability) Rate of greater than 99% over 1 month from SOP
- Attendance of detailed design meetings with other suppliers in TCAP (internal or external)

6 Bid return

Within the bid submission the contractor must provide schematic drawings to illustrate the contents of their offer. The proposals must be identified clearly and explained technically.

7 Technical Description

7.1 Process Requirements

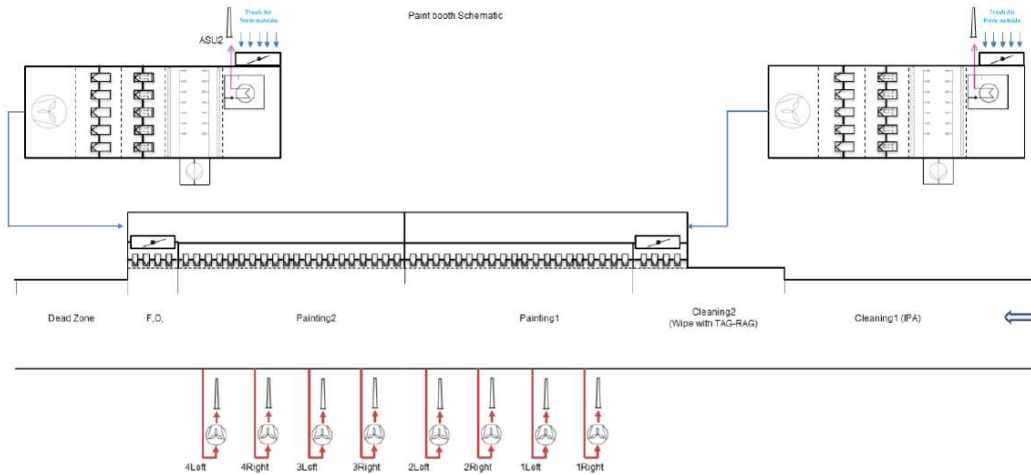
The new equipment should be able to be integrated within the existent infrastructure and control systems. It is mandatory to be able to be compliant with the standard parameters of production.

7.2 Concerns

- Legacy deficit: Current system has no active humidity control; manual ON/OFF operation only. Old age equipment: generalized corrosion.
- Quality risk: Lack of stabilization leads to non-compliance with standard parameters (18–28°C / 55–80% RH), causing application inconsistencies.
- Safety: Absence of active modelling for moisture levels in potentially hazardous atmospheres.

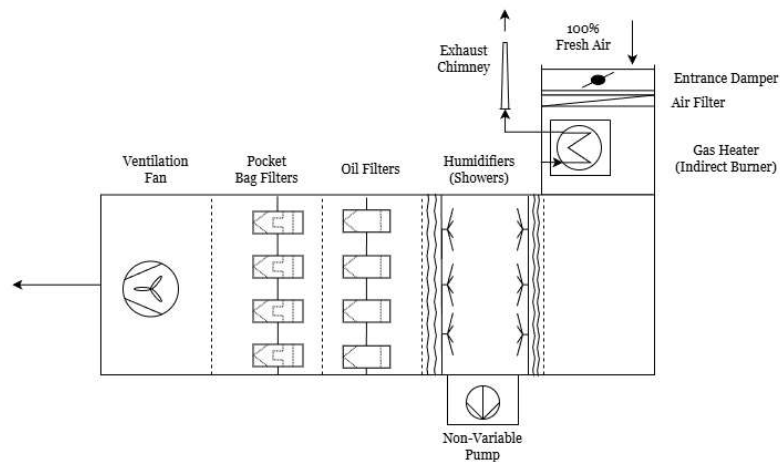
8 Description of Current Process

The painting booth is supplied with air from two Air Supply Units (ASU1 and ASU2), using 100% fresh air as it can be seen below.



8.1 Air Supply Unit (ASU)

The air supply system treatment is installed indoors and has a burner, a humidifier system (air washers) with a fixed velocity pump, filters and a ventilation fan that supplies the intake air into the painting booth, as can be seen in the schematic below.



Regarding the temperature and humidity control, now, only temperature is controlled through a GEFRA 1600V and a Pt100 (placed in the plenum) that is connected to the modulating control of the burner. It is possible for the painters to regulate the setpoint on the controller.

The humidifier system is manual ON/OFF, presenting severe deficiencies (30% of nozzles not working), low water level in both pumps and a leak in ASU2 to before the humidifier.

The current humidifier system is working with a low-pressure air washer. The nozzles used in this system are tangent right angle nozzles. The present system required a thorough cleaning, both nozzles and the water collection sump on both ASU.

There is a buoy sensor (orange) that supplies water to the collection sump for recirculation, there is also an overflow valve for security reasons.



8.2 Location

The painting booth and the ASU system is installed indoors and inside the painting booth sector.



9 Design Parameters

To ensure good functioning of the HVAC system, located in Portugal, here are the design constraints according to ASHRAE. In the table below, it is possible to see the boundary conditions and the target process envelop and target point.

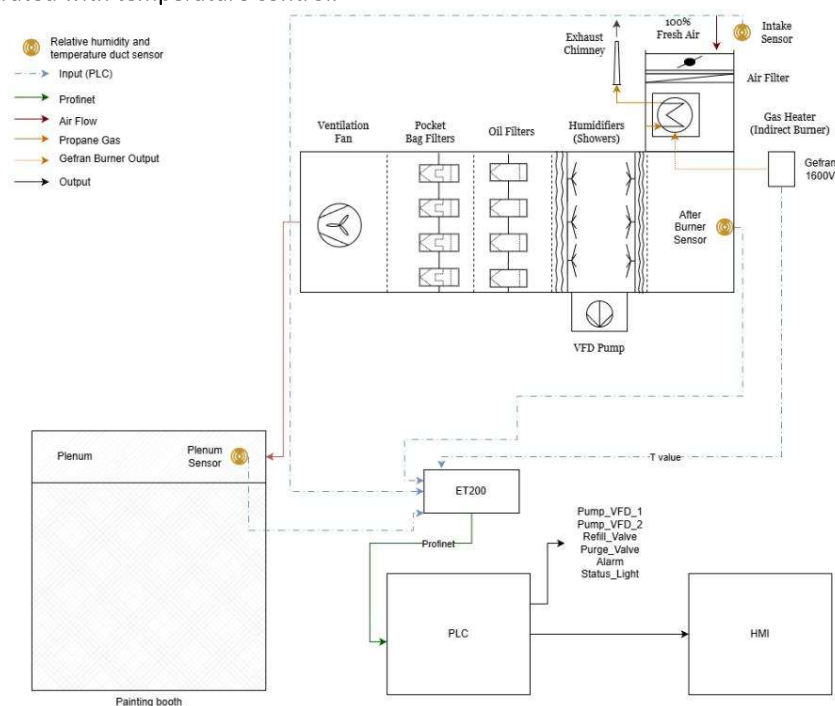
Scenario Category	Specific HVAC Design Metric	Dry-Bulb Temp. (T)	Relative Humidity (ϕ)	Dew Point (Tdp)	Moisture Content (x)
Winter Climate Baseline	Heating Design Condition (99,6% reliability)	2,0°C	90,0%	−0,4°C	3,95 g/kg
Summer Climate Baseline	Sensible Cooling Peak (0,4% reliability)	29,4°C	43,5%	16,0°C	11,13 g/kg

Summer Climate Baseline	Latent Dehumidification Peak (0.4% data)	24.4°C	75.2%	19.6°C	14.40 g/kg
Toyota Process Envelope	Minimum Lower Control Boundary	18.0°C	55.0%	—	—
Toyota Process Envelope	Target Sizing Setpoint Baseline	23.0°C	65.0%	16.1°C	11.45 g/kg
Toyota Process Envelope	Maximum Upper Control Boundary	28.0°C	80.0%	—	—

Regarding the ASU flow of air, the nominal flow is 78 000 m³/h for each ASU. However, in present conditions the flow rate of air is at around 19.05 kg/s in ASU1 and 19.15kg/s in ASU2.

10 Proposed solution

The architecture of the instrumentation layer is proposed below; it should be coupled or integrated with temperature control.



10.1 Electrical System

The new electrical board will be installed in the area adjacent to the existing paint shop Q 3.1 panel, as shown below.



It is the responsibility of the contractor to deliver offload and installed including mechanical fixing of the new equipment to the agree location.

The following consideration must be given by the supplier

- All access doors to open to min 90°. Plus 1m access for escape.
- The panel should be designed to operate in an ambient area of 40° C. If panel cooling is needed, it is the responsibility of the supplier.
- Cable tray is the contractor responsibility and, in some cases, will need to transport cables from the floor and or existing structures.
- All cable should be suitable for industrial application with oil resistance and abrasion resistance.

To ensure safety during the maintenance process, all access must be managed by a trapped key interlock system, Lockout Tagout (LOTO). The humidity control should include an emergency stop on main power panel.

10.2 Hardware and equipment

The primary solution for the humidifier will use industrial water, since the original infrastructure is prepared that way and it is made of iron.

10.2.1 Variable Frequency Drive Pumps

The present solution of a fixed speed pump does not allow a precise humidity control or a variation of flow onto the humidifier. It is mandatory to install two VFD pumps (one in each ASU) to allow for precise control of the relative humidity values of the intake air, they should be supplied by Grundfos to ensure compliance with factory standardization, including all the spare parts.

NBE 40-160/172 AAF2KESBQQEMWB



10.2.2 Piping and nozzles

Analysing the current condition of the humidifier system, it is necessary to replace the iron piping that presents signs of corrosion. For this we will replace it with PP-H, to ensure mitigation of the galvanic corrosion risk.

It will be needed to replace the nozzles to ensure a better humidification of the intake air. The chosen nozzles should be hollow cone/full cone and ensure an efficient humidification of the intake air. The standard for ASU is hollow cone, and the expected flow is around 800l/min of water at 3 bar with 60*2 nozzles. This will demand an adaptation to the current system architecture, that can be solved with the replacement of the pipes of the “nozzle tree”. Any adjustments of nozzles should be informed in the design phase.



10.2.3 Cleaning and Maintenance

The current state of the system needs to be cleaned and drained to comply with safety and health standards. It might be needed a reinforcement of the recirculating water tank on ASU2 as well as a general corrosion cleaning of the structure.

10.2.4 Sensors and Programming Logic Controller

Using a SIEMENS PLC (f.e. SIEMENS 1200) we will have an integrated control of temperature and relative humidity; this should be integrated with sensors strategically placed on the ASU and the

intake ducts. It is not encouraged to have painting booth sensors due to overspray and financial costs (ATEX certification).

For this system to allow an effective monitoring, there are sensors that are mandatory:

- 6 relative humidity and temperature duct sensors (intake, after burner and plenum);



- 2 water level sensors.



There are also some optional sensors that can be used to comply with Industry 4.0 goals and control of process efficiency.

- 2 pressure gauges (fan monitoring);
- 2 pressure gauges (filter monitoring);
- 2 water conductivity sensors (purity concerns).



Due to the distance between ASU1 and ASU2, it is necessary to use a remote data collector (f.e. ET200) that can receive and transmit the signals to the PLC through a Profinet cable. The cables of analogic signals should be protected against noise to reduce NSR and ensure a good functioning of the system.

Due to the specification of the HVAC system, the sensors need to have tolerances of signal and drift, identified in the table below.

Sensor Type	Signal Class	Protocol	Temp. Range	Tolerance	Purpose
RH/Temp (Duct)	Analog	4–20 mA	–20 to +60°C	±2.0% RH	Process Control
Water Level	Digital	24V DC	0 to +70°C	±5.0 mm	Safety
Pressure (Fans)	Analog	4–20 mA	–10 to +70°C	±1.0% FS	Efficiency
Pressure (Filters)	Analog	4–20 mA	–10 to +70°C	±0.5% FS	Maintenance
Water Conductivity	Analog	4–20 mA	0 to +80°C	±2.0% FS	Water Quality

10.3 Software and control

The control software should operate on a window, using a closed-loop feedforward, according to the standard parameters, with a VFD pump to regulate water flow onto the humidifier showers.

It should be integrated to allow for safety features and alarm systems that are specific for the type of failure to reduce repair time. The software should be accessible through a TIA Portal v20 license and should be commanded by a Siemens PLC. The control software must implement a feed-forward algorithm using the Intake and After-Burner sensors to anticipate burner thermal load changes. The system must maintain a steady-state tolerance within the 55–80% and range.

10.3.1 Human Man Interface

The HMI display should be installed between 0.8m to 1.5m from the floor to ensure compliance with ergonomic Toyota standards. The HMI display should contain:

- Status and Variable Display Panel
- Table Database
- Variable Control Graph (T and RH)

The HMI access should be divided into 3 Tiers, password or access protected that can have the following functionalities:

<i>Access Tier</i>	<i>Target User</i>	<i>Interface</i>	<i>Key Functionalities & Permissions</i>
Tier 0: User	Production Operators	HMI Local	View real-time system status (Color-coded dashboard). Analyse T & RH trends/graphs (1-week history). Monitor basic process variables.
Tier 1: Tech 1	Maintenance Members	HMI Local	All Tier 0 Permissions. Adjust Humidity Setpoints. Modify alert thresholds for non-compliant humidity. Perform Manual/Automatic system switching. Access full Error & Alarm logs.
Tier 2: Tech 2	Advanced Maintenance	HMI Local	All Tier 1 Permissions. PID Tuning: Modify characteristic parameters (P, I, D gains). Calibrate sensor offsets and pump scaling.
Tier 3: Engineering	Process Engineering	Webserver / Remote	All Tier 2 Permissions. Data Analytics of long-term trends. Sustainability Tracking: Monitor costs, water and energy consumption. Burner Analytics: Display real-time and historical gas/energy consumptions

10.3.2 Processability and audit trail

Requirement	Specification Detail
Storage Location	Non-volatile memory (SIMATIC SD Card) on the PLC/HMI.
Data Retention	Minimum of 12 months of historical logs.
Immutability	Data must be tamper-proof; users (including Engineering) cannot edit or delete entries.
Export Format	Read-only format (e.g., Checksum-protected CSV or PDF) via Webserver or USB.

11 Standards and Safety

Category	Standard	Description
Piping	ASME BPE	Bioprocessing Equipment Standard
Instrumentation	IEC 60529	Degrees of Protection (IP Code)
Process	VDI 3803	Air-conditioning: Structural & Technical principles
Cybersecurity	IEC 62443	Industrial Communication Networks
Automation	ISA-101	HMI Design for Process Automation