Faculdade de Engenharia da Universidade do Porto

Improving OEE in Packaging Lines: A Multidisciplinary Approach Integrating Mechanical Re-engineering and Industry 4.0 Technologies.

Miguel Nunes Rodrigues



Master in Mechanical Engineering
Specialization in Materials and Technological Processes

Supervisor: PhD Professor Armando Leitão

Company Supervisor: Engineer André Pinto

July 5, 2026

Improving OEE in Packaging Lines: A Multidisciplinary Approach Integrating Mechanical Re-engineering and Industry 4.0 Technologies.

Miguel Nunes Rodrigues

Master in Mechanical Engineering
Specialization in Materials and Technological Processes

July 5, 2026

Abstract

The present dissertation describes the various implementations of a multidisciplinary ecosystem focused on optimizing the reliability and efficiency of the Kisters cartoning lines at the Super Bock Group. This project proposes an internal paradigm shift, moving away from reactive maintenance practices in favor of greater proactivity supported by digitalization, the mechanical re-engineering of components, and the *Kaizen* philosophy.

To achieve this goal, the dissertation was developed around three fundamental pillars. Firstly, a diagnosis of critical equipment failures was conducted using a *Machine Learning* (NLP) algorithm, which structured the historical data stored in the SAP PM software, identifying the most critical modules, components, and failure modes. Subsequently, a digital platform (*PowerApps*) was developed for failure assessment and technical support, alongside the integration of Assisted Reality systems, which allowed for the digital leveraging of knowledge on the shop floor. Finally, mechanical re-engineering helped mitigate the chronic problem of joint contamination caused by glue dripping from the solenoid valves, through the use of retention systems properly customized for the machine's structural *design*.

The implementation of these solutions was theoretically consolidated by the TPM philosophy and *Lean* logistics, utilizing tools such as proximity *Kanban* supports, part presence sensing with IoT and *Arduino*, and the digitalization of manuals and standard operating procedures via *QR Codes*. The document further details the creation of an information management infrastructure on the *SharePoint* platform, ensuring data resilience and a compliance standard aligned with the context of Industry 4.0.

In summary, it is concluded that the convergence of the implemented technologies and methodologies results in greater mechanical reliability of the cartoning machine under study. The practical results validate a reduction in intervention times and unplanned stoppages, making it possible to reverse the asset's cycles of accelerated degradation. Beyond the technical impact, this work demonstrates that scientific engineering rigor, when applied to solving complex problems in an industrial environment, fosters an organizational culture of efficiency, conceptual scalability, and proactivity. This paradigm shift proves capable of transforming the maintenance department into a strategic, value-generating unit for the company.

Keywords: Industry 4.0, Reliability Engineering, Natural Language Processing, Autonomous Maintenance, TPM, Lean Manufacturing, Finite Element Analysis.

Resumo

A presente dissertação descreve as diversas implementações de um ecossistema multidisciplinar focado na otimização da fiabilidade e eficiência das linhas de encartonamento Kisters do grupo Super Bock. Este projeto propõe uma mudança de paradigma interno, afastando-se das práticas de manutenção reativa em favor de uma maior proatividade e sustentação na digitalização, na reengenharia mecânica de componentes e na filosofia *Kaizen*.

Para atingir tal fim, o trabalho foi desenvolvido em torno de três pilares fundamentais. Primeiramente, procedeu-se ao diagnóstico de falhas críticas do equipamento através de um algoritmo de *Machine Learning*, que estruturou os dados guardados historicamente no*software* SAP PM, identificando os módulos, componentes e modos de avaria mais críticos. Posteriormente, foi desenvolvida uma plataforma digital (*PowerApps*) para a avaliação de avarias e apoio ao técnico, bem como a integração de sistemas de Realidade Assistida, que permitiram integrar digitalmente o conhecimento no chão de fábrica. Por fim, a reengenharia mecânica ajudou a atenuar o problema crónico de danificação das articulações por escorrimento de cola proveniente das eletroválvulas, através de sistemas de retenção devidamente personalizados para o *design* da estrutura da máquina.

A implementação destas soluções foi consolidada teoricamente pela filosofia TPM e pela logística *Lean*, utilizando ferramentas como os suportes *Kanban* de proximidade, o sensoriamento de presença de peças com IoT e *Arduino*, e a digitalização de manuais e procedimentos operacionais via *QR Codes*. O documento detalha ainda a criação de uma infraestrutura de gestão de informação na plataforma *SharePoint*, permitindo garantir a resiliência dos dados e a exigência de um padrão de conformidade enquadrado no contexto da Indústria 4.0.

Em síntese, a convergência das tecnologias e metodologias implementadas resulta numa maior fiabilidade mecânica da encartonadora em estudo. Os resultados práticos validam uma redução dos tempos de intervenção e das paragens não planeadas, permitindo reverter ciclos de degradação mais acentuada do equipamento. Além do impacto técnico, este trabalho demonstra que o rigor científico da engenharia, quando aplicado à resolução de problemas complexos em ambiente industrial, estimula uma cultura organizacional de eficiência, escalabilidade de conceitos e proatividade. Esta mudança de paradigma prova ser capaz de transformar o departamento de manutenção numa unidade estratégica e geradora de valor para a empresa.

Keywords: Indústria 4.0, Fiabilidade Industrial, Processamento de Linguagem Natural, Manutenção Autónoma, TPM, Lean Manufacturing, Análise de Elementos Finitos.

Agradecimentos

Expresso, a minha sincera gratidão a todos os que, direta ou indiretamente, contribuíram para a concretização desta etapa. Em particular, agradeço ao meu orientador na Super Bock, André Pinto, por todo o apoio técnico, disponibilidade e orientação prestados ao longo do estágio. Estendo igualmente o meu agradecimento a toda a equipa da Super Bock, por me ter acolhido desde o primeiro dia e por me fazer sentir verdadeiramente em casa durante toda esta experiência.

Em primeiro lugar, um agradecimento especial ao meu orientador, Professor Doutor Armando Leitão, pela disponibilidade, apoio e rigor científico demonstrados. A sua orientação e os seus valiosos conselhos foram determinantes para a concretização desta dissertação.

Agradeço também a todos os professores, colegas e amigos que fizeram parte deste percurso, pelo conhecimento partilhado, pelo espírito de entreajuda e pelos momentos que contribuíram para o meu crescimento pessoal e profissional.

À minha família, em especial aos meus avós, tios e primos, pelo apoio e incentivo constantes ao longo desta caminhada.

À minha mãe, pelos conselhos, pelo apoio constante e pelas chamadas reconfortantes que sempre me transmitiram calma, confiança e a força necessária para superar os desafios deste percurso.

Ao meu pai, por ser o meu maior exemplo de profissionalismo, dedicação e integridade. A sua forma de estar e de encarar o trabalho será sempre a referência e o ideal que procuro seguir.

À minha irmã Ju, por ter caminhado ao meu lado nos primeiros anos deste percurso académico. Numa fase em que éramos ambos novos numa cidade desconhecida, a sua companhia tornou a distância de casa mais leve e ajudou-me a enfrentar os desafios dessa nova etapa.

À minha irmã Marta, pelo sorriso acolhedor, pela alegria que transmite e pela serenidade com que consegue tornar os momentos mais difíceis mais leves.

À minha namorada, por ter sido o meu maior apoio ao longo desta etapa. Nos momentos mais difíceis, foi o meu pilar, oferecendo-me sempre apoio incondicional, compreensão e um ombro amigo que me deram força para ultrapassar todas as adversidades. Sem ela, este percurso teria sido muito mais difícil. Foi, sem dúvida, quem mais viveu esta caminhada ao meu lado, partilhando cada desafio, cada conquista e cada momento desta etapa tão intensa quanto gratificante.

Por fim, um agradecimento muito especial e saudoso à minha avó, que, embora tenha partido fisicamente durante este percurso académico, permaneceu sempre presente no meu pensamento e no meu coração. A sua força, o seu carinho e a sua memória acompanharam-me e deram-me coragem para concluir esta etapa.

Author's Note

Although written in English, this dissertation retains Portuguese for data analysis, system interfaces, and taxonomic classifications based on three methodological requirements:

- **Data Integrity and NLP Accuracy:** The Natural Language Processing (NLP) algorithm relies on raw SAP PM logs. Translating these unstructured records would distort local technical jargon, alter the semantic context, and compromise the predictive accuracy of the Machine Learning models.
- **Shop-Floor Usability:** To ensure the successful adoption of digital tools (such as PowerApps, SOPs, and AR interfaces) by frontline teams and to mitigate human resistance to change, it is crucial that these solutions remain in the operators' native language.
- **Corporate Integration and Scalability:** Maintaining the analytical outputs and databases in Portuguese guarantees seamless interoperability with Super Bock Group's existing corporate infrastructure (SAP and SharePoint), ensuring the data remains functional for future internal audits and reliability analyses.

"The only way to do great work,
is to love what you do."

Steve Jobs

Contents

1 Introduction **1**
- 1.1 Background and Context . . . 1
  - 1.1.1 Super Bock Group: Beverage Sector and Competitive Context . . . 1
  - 1.1.2 The Maintenance Department: Structure and Operational Challenges 3
  - 1.1.3 Cartoning Equipment: Kisters Machines in Lines 1 and 2 . . . 5
- 1.2 Problem Definition and Motivation . . . 8
  - 1.2.1 Operational Bottlenecks and OEE Impact . . . 8
  - 1.2.2 The Maintenance Paradigm Shift . . . 10
- 1.3 Objectives and Research Methodology . . . 12
  - 1.3.1 Research Objectives . . . 12
  - 1.3.2 Research Methodology . . . 13
  - 1.3.3 Thesis Outline . . . 13

2 Literature Review **14**
- 2.1 Paradigm of Smart Manufacturing and Reliability Engineering . . . 14
- 2.2 Natural Language Processing in Computerized Maintenance Management Systems . . . 15
  - 2.2.1 Text Preprocessing and Feature Extraction Methodologies . . . 15
  - 2.2.2 Machine Learning Classification Architectures . . . 16
- 2.3 The Evolution of Total Productive Maintenance (TPM 4.0) . . . 18
  - 2.3.1 The Emergence of Cyber-Physical Systems and Digital Lean . . . 18
- 2.4 Human-Machine Interfaces and Assisted Reality . . . 19
- 2.5 Cyber Resilience and Data Governance in Manufacturing . . . 20
- 2.6 Fluid Dynamics and Reliability of Hot-Melt Adhesive Systems . . . 21
- 2.7 Computational Mechanics of Packaging Materials (Corrugated Cardboard) 22
  - 2.7.1 Degradation Mechanisms: Moisture and Compressive Stress . . . 22
  - 2.7.2 Finite Element Modeling and Numerical Homogenization . . . 23
- 2.8 Tribological Dynamics and Wear Simulation in Kinematic Systems . . . 24
  - 2.8.1 The Mechanics of Sliding Wear . . . 24
  - 2.8.2 Finite Element Simulation of Wear via ABAQUS . . . 25
- 2.9 Synthesis: Integrating Digital and Mechanical Reliability . . . 26

3 Research Methodology **27**
- 3.1 Strategy for Autonomous Maintenance . . . 28
  - 3.1.1 Analytical Transition and Methodological Foundation: From the Reactive Paradigm to TPM Philosophy . . . 28
  - 3.1.2 Strategic Knowledge Management: Standard Operating Procedures 30
- 3.2 Data Mining and NLP Pipeline . . . 31

4 Critical Assessment of the SAP PM Ecosystem 34
4.1 Critical Assessment of the SAP PM Ecosystem . . . 34
4.1.1 The Free-Text Challenge in Industrial Maintenance . . . 34

5 Digitalization and Asset Management 43
5.1 Interactive Diagnostic Platform (PowerApps) . . . 43
5.2 Digitalizing Maintenance and Cleaning Routines . . . 48
5.2.1 Critical Diagnosis of Operational Constraints and Hybrid System Limitations . . . 48
5.2.2 Restructuring and Hierarchical Segmentation: A Maintenance Engineering Approach . . . 50
5.2.3 Digitalization of Routines and Data Analytics: Dynamic Tasklists . 52
5.2.4 Operational Standardization and Integration with Quality Management . . . 55
5.2.5 Industry 4.0 Perspectives: Smart Factories and Voice Assistance (RealWear) . . . 57
5.2.6 Comparative Analysis and Validation of Results: The Before vs. After Impact of Implementation . . . 59
5.3 Information Architecture and SharePoint . . . 60
5.3.1 Historical Context and the Need for Cyber Resilience . . . 60
5.3.2 Limitations of the Transitional Model and the Strategic Advantages of SharePoint . . . 61
5.3.3 Hierarchical Taxonomy and Database Segmentation . . . 62
5.3.4 Equipment Structuring and Document Integration (Quality and Operations) . . . 64
5.3.5 Cyber-Physical Interfaces (QR Codes) and Future Work Roadmap . 66

6 Autonomous Maintenance Implementation and Cyber-Physical Systems (CPS) Integration 68
6.1 Operational Execution: Field Deployment . . . 68
6.2 Workplace Ergonomic Engineering: 5S Methodology and *Kanban* Systems . 68
6.2.1 Architecture and Content of Proximity Kanbans . . . 69
6.2.2 Operational Circuit for Material Replenishment . . . 71
6.3 The Digital Lean Paradigm: IoT Inventory Prototype (Cyber-Physical Systems) . . . 73
6.4 Manufacturing Optimization through Additive Manufacturing . . . 75
6.5 Internal Supply Chain Engineering and Operational Digitalization . . . 76

7 Mechanical Re-engineering and Quality Control 78
7.1 Mechanical Solution Development: Redesign and Optimization of the Hot-Melt Gluing System . . . 78
7.1.1 Problem Diagnosis and Root Cause Analysis . . . 79
7.1.2 Economic Viability Analysis and Impact on Downtime . . . 81
7.1.3 Solution Development: CAD Modeling and Technical Design . . . 82
7.1.4 Final Implementation and Integration on the Factory Floor . . . 86
7.1.5 Cleaning Standardization and Operational Impact Assessment . . . 88
7.2 Quality Control Integration: Mitigation of Non-Conforming Packaging Materials . . . 90
7.2.1 Problem Diagnosis: Material Degradation and Kinematic Impact . . 90

7.2.2 Computational Validation of Packaging: Finite Element Analysis (FEA) . . . 92
7.2.3 Kinematic Impact on the Kisters Packer . . . 96
7.2.4 Mechanical Solution: *Poka-Yoke* Conceptualization . . . 98
7.2.5 Standardization and Quality Assurance Integration . . . 101

8 Tribological Study and Kinematic Stability in the Transfer Plate: Methodological Formulation 103
8.1 Problem Identification and Operational Impact . . . 103
8.2 Analytical Stability Calculation: Center of Gravity (*CG*) . . . 104
8.3 CAD Modeling and Three-Dimensional Setup . . . 107
8.4 Future Work: Tribological Simulation and Materials Optimization . . . 108

9 Results Analysis and Operational Impact 111
9.1 Operational Impact: OEE Evolution . . . 111
9.2 Breakdown Analysis and Data Processing . . . 112
9.3 Longitudinal Analysis and Trend Normalization (2022-2026) . . . 113
9.4 Economic Viability: ROI and Payback Period . . . 115
9.4.1 Annualized Savings and Financial Performance . . . 115
9.5 Reliability and Availability Impact . . . 115

10 Conclusions and Future Work 117
10.1 Main Contributions and Final Remarks . . . 117
10.2 Research Limitations . . . 119
10.2.1 Information Systems, Data Quality, and the Human Factor . . . 119
10.2.2 Logistical Implementation Constraints . . . 119
10.2.3 Challenges in Computational Modeling (FEA) . . . 120
10.3 Future Work . . . 121
10.3.1 Digitalization, Information Systems, and *Text Mining* . . . 121
10.3.2 Assisted Reality and the Evolution of Visual SOPs . . . 121
10.3.3 Inventory Management Automation (Cyber-Physical Systems) . . . 122
10.3.4 Longitudinal Validation of Maintenance Plans . . . 122
10.3.5 Upstream Quality and Physical Barrier Implementation . . . 122
10.3.6 Advanced Tribological Simulation . . . 123
10.3.7 Horizontal Scalability (*Roll-out*) . . . 123

References 124

Bibliography 124

A Figures and Tables 128
A.1 Operational Support Documentation . . . 129
A.1.1 Autonomous Maintenance: Standard Operating Procedures (KISTERS L2) . . . 129
A.1.2 Proximity Kanban System: Infrastructure and Automation . . . 132
A.1.3 Slicing configurations for Kanban Model 2 production . . . 134
A.1.4 Digital Preventive Maintenance Interface (Microsoft Forms) . . . 135
A.1.5 Standard Operating Procedure: Ovality Determination . . . 136

B Codding **137**
B.1 Python code 137
B.2 C++ Code 139

List of Figures

1.1 Distribution of Global Beer Market Share, in million hectoliters (2024) . . . 2
1.2 Super Bock Group Supply Chain Division organizational chart. 3
1.3 Mapping of the maintenance process and allocation of responsibilities. . . . 4
1.4 Kisters KHS modular division, Line 2 6
1.5 Distribution of Total Downtime by Failure Mode, Lines 1 and 2. 8
1.6 Different OEE performance (YTD) in Leça do Balio Super Bock factory . . 9
1.7 Equipment Failure Rate, Line 1 9
1.8 Equipment Failure Rate, Line 2 10
1.9 Distributions of Maintenance Orders by Type, Kisters (Line 1 and 2) . . . 11

3.1 Methodological workflow for the creation and standardization of SOPs. . . . 31
3.2 Sequential workflow of the Natural Language Processing (NLP) framework. 32
3.3 Computational Implementation for SAP Data Processing Using Google Colab 33

4.1 Number of Interventions by Bimester (2022-2026), Line 1 and 2 (Kisters) . 35
4.2 Number of Urgent breakdowns per zone (%), Line 1 and 2 (Kisters) 38
4.3 Total time for urgent breakdowns per zone (%), Line 1 and 2 (Kisters). . . 39
4.4 Total Number Breakdowns per zone (%), Line 1 and 2 (Kisters) 40
4.5 Total Component Failure Time (%), Line 1 and 2 (Kisters) 40
4.6 Maintenance Criticality Matrix for Kisters Lines 1 and 2 (Before). 41

5.1 Main Reasons for Delay in Repairing Faults. 43
5.2 HomePage Application Fault Diagnosis Kisters, Line 2 44
5.3 Segmentation by component/module of KISTERS equipment, line 2 45
5.4 Breakdown by technician (TMM/TME) responsible for resolving the fault. . 46
5.5 Different list of defects. 47
5.6 Detailed steps to resolve a PowerApps application error. 47
5.7 Original list of weekly preventive maintenance actions in the SAP system (ZPM3 Order type) for the Kisters Line 2 machine. 49
5.8 Weekly Maintenance Preventive - spaghetti Diagram (Before) 53
5.9 Optical scanning of the QR code affixed to the KISTERS safety panel using a rugged mobile device. 57
5.10 Digital submission form (Microsoft Forms) displayed on the industrial tablet, detailing the autonomous cleaning requirements. 57
5.11 Demonstration of the use of Assisted Reality technology integrated with Personal Protective Equipment on the Kisters KHS machine (line 2), focused on hands-free usability. 58
5.12 Ad-hoc documentation repository architecture within Microsoft Teams. . . 61

5.13 Production SharePoint interface showing the structural separation by sub-department libraries. . . . 63
5.14 Internal hierarchical structure of the Line 2 KISTERS equipment in SharePoint. . . . 64
5.15 Physical posting of the Standard Operating Procedures (SOPs) for Autonomous Maintenance on the Kisters machine. . . . 66
5.16 Direct view of the Workstation Documentation accessed via QR Code on the shop floor. . . . 67

6.1 Three-dimensional modeling of the *Kanban* system support 1. . . . 70
6.2 Physical implementation and point-of-use demonstration of the *Kanban* 1 system support on the Kisters cartoning machine, showing the housing of the feed combs, conical screws, and the retention of the intervention tool. . . . 71
6.3 Flowchart of the operational circuit and material replenishment routine of the proximity *Kanban* system. . . . 72
6.4 Cyber-Physical System Prototyping. On the left, the TCRT5000 optical sensor array for mechanical Kanban detection; in the center, the Arduino Uno R3 microcontroller; on the right, the triple-signaling LED traffic light module for inventory status feedback. . . . 74

7.1 Visual inspection of hot-melt adhesive accumulation and dripping on the solenoid valve application nozzles. . . . 80
7.2 Solidified hot-melt adhesive accumulated on the articulation rollers, illustrating the aftermath of the chronic dripping issue. . . . 81
7.3 Three-dimensional CAD modeling of the top protection plate and truss support structure. . . . 83
7.4 Isometric perspective of the CAD model of the retention system bottom base plate. . . . 83
7.5 Bottom perspective of the CAD model highlighting the mechanical positioning counterbores and channels. . . . 84
7.6 Dimensioned technical drawing of the top protection base geometry against adhesive. . . . 85
7.7 Technical drawing and dimensional specifications of the mechanical reinforcement truss structure. . . . 85
7.8 Dimensioned technical drawing of the bottom base plate with standardized fixation drilling. . . . 86
7.9 Frontal perspective of the implemented retention system on the dual top valve, showcasing the welded support bracket and CHC M6x20 bolts. . . . 87
7.10 Rear perspective of the dual top valve assembly, detailing the vertical alignment of the retention plate beneath the applicator nozzles. . . . 87
7.11 Frontal view of the retention tray adapted for the single top valve, highlighting the necessary spatial clearances. . . . 87
7.12 Rear view of the single top valve setup, emphasizing the rigid fixation to the Kisters machine structure. . . . 87
7.13 Batch of cardboard blanks exhibiting severe macroscopic warpage at the upper layers due to hygroscopic softening and lack of structural support. . . . 91
7.14 Visible creasing and structural web collapse caused by excessive localized contact pressure from polymeric strapping bands. . . . 91

7.15 Von Mises stress distribution in the complete assembly (Bottom view detailing the support). . . . 94
7.16 Von Mises stress distribution across the entire assembly, highlighting the constriction (Top view). . . . 94
7.17 Geometric isolation of the card highlighting the propagation of local stresses (Peripheral view). . . . 95
7.18 Card isolation demonstrating the extent of the collapse in the transverse plane (Top view). . . . 95
7.19 CAD model of the aluminum assessment plate in the extended, operational position. . . . 99
7.20 CAD model of the plate in the folded position via mechanical hinge, accommodating spatial constraints. . . . 99
7.21 Highlight of the fixed datum plane where the Teflon-lined visual warpage gauge is strategically located. . . . 100
7.22 Measuring rod used for checking maximum allowable bending (Kisters equipment) . . . 100

8.1 Visualization of the feed plate on the KISTERS machine, showing severe wear of the lining and damage to the adjacent feed combs. . . . 104
8.2 Geometric discretization of the Super Bock bottle into 5 primitive sections for analytical calculation. . . . 105
8.3 Comparative mapping of the Center of Gravity positioning in three geometric variations of bottles. . . . 107
8.4 Three-dimensional (CAD) modeling of the simplified assembly: transfer plate and die for 0.33 cl bottles. . . . 108

9.1 OEE indicator value, June 2026 (Line 2) . . . 112
9.2 Maintenance Critically Matrix for Kisters Lines 1 and 2 (After) . . . 113
9.3 Total number of interventions per bimester (2022-2026), Kisters L2 . . . 114
9.4 Comparative isolated analysis of incidents in Bimester 4, during 2023 to 2026 (Kisters L2). . . . 114

A.1 Standard Operating Procedures - Replacement of passage combs on Kisters Line 2. . . . 129
A.2 Standard Operating Procedures - Inspection and replacement of conveyor rollers on Kisters Line 2. . . . 130
A.3 Standard Operating Procedures - Folding tractor maintenance routine on Kisters Line 2 . . . 131
A.4 Exploded view of the Kisters Kanban system support. . . . 132
A.5 Electrical topology: Sensor-to-actuator interconnection. . . . 133
A.6 Preparation for manufacturing and configuration of slicing parameters (Bambu Studio) for the upper zone of the Kanban 2 model. . . . 134
A.7 Mobile view of the digital preventive maintenance interface developed on Microsoft Forms. The platform is accessed via QR Code on the shop floor and features multimedia instructions alongside mandatory validation fields. 135
A.8 Standard Operating Procedure detailing the specific guidelines, steps, and acceptance criteria for determining ovality in corrugated cardboard packaging. 136

List of Tables

1.1 The 5 Bottle/Can Filling Lines 5

2.1 Summary of simulation components and their functions within the ABAQUS wear modeling architecture. 25

4.1 Representative sample of raw maintenance records extracted from SAP PM. 37
4.2 Example of the hierarchical classification generated by the NLP algorithm from the raw text records. 38

5.1 Segmentation and restructuring matrix of maintenance operations by component, demonstrating the leveling of execution frequencies. 51
5.2 Comparative matrix of operational and logistical indicators before and after the implementation of the engineering solutions. 59

7.1 Autonomous Maintenance routine for the hot-melt retention system. 88
7.2 Financial impact of unrealized production due to downtime. 89
7.3 Input variables for monthly packaging damage volumes and costs. 101

8.1 Geometric, volumetric, and mass characteristics for the study models. . . . 106

Abbreviations

bph	Bottles per hour
dB	Decibel
h_{CG}	Gravity Center Height
IR	Infrared
μ_k	Kinetic Friction Coefficient
MPa	MegaPascal
NdFeB	Neodymium Iron Boron
P-F	Potential-to-Functional Failure
PSI	Pounds per Square Inch
RH	Relative Humidity
Roll-out	Horizontal Scalability
Seiso	Cleaning (5S)
TP	Lost Tare
TR	Returnable Tare
TTA	Total Downtime
UCL	Upper Control Limit
UMESHMOTION	Mesh Shift Subroutine
YTD	Year-to-Date

Acronyms

3D	Three-Dimensional
5S	5S Methodology (Sort, Set in order, Shine, Standardize, Sustain)
AB InBev	Anheuser-Busch InBev
ALE	Arbitrary Lagrangian-Eulerian
aR	Assisted Reality
AR	Augmented Reality
BC	Boundary Condition
BERT	Bidirectional Encoder Representations from Transformers
BI	Business Intelligence
bph	Bottles per hour
C3D8R	8-node linear brick, reduced integration, hourglass control
CAD	Computer-Aided Design
CAPA	Corrective and Preventive Action
CapEx	Capital Expenditure
CBM	Condition-Based Maintenance
CG	Center of Gravity
CMMS	Computerized Maintenance Management System
CNC	Computer Numerical Control
CNN	Convolutional Neural Networks
COPQ	Cost of Poor Quality
CPS	Cyber-Physical System
dB	Decibel
E.D.A.	Electronic Design Automation
ECT	Edge Crush Test
ERP	Enterprise Resource Planning
E-Stops	Emergency Stops
FDM	Fused Deposition Modeling
FEA	Finite Element Analysis
FEM	Finite Element Method
FEUP	Faculdade de Engenharia da Universidade do Porto
Gemba	Real place where value is created
Go/No-Go	Binary acceptance/rejection criterion
HACCP	Hazard Analysis and Critical Control Points
h_{CG}	Height of Center of Gravity
Heijunka	Production Leveling
HMI	Human-Machine Interface
ICS	Industrial Control Systems
IDE	Integrated Development Environment

IIoT	Industrial Internet of Things
IoT	Internet of Things
IP	Ingress Protection
IR	Infrared
ISO	International Organization for Standardization
JIPM	Japan Institute of Plant Maintenance
JIT	Just-in-Time
Kaizen	Continuous Improvement
KHS	Klöckner Holstein Seitz
KPI	Key Performance Indicator
LED	Light-Emitting Diode
LOTO	Lockout/Tagout
LSTM	Long Short-Term Memory
MM	Material Management
MNC	Material Non-Conformance
MPa	MegaPascal
MR	Mixed Reality
MS Forms	Microsoft Forms
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
Muda	Waste
μ_k	Kinetic Friction Coefficient
NB	Naïve Bayes
NCR	Non-Conformance Report
NdFeB	Neodymium Iron Boron
NLGEOM	Nonlinear Geometry
NLP	Natural Language Processing
OEE	Overall Equipment Effectiveness
OHS	Occupational Health and Safety
OT	Operational Technology
PDCA	Plan-Do-Check-Act
PEEK	Polyether Ether Ketone
PET	Polyethylene Terephthalate
PETG	Polyethylene Terephthalate Glycol
P-F	Potential-to-Functional Failure
PLA	Polylactic Acid
PLC	Programmable Logic Controller
PM	Plant Maintenance
Poka-Yoke	Error-proofing mechanism
PP	Polypropylene
PPC	Production Planning and Control
PPE	Personal Protective Equipment
PSI	Pounds per Square Inch
PTFE	Polytetrafluoroethylene
QHSE	Quality, Health, Safety, and Environment
QMS	Quality Management System
QR	Quick Response
RBAC	Role-Based Access Control

RCA	Root Cause Analysis
RCM	Reliability-Centered Maintenance
RF	Random Forest
ROI	Return on Investment
Roll-out	Horizontal Scalability
RVE	Representative Volumetric Element
SAP	Systems, Applications, and Products
SAP PM	Systems, Applications, and Products - Plant Maintenance
SECI	Socialization, Externalization, Combination, Internalization
Seiso	Cleaning (5S)
SF	Safety Factor
SKU	Stock Keeping Unit
SMED	Single-Minute Exchange of Die
SOP	Standard Operating Procedure
SSOT	Single Source of Truth
SVM	Support Vector Machines
TF-IDF	Term Frequency - Inverse Document Frequency
TME	Técnico Elétrico de Manutenção
TMM	Técnico Mecânico de Manutenção
TOC	Theory of Constraints
TP	Tara Perdida
TPM	Total Productive Maintenance
TPS	Toyota Production System
TQM	Total Quality Management
TR	Tara Retornável
TTA	Total Downtime
UCL	Upper Control Limit
UHMWPE	Ultra-High-Molecular-Weight Polyethylene
UMESHMOTION	Mesh Shift Subroutine
URL	Uniform Resource Locator
UX	User Experience
VR	Virtual Reality
VUI	Voice User Interfaces
VUMAT	Vectorized User-Material Subroutine
XR	Extended Reality
YTD	Year-to-Date
ZPM1	Planned Corrective Maintenance
ZPM2	Emergency/Unplanned Corrective Maintenance
ZPM3	Preventive Maintenance

Chapter 1

Introduction

1.1 Background and Context

1.1.1 Super Bock Group: Beverage Sector and Competitive Context

The industrial evolution over the last few decades has been marked by significant technological advancements, particularly through mechanization, automation, and, more recently, the integration of intelligent systems in industrial production processes.

The current phase of globalization, often referred to as the digital revolution, began in the 1990s and has largely transformed manufacturing industries, including the beverage industry. As a result of internationalization, companies face increasing pressure to maintain their mass production while continuously improving efficiency and profitability in order to maintain their competitiveness in the international market, without compromising their own sustainability.

The continuous reduction of trade barriers has also forced business leaders in the beverage sector to transition from domestic strategies to global implementation, leading to significant changes in the sector's organizational operations, with ongoing efforts to ensure greater productivity and increasing innovation.

Beer consumption is deeply embedded in everyday customs and social traditions, fostering strong emotional connections among consumers and reinforcing brand loyalty to a select group of established beer companies, which contributes to intense and direct global competition among major brewing companies, including AB InBev, Heineken, Carlsberg, and China Resources. Collectively, these firms account for fifty percent of the global beer market (Figure 1.1)[1].

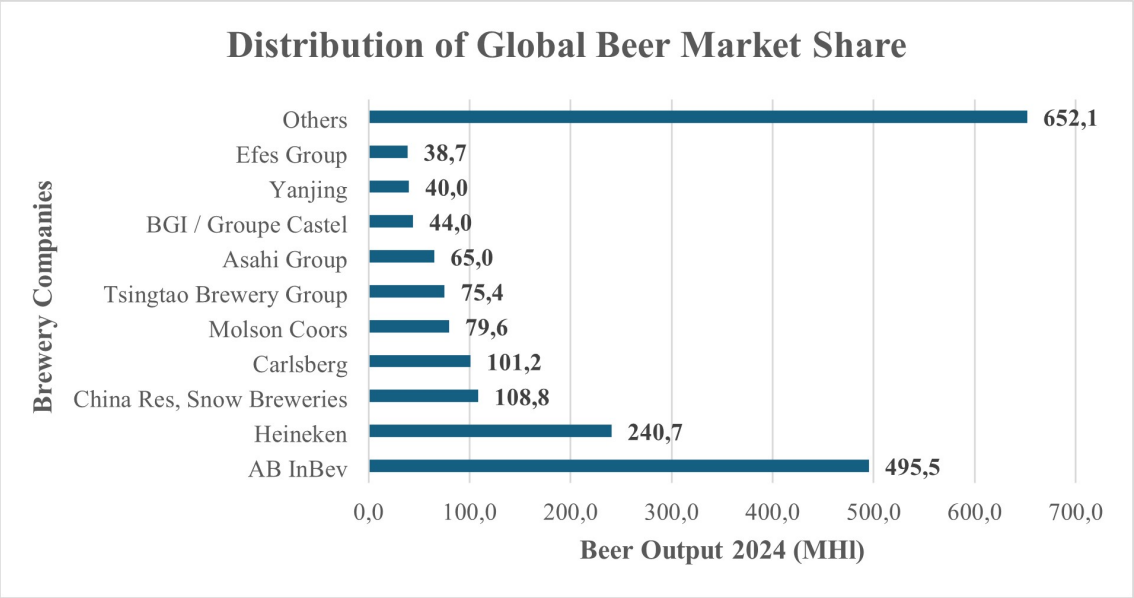


Figure 1.1: Distribution of Global Beer Market Share, in million hectoliters (2024)

The Portuguese market closely aligns with global industry trends. Approximately, ninety percent of domestic sales are concentrated in two major companies: Super Bock Group and Sociedade Central de Cervejas, also known as Sagres [2].

Super Bock has established itself as the national market leader, due to its internal development and continuous efforts to acquire innovative techniques used by other global companies. The limited scale of Portugal's domestic market reinforces the need for an international expansion mindset, which is crucial for the company's long-term growth.

Currently, Super Bock Group exports approximately forty percent of its total volume production to international markets, with the brand being represented in over fifty countries around the world.

The Super Bock Group's international expansion strategy is built upon three core pillars. Firstly, the company maintains a strong presence across Europe, focusing primarily on regions with significant Portuguese immigrant communities, commonly referred to as the *Saudade Market*. Secondly, the company pretends to consolidate and expand its footprint in Africa, particularly within former Portuguese colonies where cultural ties to Portugal remain strong. Finally, the Asian market represents the company's main focus for long-term strategic growth, with China acting as the primary driver of this new objective.

In fact, international market expansion requires that production output maintains adequate inventory levels to mitigate the risk of stock-outs and lost sales. Consequently, the Super Bock Group's factory in Leça do Balio (Porto) has undergone continuous renovations, equipment upgrades, and implementation of new production lines, all designed to ensure high operational throughput and production capacity.

To effectively manage the demands of a large-scale enterprise, managers must ensure the symbiotic alignment of the three pillars of the supply chain: production, quality,

and logistics. Production must meet market volume requirements; quality must ensure customer acceptance; and logistics must guarantee the distribution of products within rigorous delivery timelines.

Within the production department, the maintenance area plays a crucial role in ensuring adequate operational conditions for the proper functioning of production lines, thus avoiding possible prolonged equipment downtime that would result in significant production delays and, consequently, harm delivery to the end customer. In this context, OEE serves as the company's key performance indicator. This indicator evaluates the performance of production equipment and is determined by three main factors: availability, performance, and quality rate.

1.1.2 The Maintenance Department: Structure and Operational Challenges

The Super Bock Group's factory, located in Leça do Balio, is organized into several synergistic macro-functional areas, all of which are essential to ensure operational excellence and fulfill the company's intrinsic requirements. As discussed in subchapter 1.1.1, the supply chain department encompasses logistics, project and facility management, production, and quality. This dissertation focuses on the production department, with a particular emphasis on the maintenance division. The corporate organizational chart presented in Figure 1.2 details the different branches of the supply chain, highlighting the hierarchical structure within the production department.

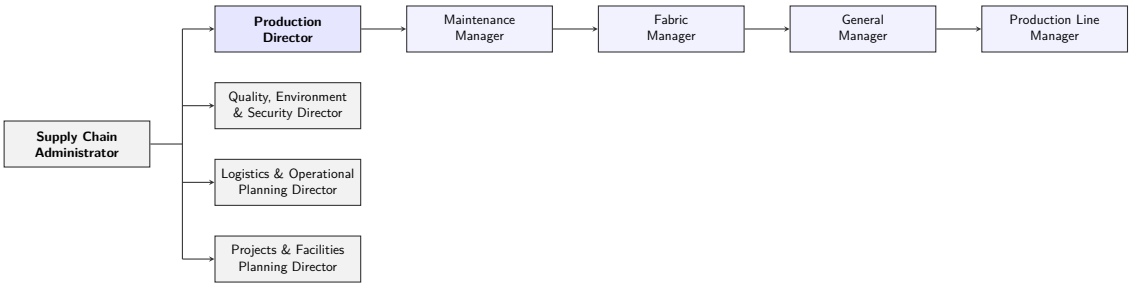


Figure 1.2: Super Bock Group Supply Chain Division organizational chart.

Within the production department, the maintenance division is structured across distinct levels of technical specialization and responsibility. The maintenance manager and senior technicians are responsible for strategic oversight, encompassing planning and structural optimization of preventive and corrective maintenance programs. Furthermore, these roles involve the analytical management of spare parts inventory and reliability engineering, as well as failure management and prevention, characterized by the continuous application of root cause analysis to address daily anomalies across production lines. Additionally, senior technicians provide ongoing technical support to the operational teams, ensuring that all maintenance activities are aligned with the broader objectives of maximizing equipment availability across each production line.

In parallel, the Maintenance Coordinators play a pivotal role in operational coordination and on-site team leadership. Their scope of action encompasses daily planning, rigorous recording of downtime, coordination of changeovers and scheduled overhauls, as well as operational troubleshooting. Furthermore, they assume human resources management responsibilities at the shop floor level, overseeing shift scheduling, leave and vacation management, and the optimized allocation of personnel across respective production shifts.

Comprehensive technical support is provided by the team of Maintenance Technicians, whose activities are complementarily divided between the production line and the workshop. On the shop floor, they ensure the meticulous execution of preventive maintenance plans and provide immediate response to equipment breakdowns. In the workshop environment, they are responsible for the repair and reconditioning of mechanical components.

The application of manufacturing processes, namely machining (turning and milling) and welding, enables the in-house recovery of critical parts. This strategy not only optimizes operational costs but also mitigates dependency on external suppliers for spare parts procurement. Figure 1.3 details the flowchart of operational responsibilities, highlighting the proactive contribution of each stakeholder toward reducing the failure rate and, consequently, increasing the facility's OEE.

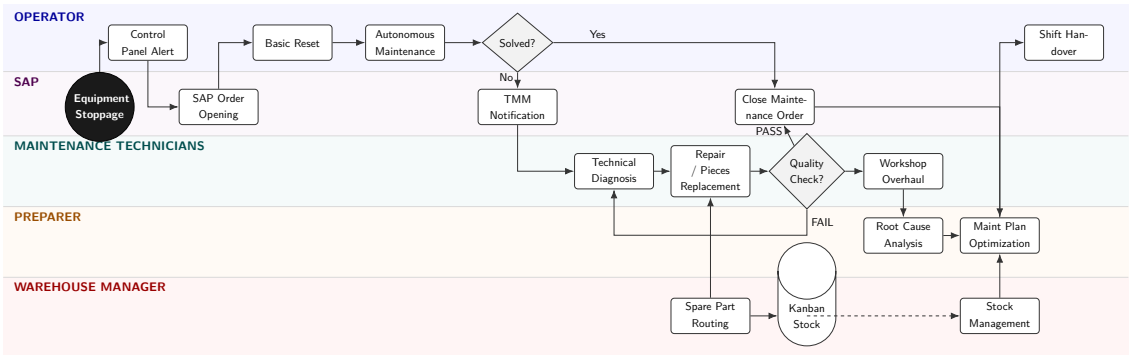


Figure 1.3: Mapping of the maintenance process and allocation of responsibilities.

In the modern environment of high industrial demands, the maintenance department faces essential challenges driven by rapid technological developments and fierce industry competitiveness. This paradigm requires a ceaseless pursuit of maximizing the operating efficiency as well as reliability of physical assets, a theme that forms the core of the following analysis.

The preliminary diagnostic of the operational setting revealed substantial opportunities for improvement across multiple levels.

One of the most critical opportunities for improvement was the clear identification of discrepancies between the scheduled preventive maintenance plan and the current state of equipment degradation.

Additionally, a low level of maturity was observed regarding the execution of Autonomous Maintenance. This reality is a direct reflection of the scarcity of standardized operational routines executed by the operators, particularly highlighted by the absence of Standard Operating Procedures for fundamental cleaning and inspection tasks.

Concurrently, organizational constraints were identified in the flow of information and materials management. Notably, among these are inefficiencies in the line-side Kanban replenishment systems, substantial gaps in the reliability of downtime logging, and a lack of taxonomic standardization when characterizing anomalies within the Computerized Maintenance Management System. Confronted with this reality, it is necessary to advance toward cyber-physical integration. This approach intends to capture reliable, live data, which is a fundamental requisite for the rigorous monitoring of operational availability and the OEE indicator.

1.1.3 Cartoning Equipment: Kisters Machines in Lines 1 and 2

The Super Bock production center comprises multiple filling lines, each defined by distinct technical specifications. These operational characteristics vary according to the type of bottle produced, the unit volume, and the nominal line capacity (bottles per hour), whose maximum threshold is dictated by the primary filler equipment (Table 1.1). Furthermore, product variability extends to the box formats, demanding accurate mechanical adaptations to the equipment for each specific batch. Changes between different SKUs are executed through format changes, which entail the replacement and rigorous adjustment of specific machine components.

Table 1.1: The 5 Bottle/Can Filling Lines

Line No.	**Type**	**Bottle Types**	**Volume**	**Capacity (bph)**	**Secondary Packaging**
1	TP	5	20cl, 25cl, 33cl	60,000	Box 12, Box 15, Box 20, Box 24, Box 30
2	TP	8	20cl, 25cl, 33cl	60,000	Box 12, Box 15, Box 20, Box 24, Box 24 6-Pack, 6-Pack, 10-Pack, 4-Pack
3	TR	3	20cl, 33cl	60,000	Crates 24, Crates 30
5	TP/TR	7	20cl, 20.8cl, 25cl, 33cl	80,000	Box 15, Box 20, Box 24, Box 30, Box 24 6-Pack, Shrink 6-Pack, 10-Pack, Crate
6	TP	7	25cl, 33cl, 66cl, 1L	50,000	Box 12, Box 15, Box 20, Box 24, Box 30, Box 24 6-Pack, 4-Pack
	Can	4	33cl, 50cl	35,000	Box 24, 6-Pack, Tray

The Kisters KHS equipment features a consistent architecture across both production lines 1 and 2, differing only in minor technical specifications. The machine is organized into several functional modules: product infeed, card feeding, formatting, folding, film wrapping, and film heating, as illustrated in Figure 1.4. Each module encompasses specific components that have been pre-categorized based on downtime duration and failure modes. This systematic classification is designed to accelerate the identification of root causes for production stoppages, thereby optimizing the troubleshooting process.

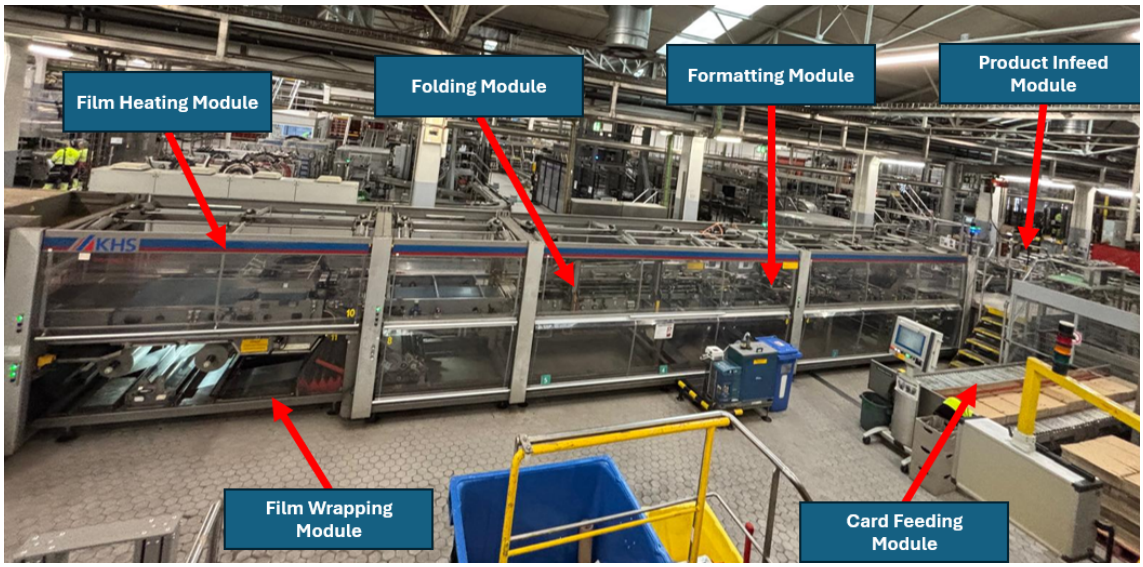


Figure 1.4: Kisters KHS modular division, Line 2

The selection of the Kisters cartoner, operating in Lines 1 and 2, as the primary case study of this project required an initial and comprehensive understanding of its architecture. This analysis encompassed the structural decomposition of the equipment into distinct modules, as well as the identification of their respective components and subassemblies. Simultaneously, daily malfunctions were monitored and discussed during maintenance briefings in order to analyze the various functional issues and their subsequent corrective interventions.

Regarding the logging of these events, the standard operating procedure dictates that the operations team must record machine downtime in the SmartPlant software. This system automatically generates a maintenance work order in SAP *software*, in which the anomaly observed during operation is manually described.

However, it became evident that the data provided by these operational logs was frequently scarce and overly abstract, rendering it inadequate for rigorous diagnostic purposes.

1.1.3.1 Impact on the Global Availability and Strategy Focus

The statistical evidence extracted from this analysis, complemented by Natural Language Processing techniques, correlates directly with the loss of Overall Equipment Effectiveness (OEE). The Availability (A), a key component of the OEE indicator, is measured through the operational availability estimator, defined as the ratio between the equipment uptime (T_{up}) and the total operational time ($T_{up} + T_{down}$). Equation 4.1) details the correlation between the different parameters [3]:

$$A = \frac{T_{up}}{T_{up} + T_{down}} \times 100 \tag{1.1}$$

While the theoretical availability can be derived from the intrinsic reliability (MTBF) and maintainability (MTTR) parameters, this operational estimator provides the precise performance measurement required for the OEE calculation. The graphical analysis demonstrates that the failures in the folding zone, such as incorrect format settings and damaged joints, directly reduce the T_{up} and increase the T_{down} components of this estimator. Figure 1.5 illustrates, for example, that damaged joints account for twelve percent of the total cumulative downtime, directly impacting the availability estimate.

Subsequently, the anomalies that most negatively impact total downtime include incorrect format adjustment during SKU changeover (thirteen percent), damaged joints (twelve percent), and broken plastic fingers (seven percent). The remaining events occur relatively frequently, however, for an immediate operational impact, resolving these individual critical failures would provide a significantly higher return over investment for the production department.

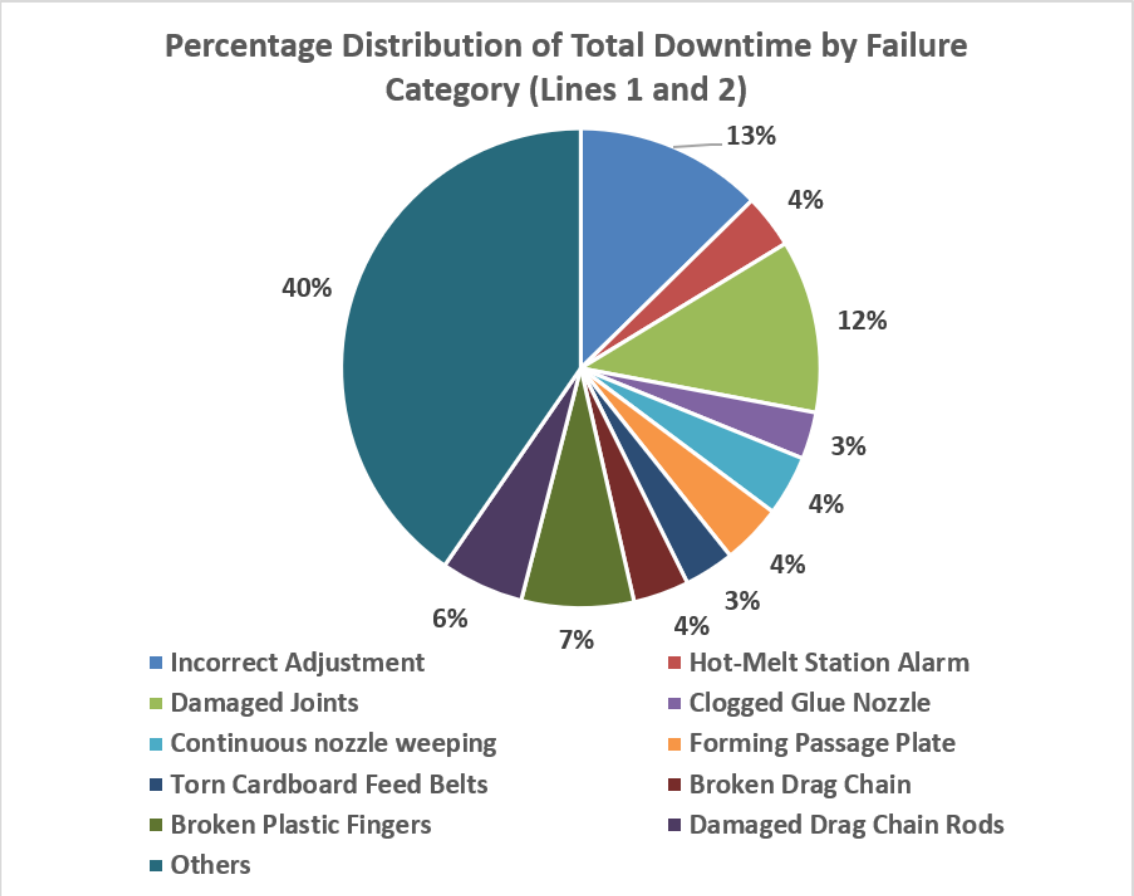


Figure 1.5: Distribution of Total Downtime by Failure Mode, Lines 1 and 2.

1.2 Problem Definition and Motivation

1.2.1 Operational Bottlenecks and OEE Impact

This dissertation addresses a tangible and urgent industrial challenge related to maximizing operational efficiency, with a specific focus on Production Lines 1 and 2. As illustrated in Figure 1.6, which shows the Year-to-Date OEE performance across the entire facility since the beginning of 2026, production Lines 1 and 2 currently (and historically) register the lowest performance indicators in the entire industrial complex. Consequently, there is an imperative need to significantly improve their benchmark performance through the implementation of robust long-term optimization strategies.

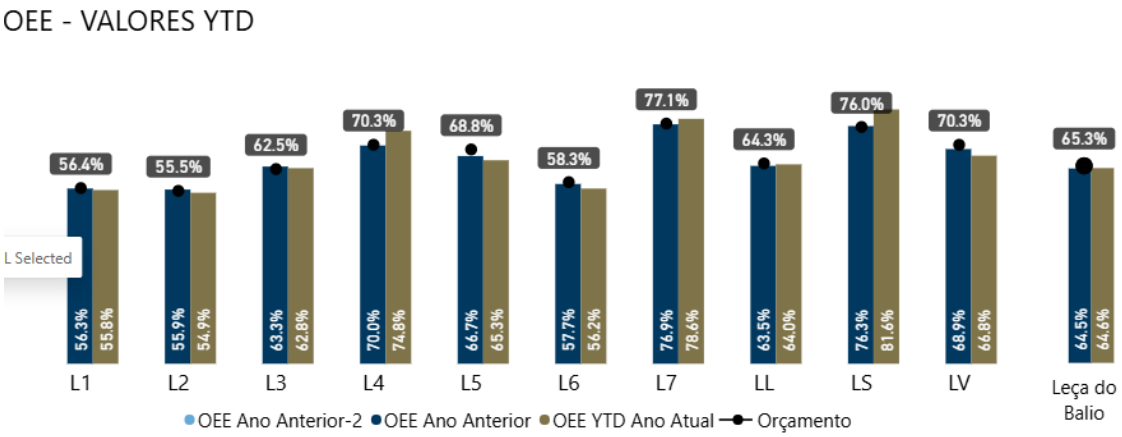


Figure 1.6: Different OEE performance (YTD) in Leça do Balio Super Bock factory

Therefore, the main objective of this dissertation is to identify, within the two lowest-performing production lines, the specific equipment that most negatively impacts the overall OEE. The analytical approach to be carried out serves to isolate the physical assets whose failures substantially compromise the efficiency of the installation. Based on data extracted from the Power BI production dashboard (see Figure 1.7), it is unequivocally established that, for Line 1, the Kisters case packer represents the critical bottleneck. Throughout this year, this specific machine has recorded both the highest volume of failure occurrences and the highest current failure rate.

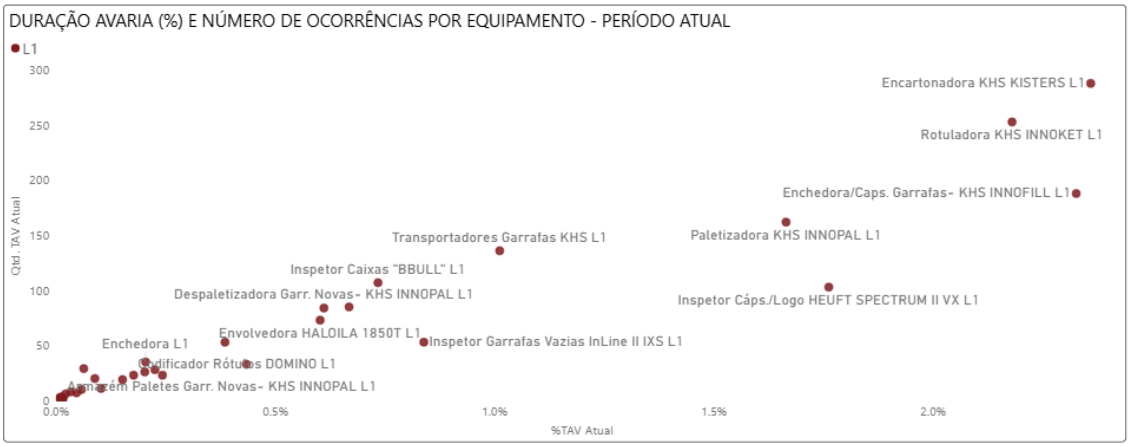


Figure 1.7: Equipment Failure Rate, Line 1

The same analytical methodology was extended to Line 2. As illustrated in Figure 1.8, the Power BI dashboard analysis was replicated to determine if the highlighted equipment exhibited similar critical failure rates on production line 2. Data evaluation reveals that both the Kisters labeling and case packing machines exhibit significantly high downtime metrics. This observation provides cross-sectional validation of the need to improve both Kisters equipments, consequently consolidating its selection as the primary focus for efficiency optimization on both production lines.

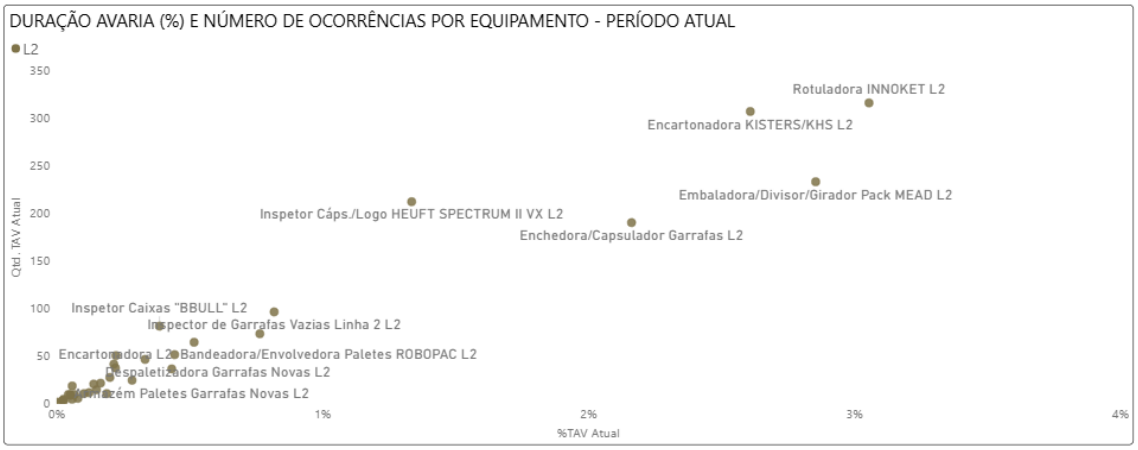


Figure 1.8: Equipment Failure Rate, Line 2

1.2.2 The Maintenance Paradigm Shift

One of the aspects highlighted as a possible initial area for improvement was the more frequent adoption of predictive and preventive measures. The Leça do Balio plant, belonging to the SuperBock Group, presented a high rate of emergency corrective actions, along with a remarkably low proportion of planned corrective and preventive maintenance. Ideally, a good parameter for the management of industrial assets dictates that eighty to ninety percent of all maintenance work orders should be dedicated to preventive maintenance, ten to twenty percent to planned corrective maintenance, and a maximum of five percent to emergency or reactive maintenance [4].

Observing Figure 1.9, the situation for the company's packaging lines under study over the last year (March 2025 to March 2026) is remarkably critical, given that preventive maintenance accounts for only sixteen percent falling severely short of the recommended eighty to ninety percent benchmark. Although planned corrective maintenance falls within an acceptable percentage range, unplanned emergency corrective actions, which should ideally represent no more than five percent, constitute seventy-six percent of the total number of failure work orders generated. These metrics reveal clear opportunities for optimization, encompassing both shop-floor practices regarding correct machine operation and the scheduling and auditing procedures managed by the maintenance planning department.

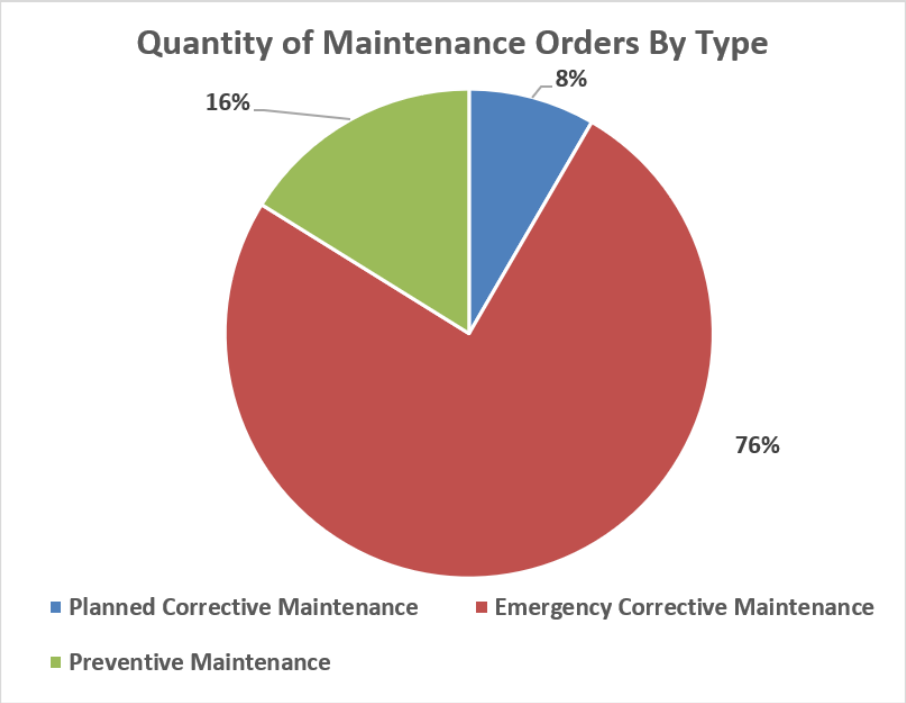


Figure 1.9: Distributions of Maintenance Orders by Type, Kisters (Line 1 and 2)

As will be analyzed later, the diagnostic assessment presented in Chapter 4 shows that the reactive culture currently ingrained at the Leça do Balio plant represents a critical bottleneck for operational efficiency. The reliance on legacy practices has led to several systemic issues, namely the lack of standardized troubleshooting methodologies, a heavy dependence on the tacit and empirical knowledge of mechanical and electrical technicians, the use of obsolete cleaning procedures, and a complete absence of autonomous maintenance. Consequently, minor mechanical anomalies force unnecessary machinery downtime, severely penalizing the production pace and the OEE.

To reverse this trend, this dissertation proposes a fundamental paradigm shift that involves transitioning from a reactive, symptom-treatment approach to proactive reliability engineering. This transformation is operationalized through a synergetic, three-tiered framework designed to stabilize the Kisters packaging lines:

1. **Digitalization and Knowledge Management:** To address the technical knowledge gap observed among maintenance team, especially among less experienced technicians, a centralized, interactive diagnostic platform was developed using *PowerApps*, ensuring accessibility via tablets and *RealWear* assisted reality glasses. Furthermore, weekly preventive maintenance and cleaning routines were systematically restructured to enhance operational efficiency. By leveraging updated, time-optimized Standard Operating Procedures mapped through multimedia content and integrated into the machines via QR codes, the execution time for SAP-registered maintenance tasks was compressed from a theoretical 12 hours and 20 minutes to

a controlled maximum of 5 hours. This optimization not only streamlines resource allocation but also ensures standardized, high-quality interventions across all shifts.

2. **Mechanical Re-engineering:** The elimination of recurrent failure root causes was achieved through mechanical redesign. This involved the implementation of stainless steel retention plates designed to protect critical mechanical joints and rollers from hot-melt adhesive contamination originating from the solenoid valve applicator nozzles. Furthermore, the transfer plate in the forming and folding zone underwent a tribological redesign using *SolidWorks* and in the future *Abaqus*, aiming to replace the currently degraded Teflon film with high-strength materials capable of withstanding severe abrasive wear caused by broken glass and organic sugar residues from the product flow.

3. **Lean Logistics and Autonomous Maintenance:** Empowering machine operators to autonomously resolve frequent, low-complexity anomalies was achieved through the deployment of the TPM methodology. This was operationalized by engineering physical proximity *Kanban* systems (Kanban 1 and 2), specifically designed to facilitate the rapid replacement of folding pads, transfer combs, and roller carriages. To ensure inventory availability and eliminate stockouts at the point of use, an IIoT proximity sensing system was prototyped, integrating 3D-printed housings, *KiCad* circuitry, and *Arduino IDE* firmware, which governs a visual LED traffic light status indicator. Finally, the replenishment logistics were optimized by establishing a rigorous *Kanban* card circulation loop, ensuring a continuous and disciplined material flow.

Ultimately, this paradigm shift transforms the maintenance department from a reactive cost center into a proactive, data-driven reliability unit, synergizing classical mechanical design with modern Industry 4.0 technologies.

The implementation of these improvement measures, supported by the active engagement of operators and maintenance technicians in the daily utilization of integrated digital tools, has demonstrably minimized time lost to immediate fault corrections. This approach has yielded significant gains, effectively reducing both the frequency of failure incidents and the mean time required for their resolution.

1.3 Objectives and Research Methodology

1.3.1 Research Objectives

The primary objective of this dissertation is to optimize the Overall Equipment Effectiveness (OEE) of the Kisters packaging lines at the Super Bock Group. To achieve this, the project focuses on two main axes of reliability enhancement:

1. **Proactive Reliability Engineering:** Promoting a minimization of equipment downtime with the support of mechanical redesign, thus mitigating the main root causes of failures and assisting in the implementation of autonomous maintenance.

2. **Digital Transformation:** Increasing asset availability through the integration of Industry 4.0 tools, involving all data-driven decision-making and efficient knowledge management.

1.3.2 Research Methodology

To achieve these objectives, all measures adopted an Action Research approach, guided by the PDCA cycle (Plan-Do-Check-Act), thus promoting guarantees of continuous improvement. The methodological approach is structured as follows:

- **Data-Driven Diagnosis:** Conducting a quantitative analysis of all maintenance records using Natural Language Processing, with the aim of identifying all critical bottlenecks.

- **Mechanical Re-engineering:** Promoting reliable analytical validation through Finite Element Analysis and CAD modeling ensured the permanent resolution of structural failures.

- **Digital Implementation:** Implementation of a connected ecosystem integrating SharePoint, PowerApps, and IoT software, ensuring proper standardization of maintenance routines and, consequently, a reduction in MTTR.

- **Operational Validation:** Longitudinal evaluation of reliability KPIs, with a special focus on the growth of MTBF, MTTR, and OEE indicators.

1.3.3 Thesis Outline

The dissertation is organized into eleven interrelated chapters, structured into three thematic blocks. The first block, Fundamentals and Diagnosis (Chapters 1–3), presents the industrial context, the theoretical state of the art to support the dissertation's content, and the initial diagnostic assessment based on data. Next, Engineering Interventions (Chapters 4–8) details both the development and implementation of different digital and mechanical solutions, including knowledge digitization and the redesign of critical components. Finally, Validation and Conclusion (Chapters 9–11) presents the final computational and operational validation of the different interventions performed during the internship, the final analysis of the results using reliability KPIs, and the final conclusions on the project's scalability and future improvements.

Chapter 2

Literature Review

This chapter provides the theoretical framework necessary to address the multidimensional challenges of maintenance reliability in high-cadence packaging environments, discussed later in subsequent chapters. The literature review is structured around three logical pillars that correspond to the development of the research. First, the different digital diagnostic and management strategies (NLP and TPM 4.0) were defined. Next, the technological interface for the connected worker is referenced. Finally, the different fundamentals of mechanics and materials science that govern the degradation of physical assets, namely the machine under study, are discussed.

The implemented structure illustrates that modern operational excellence depends on the detailed convergence of digital intelligence with the application of rigorous mechanical concepts.

2.1 Paradigm of Smart Manufacturing and Reliability Engineering

Currently, the industry is undergoing a phase of enormous transformation, driven by the principles of Industry 4.0.

This transition is fundamentally characterized by the merging, in an interconnected system, of traditional manufacturing operations and digital computer systems [5].In high-demand manufacturing sectors, such as the SuperBock group, strategies that were initially reactive and scheduled maintenance have been significantly directed towards improvement, in order to maximize the operational excellence of equipment. In fact, the changes that have occurred are inevitable, especially in the technological age in which we live, and promote an adaptation of existing traditional methods, using highly effective digital tools, to ensure the greatest possible equipment uptime, thus satisfying the demand required by the market[6]. These changes, as a whole, interconnect manufacturing and management, promoting a single common end goal: to ensure the maximization of OEE (Overall Equipment Effectiveness), minimization of financial impacts and unplanned downtime,

thus sustaining a long-term competitive advantage over competing brewing companies. The objective can also be achieved through the integration of advanced data analytics and sensors inherent to the different equipment which, connected in real time, provide hourly information on the overall operation of the production lines [7].

The transition to a proactive and predictive maintenance approach must be included in a multidisciplinary way, since modern industrial engineering must operate simultaneously with other areas [8]. In this way, it must integrate the following areas:

- Data science, with the aim of extracting and categorizing information from unstructured records.
- Implementation of technologies with direct influence and management by operators, right from the factory floor.
- Continuous improvements, with theoretical support, in complex 3D computational modeling of mechanical and material behaviors under dynamic operational stresses.

2.2 Natural Language Processing in Computerized Maintenance Management Systems

A fundamental pillar of modern reliability engineering is the transition toward data-driven decision-making. Historically, industrial facilities have accumulated vast repositories of historical failure and intervention data within Computerized Maintenance Management Systems , such as SAP PM or IBM Maximo [9]. However, the greatest inherent structural limitation in databases is their strong reliance on unstructured, free-text data entered manually by machine operators and maintenance technicians under the constraints of the factory floor [10].

The language used in these maintenance work orders generally deviates from the standard linguistic syntax imposed by the machine manufacturers. The information is usually full of technical jargon, incorrect abbreviations, local slang, spelling errors, and extremely brief descriptions of symptoms [11]. Consequently, for overall management and implementation improvements, extracting systematic failure frequencies, isolating equipment bottlenecks, and accurately calculating MTBF from these repositories represents a complex computational challenge. Therefore, traditional queries in relational databases and keyword searches are insufficient when attempting to interpret the nuanced context of a mechanical failure described in free text.

2.2.1 Text Preprocessing and Feature Extraction Methodologies

To bridge the critical gap between unstructured human writing and structured, easily analyzed writing, NLP combined with machine learning classification algorithms has gained significant prominence in recent literature [8, 12]. NLP applications enable the automated

analysis, tokenization, and vectorization of free-text records, converting qualitative human notes into quantitative mathematical matrices that can be processed by algorithmic classifiers [13].

The transformation of raw maintenance logs into machine-readable formats relies heavily on rigorous preprocessing pipelines:

1. **Initial Steps:** Normalization, stop-word removal, stemming, and lemmatization are universally applied to reduce the dimensionality of the text data and eliminate linguistic noise.

2. **Tokenization and Evaluation:** Following tokenization, the Term Frequency-Inverse Document Frequency statistic is predominantly utilized to evaluate the relative semantic importance of a specific term within a given work order, relative to the entire corpus of maintenance records [10].

The mathematical formulation of TF-IDF ensures that common, low-value words, such as "broken", "fixed" and "error" are mathematically penalized, whereas highly specific technical terms indicative of a localized failure, for example "solenoid", "servomotor", "actuator" and "hot-melt", are assigned higher computational weights [11]. Studies indicate that defining optimal n-gram boundaries, typically unigrams and bigrams, yields the highest predictive accuracy for maintenance classification, as trigrams often introduce excessive sparsity and noise into the vector space without adding proportional semantic value [14]. More recently, advanced frameworks have begun to leverage global vectors for word representation and Bidirectional Encoder Representations from Transformers to capture deeper semantic relationships and domain-specific context, substantially outperforming zero-shot models in complex industrial environments [12].

2.2.2 Machine Learning Classification Architectures

Since the text is mathematically vectorized, several supervised machine learning algorithms were used to taxonomically and hierarchically classify the records in a standardized way (e.g., Machine Module, Component, Failure Mode). The literature highlights several dominant algorithmic architectures in this domain:

Algorithm Classification	Characteristics and Application in CMMS Text Mining	Performance Metrics & Efficacy
Random Forest	An ensemble learning method constructing multiple decision trees via a bagging approach (random sampling with replacement). It excels at handling sparse matrices generated by TF-IDF, effectively mitigates overfitting, and provides high interpretability regarding feature importance [10].	Research demonstrates RF as highly effective for prioritizing task urgency and classifying failure modes, frequently achieving accuracy rates exceeding **80%** in industrial datasets [10].
Support Vector Machines	Frequently utilized for high-dimensional spaces, SVM algorithms attempt to find the optimal mathematical hyperplane separating different fault categories. They are particularly robust when applied to smaller, highly specific datasets where deep learning is unfeasible [14].	Studies report SVM achieving high F1-scores (up to **85%**) in categorizing mechanical and electrical anomalies in facility management and manufacturing [14].
Naïve Bayes	A probabilistic classifier based on applying Bayes' theorem with strong independence assumptions between features. While highly computationally efficient and fast to train, it is often overly simplistic.	Occasionally underperforms compared to RF and SVM when dealing with highly correlated mechanical failure terminologies, though useful as a baseline benchmarking model.
Deep Learning	Convolutional Neural Networks and Long Short-Term Memory networks are increasingly applied to capture sequential and temporal dependencies in text. Hybrid models (C-LSTM) have demonstrated state-of-the-art performance [13].	While capable of superior accuracy (often >**90%**), these architectures require massive, annotated datasets for adequate training and suffer from a "black box" lack of interpretability [8].

Empirical evaluations across the manufacturing sector reveal that combining traditional numerical sensor data with NLP-augmented datasets drastically improves predictive maintenance capabilities. For instance, models enriched with NLP features extracted from technician logs have demonstrated an accuracy increase to 97.3%, significantly outperforming traditional sensor-only prognostic models [9]. By automating the categorization of work orders, organizations can eliminate subjective reporting biases, calculate true operational reliability metrics with mathematical rigor, and direct engineering resources toward genuine root causes rather than symptoms.

While data-driven diagnostic tools identify where reliability is compromised, the organizational framework for executing these repairs is provided by Total Productive Maintenance, which is addressed in the following section.

2.3 The Evolution of Total Productive Maintenance (TPM 4.0)

While predictive algorithms and NLP isolate systemic failures mathematically, the physical execution of reliability engineering on the shop floor is historically governed by the principles of Total Productive Maintenance [7]. Formulated originally by the Japan Institute of Plant Maintenance in the 1970s, TPM is a holistic paradigm aimed at maximizing equipment effectiveness by involving all departments, from engineering to frontline operators, in the continuous pursuit of zero breakdowns, zero defects, and zero accidents.

The traditional TPM architecture is sustained by eight foundational pillars, namely Autonomous Maintenance, Planned Maintenance, and Focused Continuous Improvement [15]. Autonomous Maintenance represents a profound organizational paradigm shift wherein the traditional segregation of duties between the people responsible only for the operation and only for the reparation is abolished. Machine operators are empowered and trained to perform routine daily care, including cleaning, lubrication, tightening, and early abnormality detection. This localized, continuous vigilance prevents accelerated equipment deterioration and reallocates highly skilled maintenance technicians to complex, specialized interventions and reliability engineering tasks.

2.3.1 The Emergence of Cyber-Physical Systems and Digital Lean

The primary limitations of traditional TPM lie in its reliance on analog data collection, physical documentation, and human-dependent communication loops, which struggle to scale efficiently in highly complex, high-speed manufacturing environments. Consequently, current academic and industrial research is heavily focused on the intersection of TPM and Industry 4.0, a synthesis commonly referred to as TPM 4.0 or Digital Lean [6, 16].

This integration leverages IIoT sensors, edge computing, and Cyber-Physical Systems to digitize standard lean practices. For example, traditional Kanban systems, which regulate internal supply chains and spare parts inventory via physical cards passed between workstations, are inherently vulnerable to lost cards, human error, and delayed communication [17]. The evolution into electronic Kanban utilizes connected optical, ultrasonic, or RFID sensors to monitor inventory levels in real-time directly at the point of use. Upon reaching a critical predefined threshold, the cyber-physical system automatically triggers replenishment signals directly to the centralized factory general warehouse platform.

This entirely eliminates the administrative burden, search time, and motion waste previously placed on the production team, ensuring Just-In-Time material delivery [18].

Furthermore, a standardized framework for TPM 4.0 deployment emphasizes the necessity of a modular technological architecture and deep workforce integration [7]. Providing frontline operators with dynamic, digital Standard Operating Procedures via mobile devices or proximity-based QR codes ensures that the rigorous standards dictated by Quality Management are adhered to without the friction of consulting obsolete, damaged paper

manuals. This transition from reactive, paper-based management to a self-optimizing, data-driven manufacturing environment facilitates predictive quality management and drives the transformation toward zero-downtime production [6].

Effective TPM execution requires seamless information flow. As digital lean practices evolve, the human-machine interface becomes the critical bridge for operational efficiency on the shop floor.

2.4 Human-Machine Interfaces and Assisted Reality

The successful deployment of Digital Lean practices and TPM 4.0 necessitates highly efficient Human-Machine Interfaces capable of delivering real-time procedural data without imposing ergonomic constraints on the worker. In industrial environments characterized by heavy machinery, toxic chemicals, and strict Personal Protective Equipment mandates, traditional capacitive touchscreens (e.g., tablets and smartphones) present severe usability limitations. Operators wearing thick dielectric or cut-resistant gloves cannot effectively interact with screens, leading to operational friction, repeated interruptions of manual labor, and a general reluctance to utilize digital diagnostic tools [19].

To circumvent these biomechanical barriers, the literature increasingly advocates for the adoption of wearable technology, specifically smart glasses designed for industrial applications [20]. However, to understand the trajectory of this technology, it is critical to distinguish between the various paradigms of Extended Reality applied in industrial contexts:

- **Virtual Reality:** Completely immerses the user in a digitally simulated environment, obscuring the physical world entirely. While excellent for offline training, factory layout planning, and kinematic simulation, VR is fundamentally unsafe for active shop-floor maintenance due to the total loss of spatial awareness and occlusion of physical hazards [21].

- **Augmented Reality / Mixed Reality:** Overlays computer-generated 3D holograms onto the physical environment, allowing digital objects to interact with physical geometry (e.g., Microsoft HoloLens). While highly advanced, full Augmented Reality headsets can induce cognitive overload, visual fatigue, and motion sickness during prolonged shifts [22]. Furthermore, their delicate optical waveguides are often incompatible with the harsh sanitation processes and extreme temperatures found in process industries [23].

- **Assisted Reality (aR):** Represents the most pragmatic, rapidly adopted, and commercially viable technology for the frontline worker [24]. Assisted Reality does not attempt to map the 3D environment or project holograms over the user's direct line of sight. Instead, it projects a high-resolution 2D micro-display into the user's

peripheral vision, functioning essentially as a head-mounted, voice-activated tablet [25].

The primary advantage of industrial aR systems lies in their capacity for entirely hands-free operation via advanced Voice User Interfaces. Because industrial settings, such as bottling lines, frequently exceed 85 decibels of ambient acoustic pressure, these devices employ sophisticated active noise cancellation algorithms and multi-microphone arrays to isolate vocal commands from background mechanical interference.

By projecting digital troubleshooting trees, electrical schematics, and SOPs directly into the operator's peripheral vision, aR empowers technicians to maintain three points of contact on scaffolding, manipulate heavy tools safely, and log maintenance data in real-time [24]. The integration of aR with underlying CMMS platforms via APIs facilitates real-time remote expert calls (e.g., via Microsoft Teams), drastically compressing the Mean Time to Repair by eliminating the need to physically dispatch specialized engineers to the factory floor, all while ensuring stringent compliance with safety protocols [26].

Although digital interfaces streamline information access, the physical reliability of the machine depends on the underlying fluid dynamics and mechanical stability of specific components, which are analyzed next.

2.5 Cyber Resilience and Data Governance in Manufacturing

The migration from traditional methods to NLP-based environments and interconnected architectures provides agility to maintenance, but alters the organization's risk profile. This technological dependence introduces systemic vulnerabilities, where a failure in the digital layer can directly impact the physical performance of production [27]. The reliance on real-time data transmission and IoT sensor networks means that any disruption to the digital architecture directly translates into a cessation of physical production capabilities. Over the past decade, cyberattacks targeting Industrial Control Systems and Operational Technology have escalated dramatically. Threat actors increasingly exploit weak security configurations, unpatched PLCs, and internet-facing HMIs to initiate ransomware or data exfiltration campaigns, paralyzing critical infrastructure [28].

Data Governance and Cyber Resilience have therefore become inseparable from physical asset reliability [29]. When an industrial network is compromised, the inability to access engineering drawings, safety matrices, historical recovery protocols, and predictive algorithms exacerbates the duration of the outage exponentially. To mitigate these risks, organizations are shifting away from fragmented, localized storage, such as ad-hoc network drives or vulnerable local servers, toward unified, cloud-based data catalogs and enterprise document management systems like Microsoft SharePoint [27].

However, deploying platforms like SharePoint in an industrial context requires stringent architectural planning. The literature highlights the dangers of flattened permission structures, where any user can inadvertently overwrite, corrupt, or delete critical master files. To establish a resilient "Single Source of Truth", access must be strictly governed by Role-Based Access Control, ensuring that frontline operators possess read-only privileges while only authorized engineering and quality personnel can modify operational standards [29].

Furthermore, true cyber resilience mandates immutable audit logs to track document lineage, strict versioning control to comply with ISO 9001 quality audits, and offline, air-gapped disaster recovery backups to guarantee business continuity in the event of a catastrophic network breach [30]. A robust digital infrastructure ensures that the tribal knowledge extracted via NLP and digitized for aR displays remains secure, highly available, and immune to both malicious external actors and internal accidental deletion.

While robust digital infrastructure secures data governance, the physical reliability of the system remains contingent upon specific fluid-dynamic and mechanical phenomena, which are addressed in the following section.

2.6 Fluid Dynamics and Reliability of Hot-Melt Adhesive Systems

Moving from the digital architecture to the physical degradation of specific production assets, end-of-line packaging machinery frequently suffers from chronic mechanical stoppages originating from highly specialized secondary sub-systems. In wrap-around carton packers, the precision and reliability of the hot-melt adhesive dispensing system are paramount for operational continuity. Electro-pneumatic solenoid valves govern the extrusion of these high-viscosity thermal adhesives, applying precise micro-beads to securely seal the cardboard box flaps at high speeds.

A pervasive and financially debilitating failure mode identified across the packaging sector is the phenomenon of nozzle dripping, characterized by the uncontrolled, residual extrusion of molten adhesive during the closed-cycle phase of the machine [31]. The literature attributes this operational anomaly to several interconnected mechanical, thermal, and fluid-dynamic root causes:

- **Pneumatic Hysteresis and Solenoid Fatigue:** The rapid cycling of the pneumatic applicator head can lead to mechanical fatigue of the internal needle-piston return spring. Insufficient air pressure, typically dropping below the required 50 PSI threshold or clogged pneumatic mufflers prevent the piston from seating completely against the nozzle orifice, allowing pressurized residual fluid to escape [31].
- **Tribological Wear of Nozzle Tips:** The abrasive nature of certain adhesive formulations, combined with the cyclic kinetic impact of the needle-piston, gradually

deforms the internal geometry of the applicator nozzle. This micro-abrasion compromises the hermetic seal, resulting in continuous weeping [32].

- **Thermal Degradation and Oxidation:** Excessive operating temperatures induce the oxidation, charring, and gelling of the hot-melt adhesive within the main reservoir and heated delivery hoses. These carbonized particulates migrate to the applicator head, lodging between the piston and the nozzle seat, physically obstructing the mechanical closure mechanism [33].

The operational impact of adhesive dripping is severe. Due to the vertical orientation of many high-speed packaging machines, stray high-temperature adhesive droplets fall directly onto the underlying kinematic linkages and articulation rollers. Because hot-melt cools and solidifies rapidly upon contact with ambient-temperature steel, it forms an abrasive, rigid crust that acts as a locking agent. This seizes bearings, dramatically increases frictional resistance, and culminates in the catastrophic fracture of the mechanical joints [33].

Mitigating this chronic issue requires a dual-pronged engineering approach: optimizing the preventive maintenance schedule (e.g. regular flushing of inline filters, monitoring tank temperatures, and scheduled nozzle replacement) and implementing mechanical containment solutions [34]. The introduction of physical Poka-Yoke retention plates beneath the nozzles serves to intercept and pool errant drips before they can contaminate critical motion axes, thereby drastically extending the Mean Time Between Failures of the kinematic assemblies.

2.7 Computational Mechanics of Packaging Materials (Corrugated Cardboard)

In automated packaging lines, the kinematic reliability of the machinery is inextricably linked to the structural integrity and dimensional stability of the raw materials processed. Corrugated cardboard is the dominant material utilized for secondary packaging due to its high strength-to-weight ratio, cost-effectiveness, biodegradability, and excellent shock-absorbing characteristics. However, the complex micro-architecture of corrugated board that consists of a fluted undulating core sandwiched between two flat liners, results in highly non-linear, orthotropic mechanical behaviour [35].

2.7.1 Degradation Mechanisms: Moisture and Compressive Stress

The structural performance of corrugated cardboard is profoundly susceptible to environmental fluctuations and logistical handling variables. As a naturally hygroscopic cellulosic matrix, paperboard absorbs ambient moisture when subjected to environments with high relative humidity during transport or warehouse storage. This hydration process disrupts

the intermolecular hydrogen bonds within the cellulose fiber network, causing a drastic, non-linear reduction in the material's macroscopic Young's Modulus and overall flexural rigidity. The literature indicates a negative exponential relationship between the compression strength of a box and its moisture content, frequently leading to gravity-induced macroscopic warpage across the span of a pallet [36, 37].

Simultaneously, the material is highly vulnerable to localized plastic deformation induced by excessive tension from polymeric strapping tapes (PET or PP) applied by automated equipment at the supplier level. The highly concentrated radial contact pressure exerted by these tapes often xceeds the transverse compression strength of the cardboard[38].

This extreme localized pressure forces internal corrugation, which structurally acts as the stabilizing web of a beam undergoing

irreversible plastic buckling, effectively creating a structural hinge that collapses the board profile[39].

When these warped, moisture-degraded, or physically crushed blanks are fed into the high-speed gravity magazine of a packaging machine, they immediately consume the calibrated geometric clearances. This physical interference leads to severe sliding friction against the guide rails, servomotor torque overloads, missed synchronization pitches, and ultimately, catastrophic product damage and glass breakage inside the machine.

2.7.2 Finite Element Modeling and Numerical Homogenization

To quantitatively diagnose these structural failures, predict Edge Crush Test values, and establish rigorous, data-driven quality control thresholds, engineers rely heavily on the Finite Element Method, predominantly utilizing advanced commercial solvers such as ABAQUS [40]. However, modeling the exact 3D sinusoidal geometry of every individual flute across a large cardboard blank requires an exorbitant computational cost due to the millions of degrees of freedom and complex contact interactions involved.

To circumvent this computational bottleneck, contemporary computational mechanics heavily employs numerical and analytical homogenization techniques [35]. Homogenization translates the complex 3D sandwich structure into an equivalent, mechanically representative 2D orthotropic plate. By deriving an effective stiffness matrix that links the generalized strains to the resultant forces across a Representative Volumetric Element, the computational solver can accurately predict macroscopic behaviors, such as bending stiffness, transverse shear deformation, and localized buckling limits, at a fraction of the computational expense required for full 3D modeling [41].

Implementing this hygro-elasto-plastic continuum model in Abaqus typically involves the development of custom user material subroutines to accurately capture the anisotropic yielding, strain hardening, and post-buckling behavior of the cellulosic material under varying states of multi-axial compression and moisture content [42, 43]. This advanced computational framework empowers organizations to transition away from subjective, qualitative visual inspections of raw materials. Instead, they can establish objective, data-driven

supplier audits based on the precise mapping of Von Mises stress distributions, holding suppliers accountable for strapping damage through irrefutable mathematical evidence.

2.8 Tribological Dynamics and Wear Simulation in Kinematic Systems

In addition to processing raw materials for packaging, the internal mechanical components of industrial machines are subjected to relentless cyclic friction. In packaging lines, the bottle transfer plates between the folding/forming module are responsible for supporting the continuous, high-speed transit of glass bottles. The plates are particularly susceptible to abrasive wear and severe adhesive wear.

The transfer plates are often constructed of stainless steel (e.g., AISI 316L or 304L) coated with low-friction polymers such as polytetrafluoroethylene (PTFE/Teflon), or utilize solid ultra-high molecular weight polyethylene (UHMWPE) wear strips to minimize drag [44].

2.8.1 The Mechanics of Sliding Wear

The tribological interface between the hard silica matrix of glass bottles, the residual organic sugars from spilled beverages, and the polymer-coated steel plates creates an exceptionally aggressive wear environment [45]. The continuous sliding contact induces localized micro-ploughing, fatigue, and eventual delamination of the polymer layer. Once the low-friction polymeric coating is compromised, the exposed rough stainless steel substrate drastically increases the kinetic coefficient of friction. This sudden spike in drag leads to kinematic instability, bottle tipping, and subsequent glass breakage, which acts as a severe abrasive agent, accelerating the destruction of surrounding mechanical components.

To analytically quantify and predict this material loss over time, the fundamental formulation utilized in modern tribology is Archard's Wear Law [46]. As expressed in Equation 2.1, the volume of material removed (V) is directly proportional to the applied normal load (W) and the total sliding distance (L), and inversely proportional to the hardness of the softer material (H):

$$V = K \cdot \frac{W \cdot L}{H} \tag{2.1}$$

where K represents the dimensionless wear coefficient, a parameter determined empirically through pin-on-disk or reciprocating laboratory testing for specific material pairings (e.g., UHMWPE against stainless steel or glass) [47].

Extensive literature indicates that while UHMWPE exhibits excellent self-lubricating properties and forms a highly stable protective transfer film against smooth steel counterfaces, its wear rate accelerates exponentially if the surface roughness (Ra) of the steel

exceeds optimal microscopic thresholds, triggering severe abrasive cutting [48]. Furthermore, advanced wear models expand upon Archard's foundational equation by incorporating thermal degradation factors and the critical phenomenon of cross-shear. Cross-shear recognizes that multidirectional sliding paths disrupt the polymer's linear molecular orientation, drastically reducing its shear strength and exponentially increasing the volumetric wear rate [46, 49].

2.8.2 Finite Element Simulation of Wear via ABAQUS

Transitioning from analytical equations to full 3D predictive simulation allows engineers to map localized wear depth and contact pressure distributions over time, while accounting for complex geometries. The FEM software ABAQUS is widely recognized as the industry standard for simulating such complex, non-linear tribological interactions [50].

Simulating progressive wear is an inherently complex transient boundary-value problem, as the physical boundaries of the contacting bodies continuously erode, thereby altering both the geometric conformity and the distribution of contact stresses. To capture this phenomenon without initiating catastrophic mesh distortion, ABAQUS utilizes the UMESHMOTION user subroutine coupled with Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing techniques [51], as summarized in Table 2.1.

Table 2.1: Summary of simulation components and their functions within the ABAQUS wear modeling architecture.

Component	Function within ABAQUS Wear Modeling Architecture
Archard's Law	Encoded via FORTRAN in the UMESHMOTION subroutine; calculates material loss at each boundary node based on contact pressure and sliding slip [50].
UMESHMOTION	Translates boundary nodes on the "slave" surface (e.g., UHMWPE plate) inward, perpendicular to the contact plane, mirroring the calculated eroded volume.
ALE Meshing	Relocates internal nodes independently of material flow to preserve optimal element aspect ratios and prevent mesh distortion [51].
Extrapolation	Applies acceleration factors to the wear increment per cycle, enabling the prediction of months of physical degradation in an expedited timeframe [52].

By deploying this advanced computational methodology, the engineering team can virtually prototype varying structural profiles and alternative high-performance polymers, such as highly cross-linked UHMWPE or PEEK, before committing to costly physical machining. Furthermore, the extraction of 3D Wear Depth Maps facilitates the precise prediction of functional failure timelines, allowing the organization to schedule preventive replacements far in advance of sudden, catastrophic machine jamming [50].

2.9 Synthesis: Integrating Digital and Mechanical Reliability

The literature review reveals that packaging line reliability should be achieved, among other things, through a multidisciplinary integration of three distinct engineering domains:

1. **Diagnostic Intelligence (NLP):** Ensures the ability to transform unstructured historical records into a structured taxonomy, which is the main prerequisite for an initial identification of where the main equipment reliability loss occurs [10].
2. **Operational Management (TPM 4.0/aR):** The strategic combination of TPM philosophies and augmented reality interfaces promotes the guarantee of how to change negative operational trends, making knowledge outsourced and accessible to the connected worker [7, 24].
3. **Physical Optimization (Tribology/FEM):** Computational mechanics, through FEM software and wear simulation, ensures responses to effective equipment problems, and the durability of the kinematic interface material under extreme operating conditions [35, 50].

This dissertation interconnects all the detailed domains, applying NLP-based diagnostics to guide mechanical reengineering and the implementation of digitized SOPs. By combining the different theoretical pillars, a scalable structure is created that transforms the maintenance paradigm, from reactive response to proactive, data-driven asset management.

Chapter 3

Research Methodology

To carry out this project, the Action Research methodology was adopted. The model is distinguished by its iterative nature, where the combination of initial research and final action allows addressing and solving the different practical problems that occur in a real context. The methodology allowed for the analysis of the identified challenges, direct intervention with a view to driving fundamental transformations, and ensuring their immediate implementation.

The methodology is based, in its entirety, on the Kaizen philosophy, with a central focus on continuous improvement. In other words, instead of seeking isolated solutions, the focus is on the continuous optimization of processes, ensuring a comprehensive approach to detected inefficiencies and thus promoting maximum process quality. From this perspective, Kaizen served as the initial engine of change, driving small daily adjustments that, cumulatively, produced highly beneficial results for the company.

To implement this methodology in a structured and rigorous manner, the PDCA cycle (Plan-Do-Check-Act) was used as a standard framework to guide the entire project:

- **Plan:** The initial phase involved a rigorous diagnosis to define the strategic objectives and quantitative success indicators of the measures to be implemented, establishing a detailed plan to fill the identified gaps.
- **Do:** This stage involved implementing the planned actions, thus ensuring that the execution of the measures is accompanied by organized documentation of all phases and challenges encountered.
- **Check:** Subsequently, the results obtained were monitored and compared with historically existing performance, taking into account the established goals. This step is crucial for data analysis, validating whether the actions produced the desired effect.
- **Act:** Finally, based on the final data and evidence collected, the improvements that proved to be most effective were implemented, thus putting the theoretical ideas into practice.

Whenever deviations were detected, the cycle restarted, ensuring that the improvement process never stagnated. The combination of Action Research and the PDCA cycle thus allowed the complexity of each problem to be transformed into a controllable improvement process. The result was the implementation of an organized work method that prioritizes agility, learning and continuous improvement, and operational excellence at each stage of the intervention.

3.1 Strategy for Autonomous Maintenance

To implement this operational improvement cycle, the methodology integrated the TPM philosophy. Specifically, the Autonomous Maintenance pillar was adopted, restructuring the traditional segregation of duties that exists between operators and maintenance technicians. Autonomous maintenance was implemented through a structured knowledge transfer process based on the SECI model, with the goal of transforming the empirical and technical experience of senior technicians into explicit and auditable Standard Operating Procedures available to operators.

3.1.1 Analytical Transition and Methodological Foundation: From the Reactive Paradigm to TPM Philosophy

The evolution of current manufacturing systems demands a paradigm shift in the management of physical equipment, particularly regarding its reliability. As will be demonstrated by the quantitative modeling and NLP workflows detailed in Chapter 3.2, the mechanical bottlenecks of the Kisters case-packing machine are not strictly limited to the frequency of failures. On the contrary, they are amplified by a high MTTR.

Previous data analysis revealed that there are specific failures that are responsible for a very significant percentage of total equipment downtime, such as fracture of the plastic tabs of the joints, accelerated degradation of the roller carriages, and abrasive wear of the transfer combs. This is precisely one of the causes that affects and continuously reduces OEE.

To mitigate this problem, a problem-solving methodology was adopted using the PDCA Cycle. The data screening and subsequent formulation of the Criticality Matrix (detailed in Chapter 4) constituted the *Plan* phase, in which the main root causes of the longest equipment downtime were successfully isolated.

Although this chapter describes the methodological structure, the following chapters will detail the Execution (*Do*) phase, describing the conceptual beginning of the project, its technical development, and the practical implementation of the designed ideas. This transition aims to prepare the operational infrastructure for the Verification *(Check)* of the new cycle times and the Standardization *(Act)* of work practices.

Considering the established diagnosis, the strategy focused primarily on transitioning from a reactive maintenance model to the implementation of Autonomous Maintenance. Autonomous Maintenance is one of the eight fundamental pillars of the TPM methodology.

Line operators, due to their symmetrical position and continuous contact with equipment, are ideally positioned to take on daily routines of inspection, cleaning, lubrication, and low-complexity repairs.

This principle is thus intrinsically aligned with the Kaizen philosophy, which advocates continuous improvement through small, standardized daily adjustments.

The intelligent delegation of these skills provides a double benefit. In practice, it encourages a sense of responsibility and technical mastery among operators regarding their position in the company and their work.

On the other hand, it frees up valuable human resources within the specialized maintenance team.

Simultaneously, the elimination of duties from the specialized maintenance team allows maintenance technicians to be reallocated to more complex analytical interventions, the development of maintenance routines based on equipment condition, and activities related to reliability engineering, namely improvements to be implemented in the equipment.

During the annual overhaul shutdowns of lines L1 and L2 (which took place in February and March 2026), it was observed that the operators possess the mechanical dexterity and cognitive aptitude necessary to perform tasks of medium complexity, provided they are properly oriented a priori. However, the formalization of this responsibility was hampered by three systemic constraints:

- **Lack of standardized and accessible knowledge:** Knowledge of procedures for optimal equipment repair is implicit in the minds of even the most experienced maintenance technicians. This prevents the exact and widespread replication of this knowledge without errors.
- **Unavailability of resources at the point of use:** The absence of intervention tools and spare parts at the exact location of the equipment failure causes downtime in transport, where the operator waits for the arrival of an external resource equipped with the appropriate material.
- **Organizational Resistance:** The workshop floor constitutes a complex system where operators typically resist taking responsibility for equipment failures for fear of being penalized for operational errors. Thus, maintenance teams express concerns about a potential loss of technical autonomy for this reason.

3.1.2 Strategic Knowledge Management: Standard Operating Procedures

To effectively empower line operators and overcome the identified technical deficiency, it became essential to allocate the vast undocumented empirical experience into rigorous, auditable, and standardized work instructions. Through the perspective of Systems Engineering and Knowledge Management, this challenge was addressed by the practical application of the SECI Model.

The methodological core resided in the vector of "Externalization": the arduous process of converting technical knowledge into explicit knowledge (manuals, diagrams, and formally documented procedures).

The primary data collection for this outsourcing was supported by technical observation sessions, namely the non-intrusive daily monitoring of the maintenance technicians' operating model.

Over several days, two senior mechanical maintenance technicians were observed troubleshooting the Kisters machine, essentially on lines 1 and 2. Each intervention was dissected into its steps, mapping each one and photographically recording the process to ensure visual and temporal tracking of the operations. This thorough analysis allowed for the identification and elimination of redundant operations that did not add value to the repair process.

The compilation of this data culminated in the development of Standard Operating Procedures. The design of these documents was influenced by the principles of Visual Management, since Visual Management acts as a cognitive facilitator. Thus, dense blocks of text were replaced by infographics, color-coded markings (for example, yellow boxes delimiting the area of action, red arrows indicating the axes of rotation) and flowcharts, making the operator's cognitive load drastically lower. Visual standardization ensured that procedures are interpreted without ambiguity, thus mitigating linguistic anomalies and ensuring that execution is carried out correctly, even under the time constraints inherent in a failure during production (see Appendix A.1, A.2, and A.3).

The created documents also integrate critical occupational health and safety information, as well as photographic mapping of the exact tools to be used in the technical intervention, namely a combination wrench with a 13 mm ratchet. In a subsequent methodological validation phase, the procedures underwent a peer review process involving shift supervisors and the maintenance engineering department.

Finally, to ensure strict compliance with the ISO 9001 standard applicable to document management and to strengthen the company's data infrastructure against cybersecurity threats (mitigating the vulnerabilities exposed in the 2023 cyberattack), the revised procedures were integrated, monitored, and secured on the SharePoint business platform. Therefore, after the approval and formalization of these documents, the methodology

determined that the SOPs should be physically allocated to the Kisters machine (Figure 5.15). This ensures that, in the event of a temporary lack of an operational electronic device or issues accessing the QR Code, operators can still seamlessly carry out the required tasks.

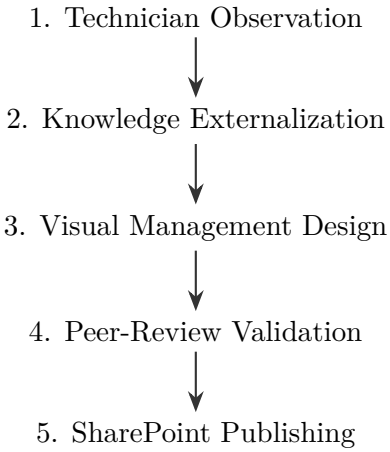


Figure 3.1: Methodological workflow for the creation and standardization of SOPs.

The systematic development and formalization of these procedures, structured through the methodological workflow illustrated in Figure 3.1, ensure a robust information pipeline that bridges the gap between technical knowledge and standardized operational execution.

3.2 Data Mining and NLP Pipeline

The inherent lack of standardization in SAP maintenance records makes traditional keyword-based analysis virtually impossible. To transform these raw, unstructured inputs into actionable reliability insights, a data-driven approach was needed. Consequently, a Natural Language Processing framework was developed to automate the classification of failure modes. This methodology allows the conversion of technician reports into a structured dataset, providing the empirical basis for the mechanical and digital improvements described in subsequent chapters.

The development of this machine learning framework was structured across sequential phases. First, a static database comprising approximately 700 maintenance work orders was consolidated to serve as the human-labeled training set. To streamline the training process and reduce the statistical complexity of a dual-classification task, the classification columns were combined into a single, joint categorical variable (e.g., “Folding - Pusher”). In the subsequent stage, text vectorization was implemented using the TF-IDF technique. Since computational models operate solely on mathematical structures, the textual descriptions were converted into numerical matrices, applying a weighting scheme that de-emphasizes generic words such as “failure” or “machine” in favor of highly specific technical terms, such as “pusher” or “chain”.

In the third phase, these numerical vectors were fed into a supervised *Random Forest* classifier. This model generates an ensemble of decision trees, cross-referencing variables to learn and memorize the key terms governing the correct categorization. Finally, in the production phase, whenever a new spreadsheet containing unclassified failure logs is submitted, the program applies the assimilated rules to predict the correct categories, automatically exporting a structured, query-ready Excel file. The seamless execution of the code within the *Google Colab* environment relies on two strict operational premises, namely the presence of the static training file, named "*Linha12_com_tempo_intervencao_teste*", and the submission of a production file containing exclusively the raw free-text fields extracted from SAP. The sequential logic of this Machine Learning Framework is illustrated in Figure 3.2.

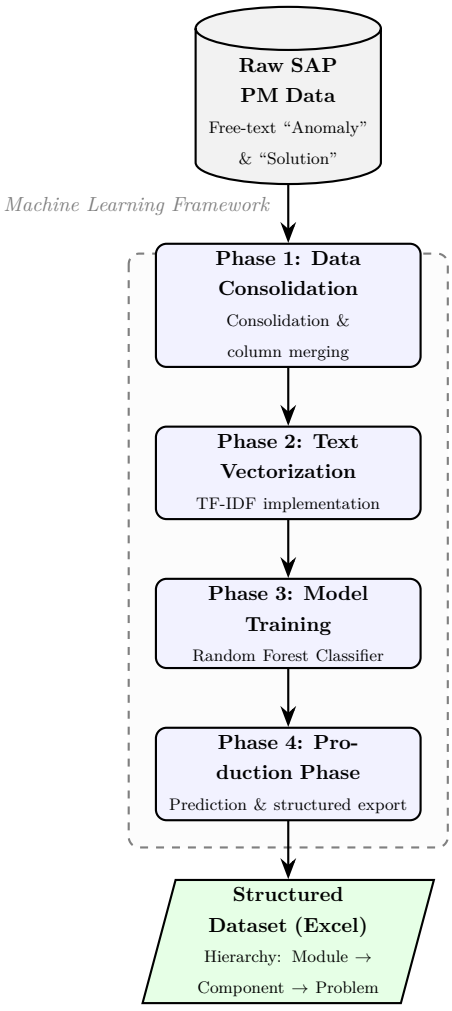


Figure 3.2: Sequential workflow of the Natural Language Processing (NLP) framework.

As shown in Figure 3.2, the transition from raw, unstructured SAP data to a structured hierarchical output (Module → Component → Problem) is achieved through a multi-stage pipeline, ensuring that all interventions are taxonomically categorized for subsequent

reliability analysis.

Despite its demonstrated efficacy, the algorithm presents inherent architectural limitations that must be acknowledged. Because it relies on a standard statistical TF-IDF model, any typographical errors or misspellings introduced by the operators are treated as entirely unknown mathematical entities, which can compromise predictive accuracy. Furthermore, as the training horizon is relatively circumscribed, rare or sporadic failure modes may not be represented within the learning matrix, hindering the model's predictive capability during atypical events. To mitigate these constraints as a prospective future development, it is recommended to parameterize the *SmartPlant* software using predefined keyword dropdown menus, thereby securing data integrity at the source. The *Google Colab* interface and the developed source code are illustrated in Figure 3.3 and Appendix B.1, respectively.

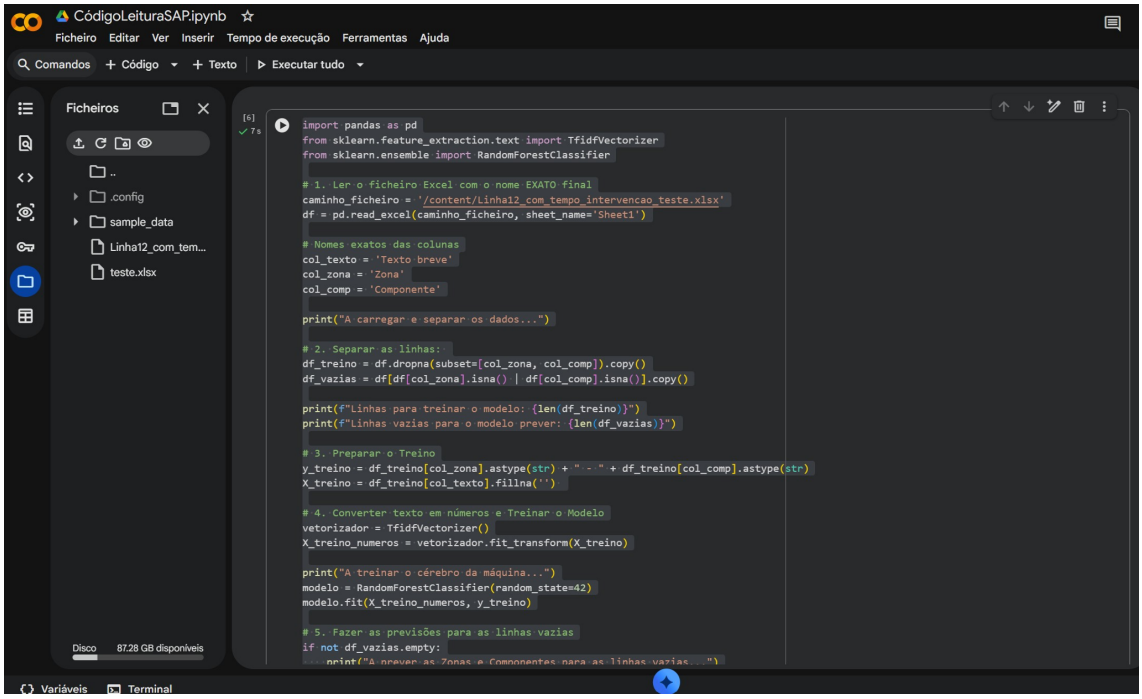


Figure 3.3: Computational Implementation for SAP Data Processing Using Google Colab

In summary, the implementation of autonomous maintenance routines, supported by standardized SOPs and IIoT-enabled Kanban systems, effectively decentralized reliability tasks. This shift, underpinned by a rigorous NLP-based data treatment, establishes the methodological groundwork necessary to mitigate the chronic unavailability of the Kisters assets in the following execution phases.

Chapter 4

Critical Assessment of the SAP PM Ecosystem

4.1 Critical Assessment of the SAP PM Ecosystem

4.1.1 The Free-Text Challenge in Industrial Maintenance

The initial proposal developed by the Super Bock Group focused on maximizing the operational efficiency of Lines 1 and 2, specifically targeting the Kisters cartoner manufactured by the German company KHS. To establish a baseline justifying the selection of these specific production lines and equipment based on failure rates, it was essential to identify and extract the most relevant data. Initially, data from maintenance requests logged directly by machine operators was gathered. This process begins with the operator opening a maintenance notification via the SmartPlant platform, where the observed anomaly is manually described on a tablet, concluding with the recording of the respective timestamps. Subsequently, the maintenance technician assigned to the workshop reviews these open orders to provide a more comprehensive and technically detailed description of both the identified root causes and the corrective solutions implemented upon intervention on the shop floor.

This information is subsequently stored in the SAP PM software (Plant Maintenance), where work orders are classified by anomaly/solution, creation and closure dates, respective production line, intervention time, and order type. The intervention time encompasses the duration from the initiation of the work order to the technical completion of the tasks. Meanwhile, the order type is categorized into ZPM1 (Planned Corrective Maintenance), ZPM2 (Emergency/Unplanned Corrective Maintenance), and ZPM3 (Preventive Maintenance).

Given the high volume of extracted data during the initial phase, comprising approximately 700 work orders generated between November 1, 2024, and February 25, 2026, it was imperative to structure the dataset in accordance with the company's strategic optimization goals.

As a starting point for the re-engineering of methodologies aimed at continuous improvement, a temporal analysis of the failure frequency derived from operator-logged notifications was conducted, segmented bimonthly over the investigated timeframe (Figure 4.1). By plotting these data points and fitting a logarithmic trendline, a consistently increasing failure trend becomes evident from the beginning of the study period. This analytical insight indicates that the existing mitigation and control measures implemented on the Kisters cartoner for Lines 1 and 2 lack statistical and operational efficacy, thereby demanding a fundamental re-evaluation of the current maintenance strategies.

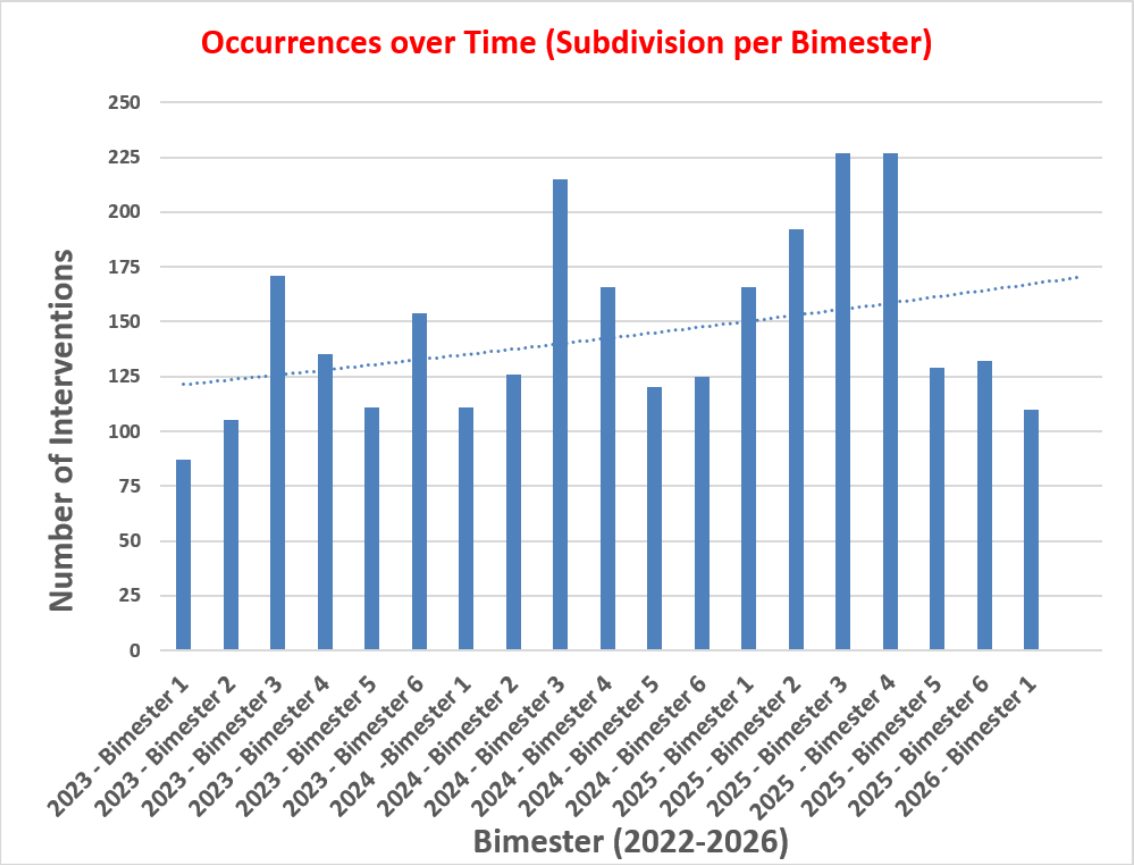


Figure 4.1: Number of Interventions by Bimester (2022-2026), Line 1 and 2 (Kisters)

To understand the distribution of the generated work orders, the different order types were quantitatively aggregated, and a comparative percentage pie chart was developed to illustrate the breakdown across the various maintenance categories.

A healthy benchmark in industrial asset management dictates that 80% to 90% of all maintenance work orders should be dedicated to preventive maintenance, leaving 10% to 20% for planned corrective maintenance, and a maximum threshold of 5% for emergency corrective actions [4].

Observing Figure 1.9, the company's operational baseline for the production lines under study is remarkably critical, given that preventive maintenance accounts for a mere

16%, falling severely short of the recommended literature guidelines. Although planned corrective maintenance falls within an acceptable percentage range, unplanned emergency corrective maintenance, which should ideally represent a marginal fraction of 5%, constitutes an expressive 76% of the total volume of generated failure work orders. These metrics reveal clear opportunities for systemic optimization, encompassing both shop-floor practices regarding proper machine operation and the scheduling and auditing procedures managed by the maintenance planning department.

To re-align and focus the primary objectives of this study in light of the diagnosed scenario, the analytical scope was exclusively restricted to ZPM2 (Emergency Corrective Maintenance) work orders, with the purpose of rigorously evaluating the efficacy and impact of critical failure resolutions on the production line. To achieve this, a systematic extraction of work orders was conducted, mapping their respective failure modes and implemented solutions. This data collection was further complemented by an exhaustive review of instruction manuals for the machine and its multiple components.

Additionally, regular briefings were held with the plant's maintenance technicians to decipher the asset's detailed kinematic behavior and capture the failure analysis methodologies and practical solutions consolidated through the empirical experience accumulated by these professionals over their years of service.

In its initial development stage, structurally decomposing the equipment into distinct modules, components, and mechanical subassemblies was considered a priority. However, the analysis revealed that the raw data extracted from the SAP PM module, primarily originating from operator logs, lacked the technical granularity required for a rigorous engineering diagnosis. The extraction of these operational and reliability datasets highlighted a profound structural challenge: the critical dependence on free-text fields for describing anomalies and subsequent corrective actions. As illustrated in Table 4.1, the original records entered into the SAP PM ecosystem exhibit a severe lack of standardization, a taxonomic deficiency that extends even to the descriptive nomenclature of the factory assets.

Given this limitation, the analytical approach was readjusted to center the study's focus exclusively on the anomalies reported by maintenance technicians. This decision was grounded in the fact that technical logs offer a significantly higher level of depth and rigor, both in the characterization of the failure mode and in the detailed description of the corrective action implemented.

To overcome the barriers imposed by the lack of standardization in the raw records, a Natural Language Processing pipeline was developed, as detailed in the research methodology (Chapter 3). The primary objective of this computational tool is to interpret the unstructured technical language found within the SAP PM 'Anomaly' and 'Solution' fields, applying supervised machine learning to reclassify each intervention into a standardized three-level hierarchy: Machine Zone, Component, and Failure Mode.

Table 4.1: Representative sample of raw maintenance records extracted from SAP PM.

Line	**Equipment**	**Anomaly (Original Record)**	**Solution (Original Record)**
Line 1	KISTERS/KHS Carton Packer	Broken articulation finger, operator side	Replacement of 2 broken plastic fingers on the left side
Line 2	KHS KISTERS Carton Packer	Lubrication system error	Low grease reservoir level, refill required, error cleared
Line 2	KHS KISTERS Carton Packer	DP station fault.	Fault reset
Line 1	KISTERS/KHS Carton Packer	Film glue nozzle leaving too much film on the roll during changeover	Film roll end adjustment
Line 2	KHS KISTERS Carton Packer	2 broken plastic fingers	Replacement of broken fingers
Line 2	KHS KISTERS Carton Packer	Broken or dislocated articulation.	Repositioned articulation

This transition from subjective, free-text inputs to a structured taxonomy ensures that subsequent reliability analyses are based on rigorous, quantifiable data rather than anecdotal descriptions. By identifying specific keywords and leveraging semantic cross-referencing between the reported symptoms and the subsequent corrective actions executed, the algorithm successfully harmonizes disparate logs into structured, quantifiable categories.

As demonstrated by the sample presented in Table 4.2, the algorithm exhibits significant robustness when handling taxonomic ambiguities and initial diagnostic errors. A prime example is illustrated in the third row of the dataset, where the anomaly originally logged by the operator reported a "Broken joint", whereas the corrective action executed confirmed the "replacement of the plastic finger". By cross-referencing both variables, the system successfully mitigated human entry errors and accurately categorized the event under the "Plastic Fingers" component.

To highlight where resource allocation and engineering efforts should be prioritized, the equipment modules were characterized based on total downtime, mean downtime, and the number of mechanical interventions. This statistical analysis was supported by programmatic data extraction from a database spanning from the end of the second semester of 2024 to the first quarter of 2026. From a macroscopic perspective, the folding zone acts as the asset's primary bottleneck, representing approximately 68% of the total cumulative downtime, followed sequentially by the forming, blank feeding, and product infeed zones (Figure 4.3). On an aggregate level, the mean downtime per failure event stands at 105 minutes.

Table 4.2: Example of the hierarchical classification generated by the NLP algorithm from the raw text records.

Anomaly (Original Record)	**Solution (Original Record)**	**Module**	**Component**	**Problem (Standard)**
broken joint finger, operator side	Replacement of 2 broken plastic fingers on the left side	Folding	Plastic Fingers	Broken Plastic Fingers
glue dots adjustments	Initially, we were called by operations to rectify the glue dots...	Folding	Hot-Melt Device	Hot-Melt Device Problems
Broken joint	replacement of the broken plastic finger	Folding	Plastic Fingers	Broken Plastic Fingers
Cardboard magazine plate does not advance.	Adjustment of the cardboard magazine side guide	Folding	Separation Chain	Guide Rails Adjustment - Transport Chains

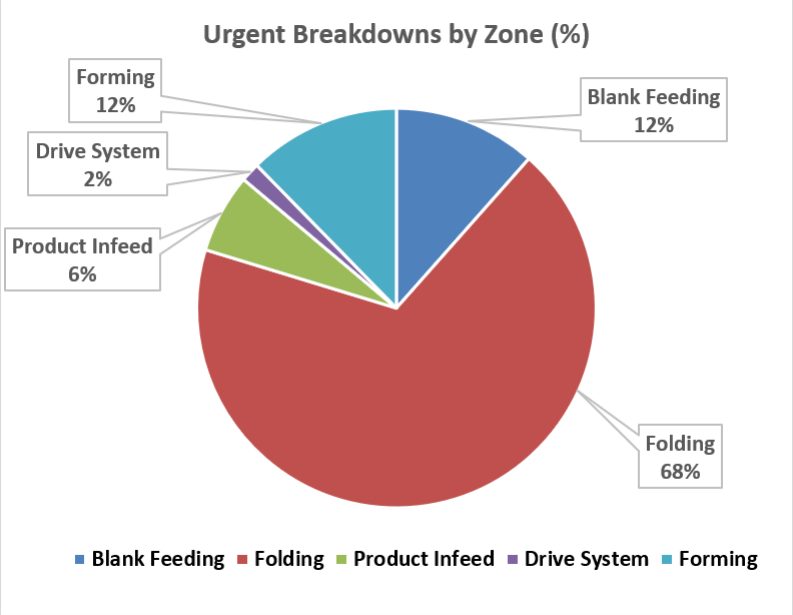


Figure 4.2: Number of Urgent breakdowns per zone (%), Line 1 and 2 (Kisters)

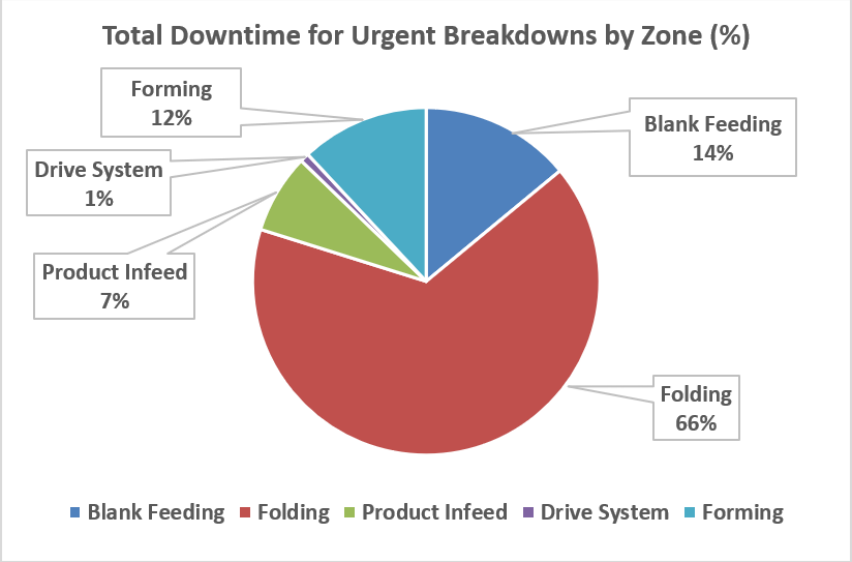


Figure 4.3: Total time for urgent breakdowns per zone (%), Line 1 and 2 (Kisters).

The analysis leveraging NLP models was expanded to the individual components of each module to determine their specific impact on overall failure rates. Utilising the same dataset and timeframe from the modular assessment, it was concluded that the folding lugs constitute the primary mechanical bottleneck, accounting for 55% of the total cumulative downtime. This critical vector is followed sequentially by the *Hot-Melt* glue application heads, servo drives, the separation system, and the blank transfer conveyors.

The operational availability (A) is analytically quantified through the following estimator, defined as the ratio between the equipment uptime (T_{up}) and the total operational time ($T_{up} + T_{down}$) (Equation 4.1):

$$A = \frac{T_{up}}{T_{up} + T_{down}} \times 100 \tag{4.1}$$

Additionally, the total downtime (T_{down}) is calculated based on the frequency and duration of breakdown events (Equation 4.2):

$$T_{down} = MTTR \times N \tag{4.2}$$

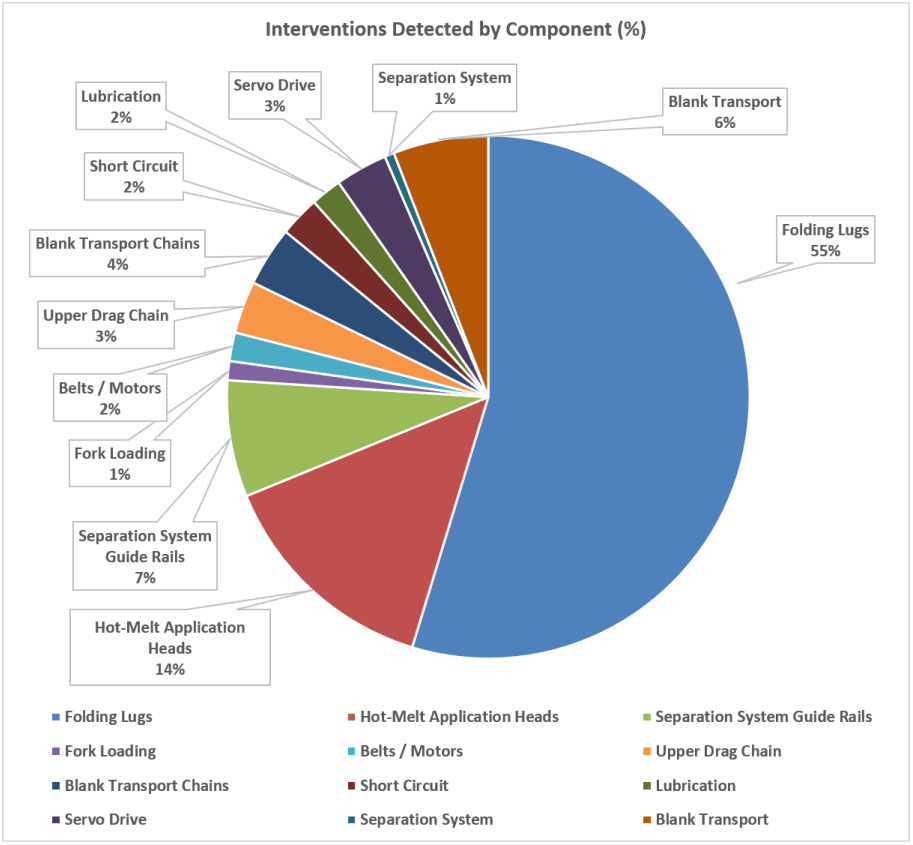


Figure 4.4: Total Number Breakdowns per zone (%), Line 1 and 2 (Kisters)

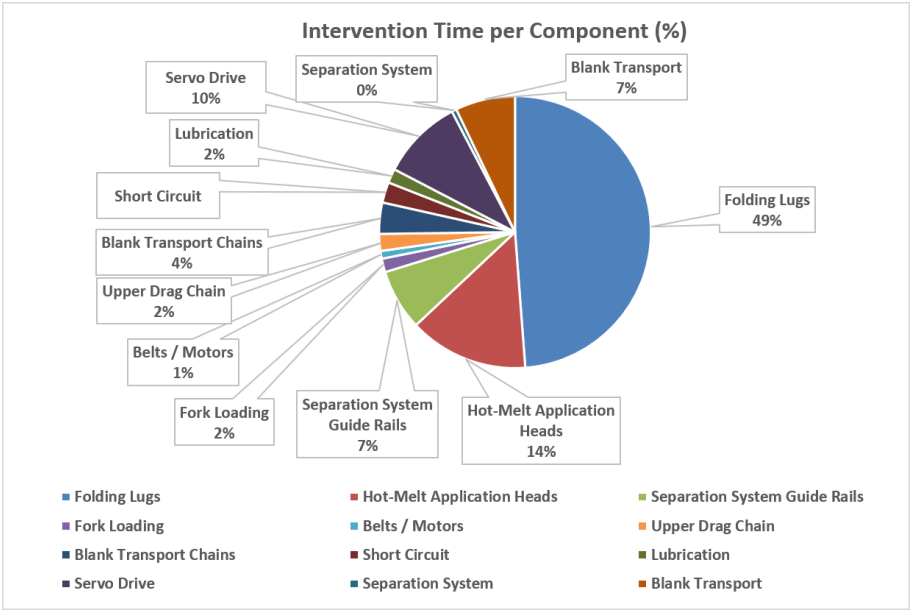


Figure 4.5: Total Component Failure Time (%), Line 1 and 2 (Kisters)

At the company's request, and to establish an effective maintenance strategy, it became imperative to isolate specific failure modes with a high level of granularity, enabling a

concise and highly visual classification of the problems to be targeted. Under this more rigorous analytical approach, the time horizon of the study was restricted to the period between November 2025 and May 2026. This sampling window was strategically selected to balance analytical depth with a manageable yet statistically representative dataset volume.

Initially, a Pareto Chart was constructed to map the distribution and absolute frequency of maintenance interventions across the various equipment components. However, while the Pareto analysis successfully demonstrates the correlation between work order volume and specific mechanical degradations, relying exclusively on failure frequency provides a one-dimensional and incomplete overview of the events that most severely penalize the asset's operation. Consequently, to achieve a comprehensive assessment of real operational criticality, it is imperative to cross-reference the frequency of each malfunction with its respective temporal severity. This correlation is mathematically expressed by the MTTR.

This dual-axis evaluation is embedded within the Scatter Plot presented in Figure 4.6. By cross-referencing the mean time to repair against the cumulative number of occurrences, this criticality matrix segments the different failure modes into distinct operational domains:

- Chronic Breakdowns (High Frequency / Low MTTR);
- Severe Failures (Low Frequency / High MTTR));
- Critical Breakdowns (High Frequency / High MTTR).

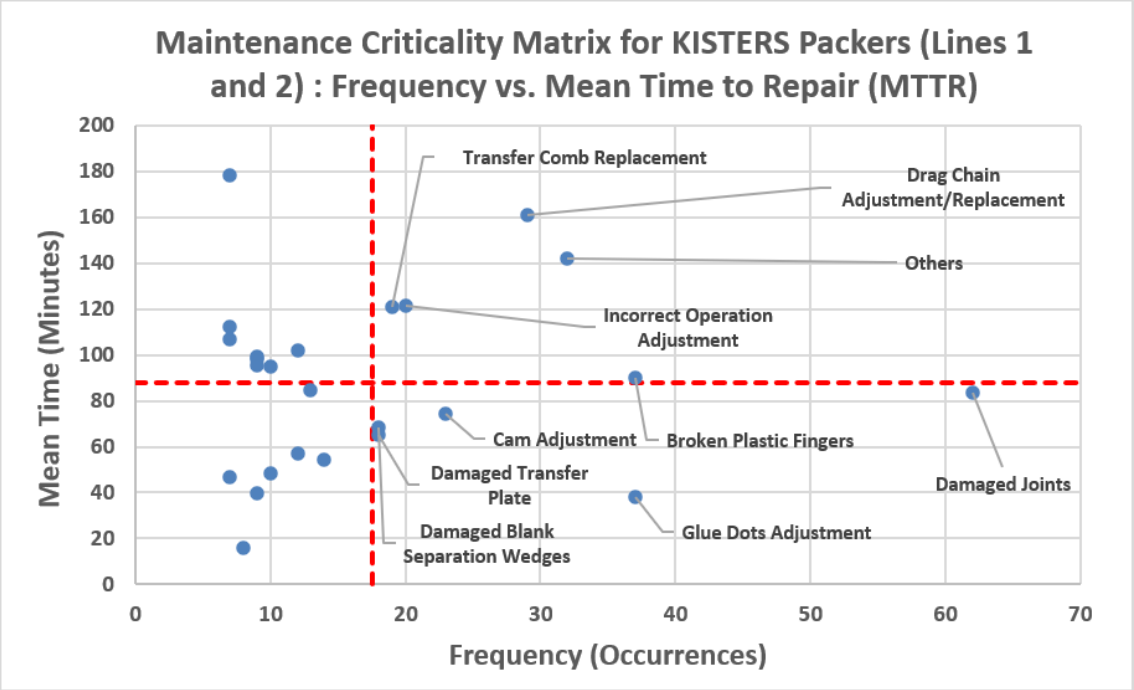


Figure 4.6: Maintenance Critically Matrix for Kisters Lines 1 and 2 (Before).

The failure modes located within the lower-right quadrant represent a severe source of operational instability. Although individual MTTR are relatively short, their persistent and high frequency of occurrence sharply degrades the MTBF. This behaviour triggers chronic minor stoppages that disrupt production flow and prevent the packaging line from sustaining its nominal throughput. Conversely, the outliers positioned in the upper-left quadrant demand disproportionately high recovery times, frequently exceeding the 100-minute threshold per event. These occurrences typically signal a deficiency in Standard Operating Procedures or a lack of SMED tailored to the equipment.

The primary analytical focus of this dissertation, however, resides within the upper-right quadrant. Components plagued by chronic issues, such as Broken Plastic Fingers or those requiring the Replacement of Transfer Combs, constitute the true mechanical bottlenecks of the asset. These failure modes represent the worst-case scenario from a reliability engineering standpoint: they not only collapse with an alarming regularity that penalizes the MTBF, but they also demand complex, time-consuming interventions that yield a high MTTR, thereby establishing the highest priority for mitigation within this study.

Chapter 5

Digitalization and Asset Management

5.1 Interactive Diagnostic Platform (PowerApps)

A preliminary survey was conducted among maintenance technicians to identify the primary root causes of downtime. Despite a limited response rate due to initial technical staff resistance, the findings highlighted significant challenges in fault diagnosis and resolution (Figure 5.1).

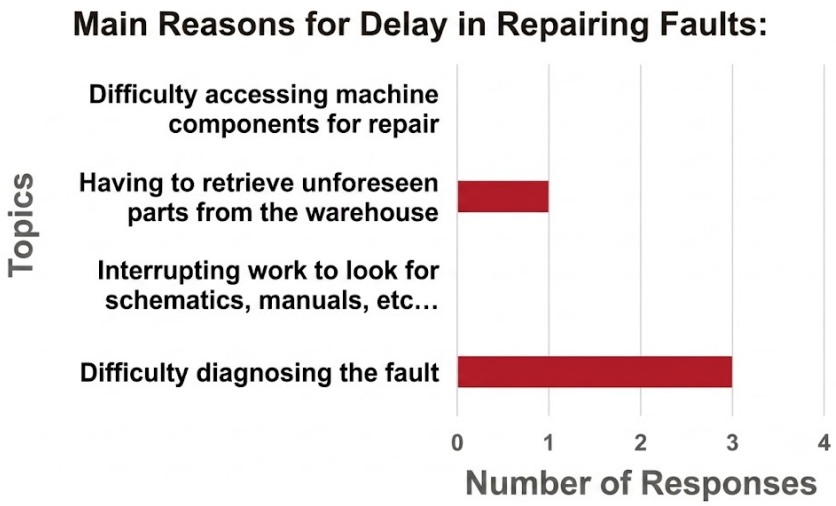


Figure 5.1: Main Reasons for Delay in Repairing Faults.

In light of the gaps identified during the preliminary assessment, the design and deployment of an interactive digital support application emerged as a high-priority solution to mitigate operational volatility. To establish a framework for this tool, it was essential to analyze the architecture and competitive advantages of the *PowerApps* platform. The

selection of this software was primarily justified by its low learning curve and ease of parameterization; a critical premise to ensure future project scalability, enabling maintenance engineers to continuously update the knowledge base with sporadic failure modes not captured during the study's timeframe. Furthermore, as an integral part of the *Microsoft* ecosystem, the platform allows seamless native integration with pre-existing corporate infrastructures such as *SharePoint*, *Excel*, and *Teams*. Additionally, its cross-platform compatibility fulfills a strict operational requirement within the *Super Bock Group*, where operations supervisors, maintenance team leaders, and planners routinely rely on tablets and mobile devices for shop-floor task management and technical document consulting.

The implemented methodology initially involved an exhaustive review of technical manuals and component catalogs from the Kisters manufacturer.

Cross-referencing these engineering specifications with historical SAP PM data proved vital to prevent algorithmic redundancies during application development while clarifying the standardized troubleshooting sequences. Following the triage and categorization of failure events by mechanical module, specific component, and technical trade, the plant's most experienced maintenance technician was embedded into the project.This collaboration focused on the technical validation of failure-solution matrices, the acquisition of photographic and video logs to establish visual standards for repairs, and the continuous evaluation of the prototype to gather interdepartmental feedback regarding project viability and usability. Consequently, the application architecture was segmented modularly, as demonstrated by the diagnostic interface illustrated in Figure 5.2.

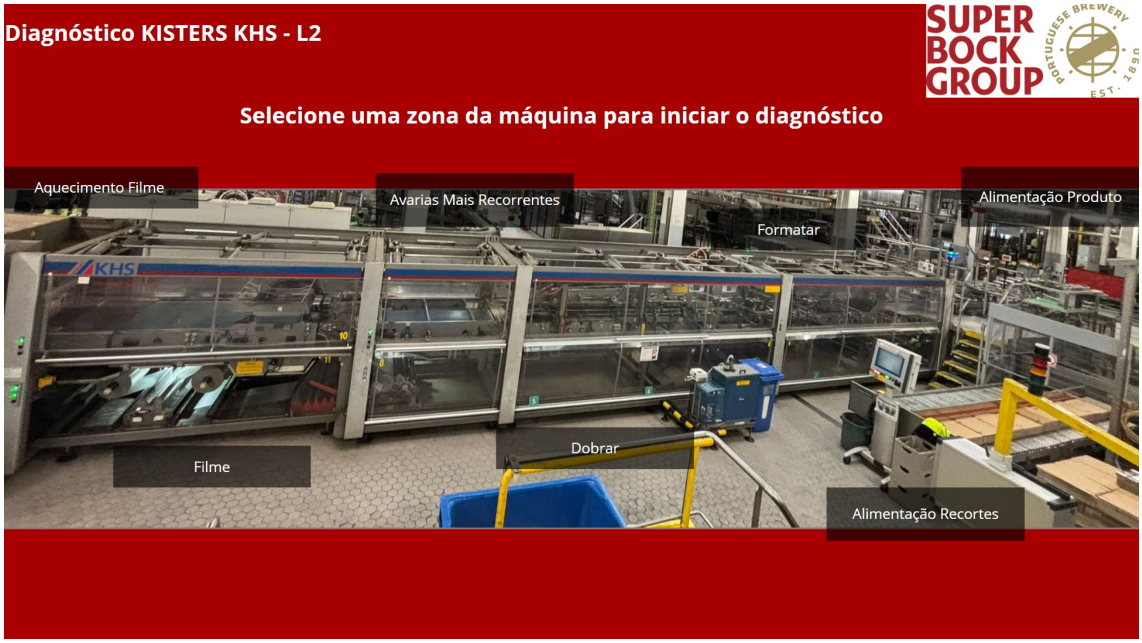


Figure 5.2: HomePage Application Fault Diagnosis Kisters, Line 2

The software's systemic architecture is organized around six core operational modules: Product Infeed, Blank Feeding, Forming, Folding, Film Wrapping, and Film Heating.

Based on recommendations from the industrial plant's technical staff, a "Most Recurrent Failures" section was integrated, explicitly designed to optimize reaction times when addressing chronic failure modes. This design layout prevents redundant navigation through subsequent submenus, such as individual component selection screens or areas parameterized by technical trade.

The diagnostic workflow is triggered when an operator flags a malfunction on the machine's primary Human-Machine Interface. Upon selecting the affected module within the application, the user is presented with a detailed view of its constituent components, which are sequentially numbered and labeled as illustrated in Figure 5.3. Furthermore, to enhance user experience and mitigate potential selection errors, a back-navigation command ("Voltar") was embedded, ensuring seamless movement between the platform's different hierarchical screens.

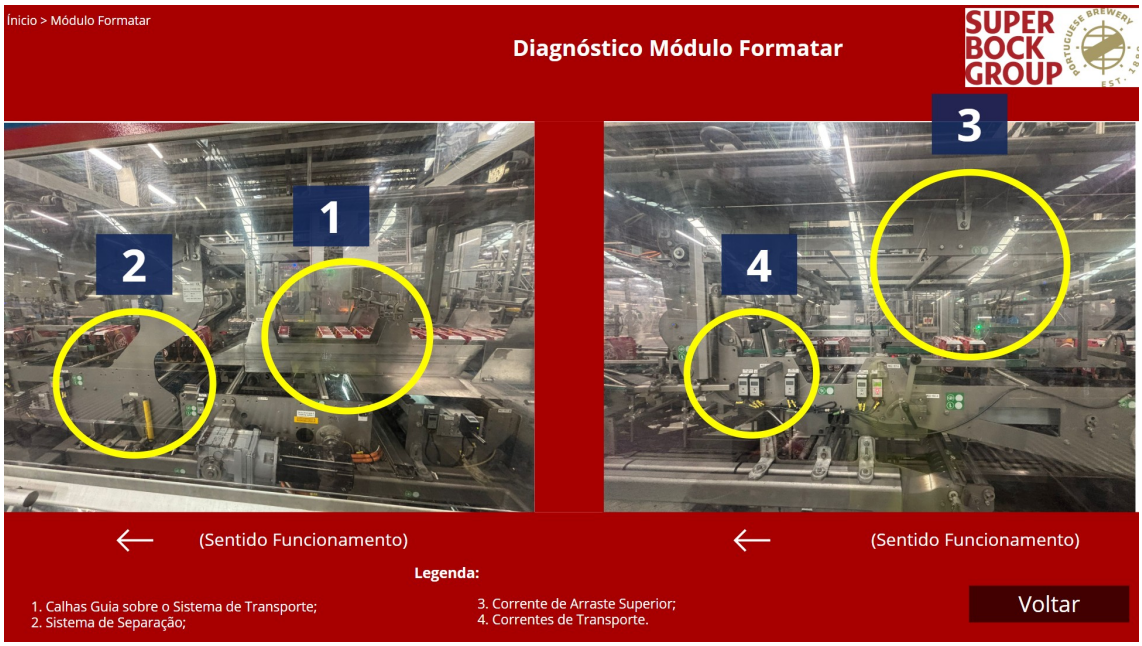


Figure 5.3: Segmentation by component/module of KISTERS equipment, line 2

In the subsequent stage, the interface enables the filtering and selection of the specialized technical trade responsible for identifying and resolving the respective failure, as illustrated in Figure 5.4.

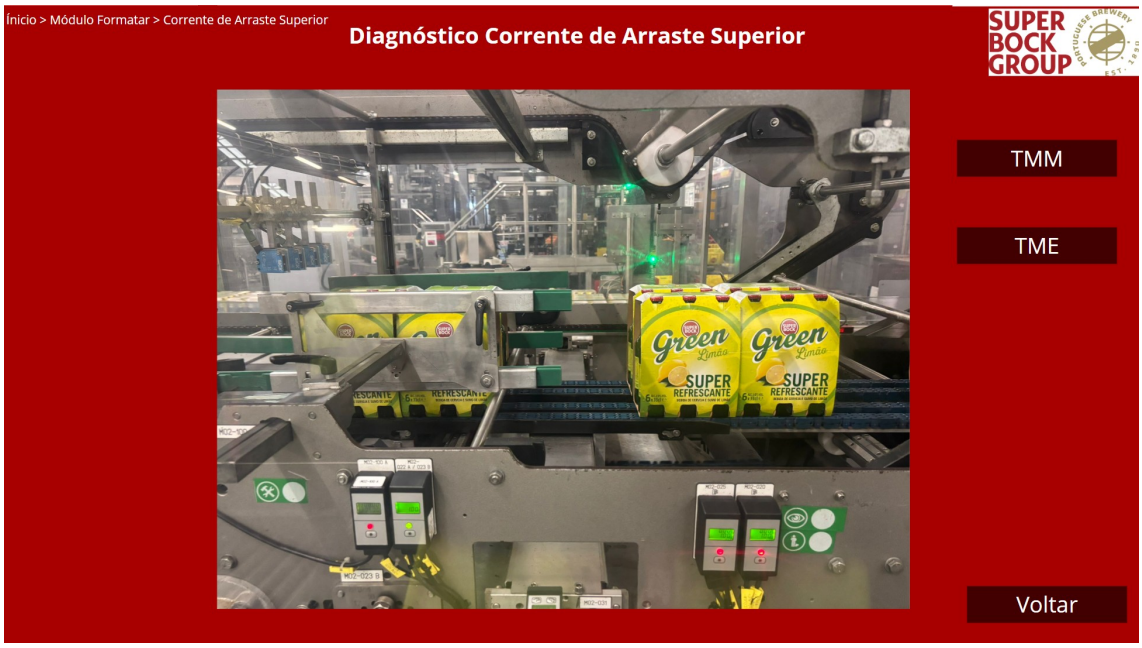


Figure 5.4: Breakdown by technician (TMM/TME) responsible for resolving the fault.

Finally, the user selects the specific malfunction via the sequential numbering parameterized on the interface in Figure 5.5. In instances where the simplified textual description proves insufficient for a definitive diagnosis, the platform provides access to detailed, step-by-step Standard Operating Procedures, complemented by multimedia resources such as photographic and video logs of the corrective action (Figure 5.6). This framework ensures an efficient and comprehensive consultation, serving as a visual guide to standardize repairs on the shop floor.

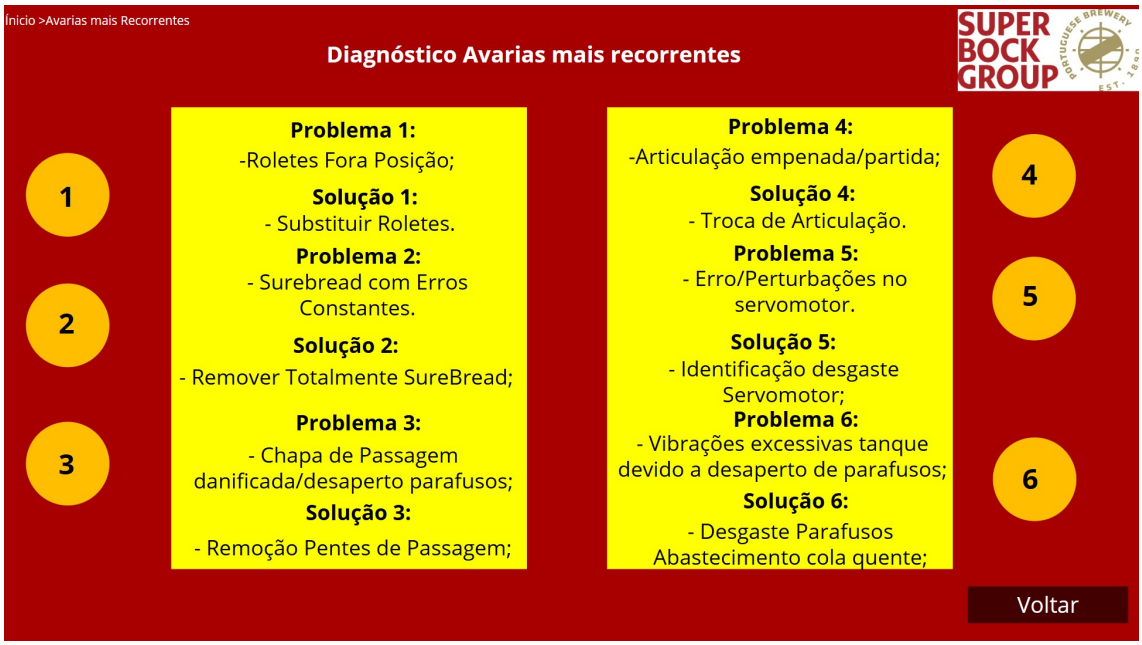


Figure 5.5: Different list of defects.

.

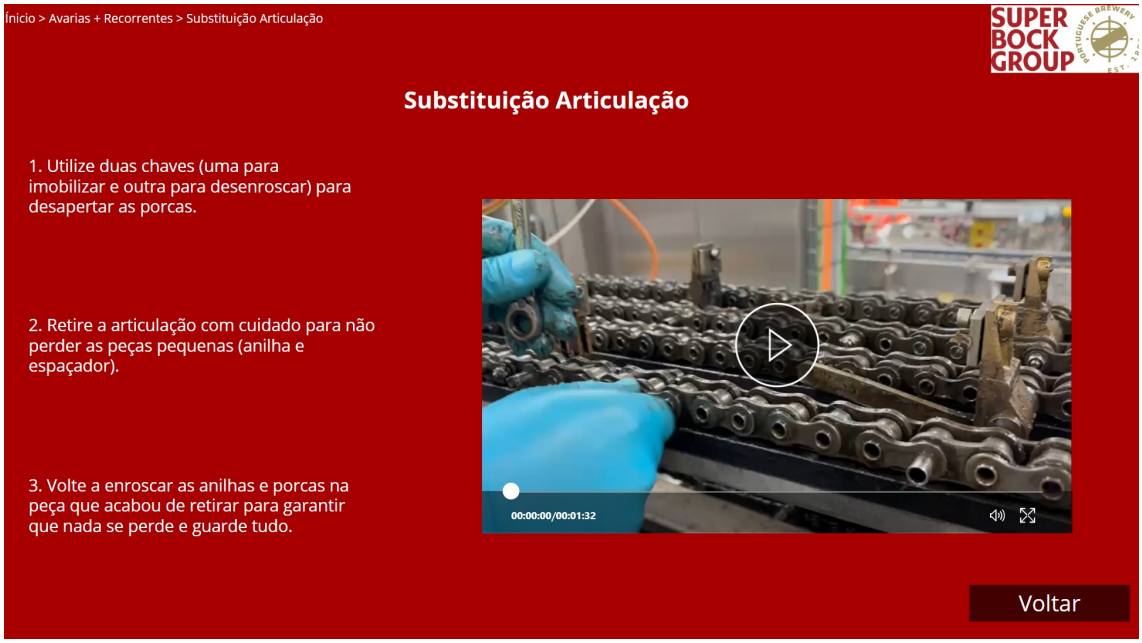


Figure 5.6: Detailed steps to resolve a PowerApps application error.

Beyond its function as a documentation repository, the developed platform serves as a Decision Support System designed to reduce ambiguity in maintenance technicians' diagnostics and mitigate the risk of operational failures.

Within the scope of industrial maintenance at the SuperBock group, this decision support system has helped minimize the cognitive load on technicians during troubleshooting,

by structuring the decision making process through predefined and verified logical paths, in this specific case, fault solution matrices.

The system systematically guides the user through the diagnostic hierarchy (Module → Component → Failure Mode), acting as an interface between the empirical knowledge of senior technicians and the real-time diagnostic requirements of the production line.

This approach effectively seeks to reduce information retrieval time and, more importantly, to minimize the variance in repair quality currently observed among operators with different levels of experience. Consequently, the application transforms complex technical data into an intuitive, easily accessible platform, ensuring that future corrective interventions are consistent, compliant with machine specifications, and optimized to achieve the lowest possible MTTR.

5.2 Digitalizing Maintenance and Cleaning Routines

5.2.1 Critical Diagnosis of Operational Constraints and Hybrid System Limitations

The analysis of the current state at the manufacturing facility revealed a profound asymmetry between theoretical preventive maintenance planning and the reality imposed by the high-cadence production pace. The first major inefficiency parameter identified in the equipment Kisters KHS ecosystem centered around the architecture and parameterization of the current enterprise information system (SAP PM / SmartPlant).

From an Information Systems perspective, it was found that the parameterization of these enterprise resource planning platforms exhibited excessive procedural rigidity. On a weekly basis, maintenance technicians were faced with the exact same issuance of a preventive Work Order, completely decoupled from the previous week's failure history or the actual condition of the asset. This lack of dynamism and feedback loops in the data flow prevented the planning team from adopting an agile, adaptive strategy. The direct consequence was a sub-optimal allocation of human and material resources, performing time-based maintenance on healthy components while neglecting areas of accelerated degradation, thereby fostering the reincidence of systemic failure modes.

The most severe constraint, however, materialized as a direct capacity-constrained scheduling conflict, unequivocally evidenced in the SAP system interface (Figure 5.7).



Ordem ZPM3 0000426749 Kisters L2 - Preventiva Semanal
Stat.sist. ENTE CONF CAPC NOLQ SCDM

DdsCabeç. Operações Componentes Custos Objetos Dados adic. Localiz. Planej. Controle Ampliação

Oper	Chave d...	CenTrab	Centro	TpAtiv	Núm...	Dur.	Trabalho real	Un	Trab.	Un	Txt.breve operação
0010	PM01	SE	D022	MOB1	1	30	121	MIN	30	MIN	Inspeção Geral das Correias Acionamento
0020	PM01	SE	D022	MOB1	1	60	1	MIN	60	MIN	Servomotores de Acionamento - Verificar
0030	PM01	SE	D022	MOB1	1	60	1	MIN	60	MIN	Processamento e Transporte de Cartão
0040	PM01	SE	D022	MOB1	1	90	1	MIN	90	MIN	Mesa de Entrada de Garrafas - Inspecion
0060	PM01	SE	D022	MOB1	1	120	1	MIN	120	MIN	Formatação e Colagem - Inspecionar o ní
0100	PM01	SE	D022	MOB1	1	120	1	MIN	120	MIN	Processamento e Transporte de Cartão -
0110	PM01	SE	D022	MOB1	1	10	1	MIN	10	MIN	Inspeção Estado Lubrificação da Máquina

Figure 5.7: Original list of weekly preventive maintenance actions in the SAP system (ZPM3 Order type) for the Kisters Line 2 machine.

As observable in Figure 5.7, the parameterization of the plan aggregated long-duration and complex operations into a single weekly execution block. Critical tasks such as the "Inspection of Cardboard Processing and Transport" (Operations 0030 and 0100) and "Forming and Gluing" (Operation 0060) individually required estimated intervention times between 60 and 120 minutes. In the sum of all tabulated items, the theoretical plan stipulated:

- Weekly Autonomous Cleaning (Operations Team): 4 hours (04:00 h).
- Specialized Preventive Maintenance (Maintenance Technicians): 8 hours and 20 minutes (08:20 h).

Under the lens of Production Management and the Theory of Constraints this scenario presented a mathematically unsustainable scheduling problem in practice. Due to mandatory Occupational Health and Safety regulations, specifically *Lockout/Tagout* (LOTO) and equipment consignment procedures, combined with space constraints inside the machine frame, cleaning operators and maintenance technicians are strictly unable to work simultaneously. The mandatory serial execution of these tasks demanded a total continuous planned downtime window of 12 hours and 20 minutes.

However, the weekly maintenance window, rigidly established by the Production Planning and Control department for gaps between bottling chageovers, is limited to a maximum of 8 hours.

The physical and chronological impossibility of fitting a 12-hour-and-20-minute workload into an 8-hour time constraint invariably resulted in the systematic neglect of critical maintenance operations. This phenomenon of deferred maintenance created a vicious cycle of asset deterioration. By suppressing scheduled inspections and lubrications to meet line startup deadlines, the organization precipitated the accelerated degradation of mechanical reliability and asset availability, the two core pillars for sustaining the OEE indicator.

5.2.2 Restructuring and Hierarchical Segmentation: A Maintenance Engineering Approach

To mitigate the diagnosed temporal saturation (12h20 workload for an 8-hour window), a complete reengineering of the preventive maintenance plan became imperative. A filtering methodology based on the principles of *Reliability-Centered Maintenance* was adopted, supported by an empirical failure criticality analysis and the structured elicitation of the technical knowledge of senior technicians. This extraction of knowledge proved vital, as the SAP database lacked the granularity required to distinguish between critical inspections and redundant overhauls.

Leveraging process optimization and operations scheduling, the global macro-operations dictated by the SAP system were audited and fragmented into elementary tasks. The primary objective function was to minimize the total processing time of contiguous tasks during the weekly shutdown, ensuring strict compliance with the downtime window dictated by the PPC. Under this premise, the inefficient logic of the static weekly block was eliminated in favor of a dynamic maintenance frequency matrix, illustrated in Table 5.1.

Table 5.1: Segmentation and restructuring matrix of maintenance operations by component, demonstrating the leveling of execution frequencies.

Task Description	**Execution Frequency (SAP)**				
	Wk.	**Mo.**	**Qtr.**	**Semi.**	**Ann.**
Cardboard Processing and Transport					
Inspect the horizontal balance of the cardboard transport fork.				×	
Check the condition of the fingers on the cardboard transport chains.	×				
Drive Servomotors					
Check all servomotors for leaks.				×	
Check the gear clearances of the separation system.			×		
Bottle Infeed Table					
Inspect the integrity of the oscillating guide cylinders at the infeed.			×		
Check the tension of the conveyor belt.		×			
Bottle Separation and Conveyance					
Check the clearances in the drag bar chains using the gauge.				×	
Check or repair any oil leaks in the servomotors.					×
Package Rotation					
Check clearances, condition, and operation of belts and chains.					×
Plastic Wrapping					
Confirm the integrity of all cutting blade teeth.	×				
Ensure there are no air leaks in the vacuum mandrels.					×
Shrink Tunnel					
Clean plastic residues and assess the condition of the thermal curtains.					×
Lubrication Status Inspection					
Inspect all active lubrication zones.				×	

The resulting matrix reflects a rigorous strategic rationalization, scientifically grounded in the concept of the P-F Curve. The P-F Curve dictates that the inspection interval of a component must be proportional to its degradation time between the initial detection of a potential failure (P) and its actual functional failure (F).

Although the P-F Curve concept was not applied in theory, its fundamentals were explained to the maintenance technicians, applying the empirical and practical knowledge acquired over the years in defining the maintenance schedules to be applied to each operation.

Applying this logic to the "Cardboard Processing and Transport" module, actions preventing short-term failures with a very short P-F interval, such as verifying the mechanical integrity of chain lugs and ensuring the absence of kinematic binding in the indexers, were imperatively retained at a weekly frequency.

Conversely, operations associated with slow-wear mechanisms were surgically redistributed across the temporal horizon. For instance, checking elastic tension and belt retightening transitioned to a monthly frequency, chain geometric alignment shifted to quarterly, and tribological integrity monitoring and journal bearing lubrication were allocated to a semi-annual cycle.

An identical analytical logic was extrapolated to the remaining critical modules of the equipment, namely the “Bottle Infeed Table” and “Film Wrapping”. From an Operations Management perspective, distributing long-term maintenance tasks (monthly, quarterly, and semi-annual) alternately across the 52 weeks of the year smooths out technical workload peaks.

This restructuring successfully purged systematic redundancies from the original weekly routine, mathematically balancing the technicians’ workload within the restrictive 8-hour window. Ultimately, transitioning to this dynamic matrix not only resolved the capacity-constrained scheduling conflict but also guaranteed that long-term inspections are planned, audited, and executed effectively, reversing the asset’s degradation cycle without penalizing the line’s manufacturing availability.

5.2.3 Digitalization of Routines and Data Analytics: Dynamic Tasklists

Following the strategic definition and distribution of the new, updated, and optimized weekly preventive maintenance operations, for real-world testing in an operational environment, the physical printed documents and procedures located on the machine were replaced with digitized versions in an ecosystem accessible directly on the factory floor.

As will be detailed in subchapter 5.3, the structuring of an internal information system, namely using Microsoft Forms platforms for recording preventive maintenance times and including access via SharePoint from Production, defined all the operational steps to be performed for the correct execution of the weekly preventive maintenance.

Operators will have fluid access to view and consult the forms present in SharePoint through QR codes strategically placed on the Kisters KHS machine.

The technical documentation, diagrams, technical drawings, and operational procedures present in SharePoint are thus updated, and the operator has access to the updated version approved by both the Quality department (Internal SharePoint Backup) and the Production department. This updated record prevents operators from consulting outdated and obsolete documents.

To ensure operational fluidity and link digital information to physical assets, access to these forms was decentralized by inserting QR codes at nodal points on the Kisters KHS packaging machine.

This topology ensures that the technical documentation, engineering diagrams, and work instructions consulted by the operator invariably correspond to the most recent version approved by Quality Management, mitigating the classic risk of consulting obsolete or deteriorated paper manuals (appendix A.7).

All documents were actively restructured and transcribed from the physical version to the digital version. Lean principles were the basis for segmenting the steps and the logical flow of tasks in the weekly form, in the Microsoft Forms application. Until this update, preventive maintenance orders were grouped individually without a well-defined criterion, which forced the maintenance technician to circulate around the equipment to complete the different tasks defined in each weekly preventive maintenance. In process engineering, non-sequential and disorganized movement leads to wasted time due to unnecessary movements and transport, known as Muda. The Spaghetti diagram was initially obtained during a first preventive maintenance visit viewed via video, where it is possible to see a lack of sequence in the tasks to be performed (Figure 5.8). The standard tasks are shown in blue, and a displacement that occurred due to forgetting to perform a task at the end of the weekly preventive maintenance is indicated in red.

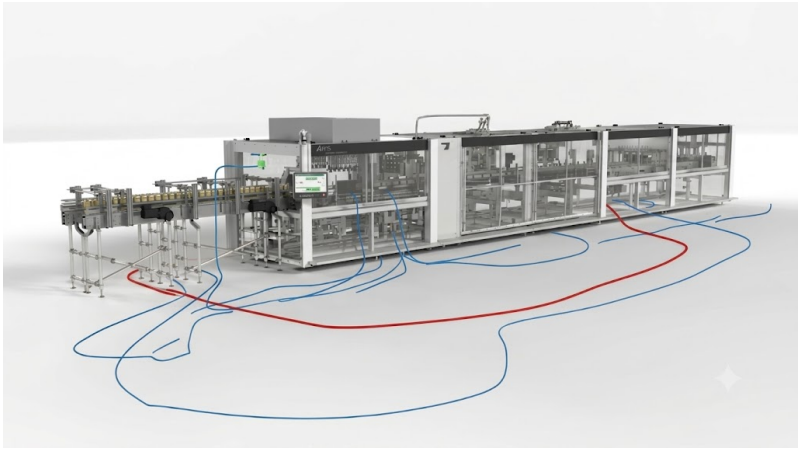


Figure 5.8: Weekly Maintenance Preventive - spaghetti Diagram (Before)

Therefore, in order to eliminate movement inefficiency, a new list of sequentially organized operations was created, based on the geographical proximity between the different

modules of the Kisters KHS equipment. The workflow was organized so that the maintenance technician performs all the mechanical and electrical operations inherent to a given module before moving on to the next one. Although it was not possible to physically test the maintenance technician's movement via video due to lack of time, this test is planned as future work.

However, it is expected that optimizing preventive maintenance will significantly reduce the total distance traveled by the technician, helping to decrease the time required for preventive maintenance and minimizing technician fatigue.

The adoption of Microsoft Forms software for controlling preventive maintenance operations, in terms of information system and data analysis, eliminated the lack of traceability of task durations and also the generation of delayed reports.

The digitization of tasks presents a lower probability of errors occurring, since Forms was developed with the requirement that, to close the preventive maintenance, it is necessary to fill in all fields and perform all tasks.

In addition, each record in the system is automatically submitted to a database that specifically includes the record of the exact date and time for the start and completion of each operation.

The data acquired and recorded in the database allows the maintenance team to audit and analyze the average time to perform the actual preventive maintenance, evaluate the effect of small changes in operations on the final record, and recalibrate variations in standard times in the SAP system, promoting the existence of reliable statistical data to replace the previous existing empirical values.

Despite the reliability and accessibility of the developed digital system, which will result in greater ease in acquiring real data, the initial practical implementation on the factory floor presented challenges in terms of ergonomics and human interaction, particularly in the Human-Machine Interface.

The Human-Machine Interface was achieved using tablets or smartphones, both accessible via capacitive touch on the screen.

However, maintenance technicians reported that the physical environment of mechanical intervention required, according to safety regulations, the constant use of protective gloves and continuous contact with lubricating fluids, namely oils and other thick liquids.

During handling, the combined effect of these residues on the screen and the use of gloves themselves impairs the sensitivity of the devices, causing erratic touches.

This operational difficulty generates discomfort and frustration for the maintenance technician, as they need to repeatedly remove their safety gloves to validate operations on the devices. Furthermore, the increased time spent removing gloves leads to a loss of productivity, which contradicts the Lean philosophy.

Thus, the practical limitation in the operational environment highlights the need for the transition to Industry 4.0, promoting a greater symbiosis between software and the maintenance technician. That being said, the use of touchless equipment is part of the

future. The exploration of voice recognition technologies for industrial use and Assistive Reality technologies (RealWear) was part of an initial work developed with prospects for future comprehensive affirmation in the company.

The goal of RealWear is to combat the identified problem, allowing the technician to have all the tools to perform tasks in the shortest possible time.

5.2.4 Operational Standardization and Integration with Quality Management

After investigating the root causes of the constant malfunctions in the Kisters KHS equipment, it was empirically observed, through visual observations, that the weekly cleanings (responsibility of the operating teams) were performed inefficiently and without well-defined procedures. The most critical malfunctions occurred due to the accumulation of debris, cardboard dust from the boxes and trays, and hot glue residue frequently present in the joints and sensors (generating false-positive signals), thus promoting significant wear due to friction.

Based on the philosophy and methodology of TPM, the fundamental principle of Seiso (cleaning is inspection) is ignored. Therefore, the operator must be part of the initial inspection, where they must alert the maintenance technician to any easily detectable anomaly for subsequent correction.

Thus, the solution requires exporting empirical knowledge to an application of TPM principles.

To ensure efficient preventive maintenance, a multidisciplinary team was initially created, comprising one senior technician that is responsible for analytically discussing the feasibility of each operation, one operations team leader, and one maintenance technician, responsible for reaching a dialogue on the tasks to be updated. Finally, after three weeks of weekly dialogue, the first standard operating procedure was defined for both cleaning and preventive maintenance, specifically designed for the Kisters KHS cartoning machine.

The absence of a normative standard implies the implicit acceptance of process variability, making it impossible to guarantee repeatability and rendering any compliance audit unfeasible. To reverse this scenario, the new SOP was designed to purge any interpretative ambiguity. It unequivocally outlines critical target areas, specifies approved industrial chemical reagents to prevent the accelerated degradation of rubbers and polymers caused by the improper use of aggressive solvents, lists appropriate tools, and introduces Visual Management concepts using “Before/After” photographic standards

Beyond theoretical standardization, effective process control required the implementation of traceability mechanisms. To this end, the completion of a mandatory digital form was instituted at the end of each order. The implementation falls within the verification phase of the PDCA cycle, which requires detailed recording and nominal validation of the tasks performed, promoting accountability and allowing supervisors to intercept quality deviations in a timely manner.

In parallel, the document management structure was thoroughly restructured.

The internal Quality Management system is aligned with the international ISO 9001 standards, so all documents are actively and rigorously controlled, almost completely eliminating the risk of operators performing tasks with obsolete instructions.

In accordance with the ISO 9001 standard, the archive of standard operating procedures was allocated to the Quality department's SharePoint, thus establishing a single source of trust.

However, the central management of operational documents frequently introduces problems in accessing operational data.

To bypass this barrier and promote accessibility at the *gemba* (the place where value is physically created), a direct dynamic hyperlink was embedded within the tactical Production SharePoint. This information architecture ensures a perfect symbiosis: the operations team instantaneously accesses the most updated document revision via mobile devices, preserving the rigor and compliance demanded by Quality without sacrificing the agility required by the fast-paced shop floor.

In practical terms, during the autonomous cleaning routines, operators utilize tablets or mobile devices to scan the QR codes strategically affixed to the machine's safety panels. As illustrated in Figures 5.9 and 5.10, this immediate optical reading redirects the user directly to the digital checklist (e.g., the Weekly Cleaning Record via Microsoft Forms). This interface provides step-by-step visual instructions and allows for real-time compliance logging directly at the *gemba*. By anchoring the digital interface to the physical environment, the process becomes highly intuitive, completely replacing cumbersome paper dossiers with a highly agile and interactive digital workflow.

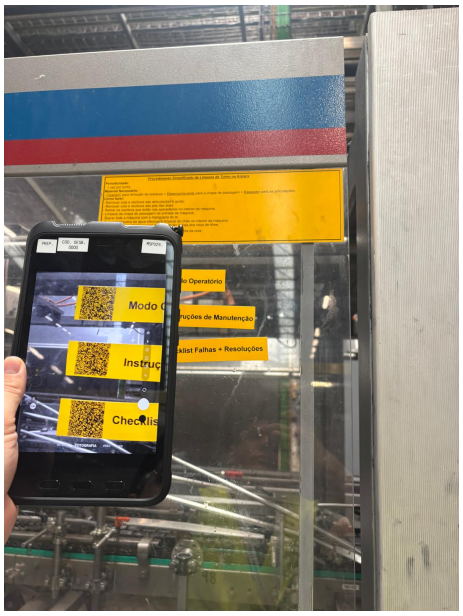


Figure 5.9: Optical scanning of the QR code affixed to the KISTERS safety panel using a rugged mobile device.

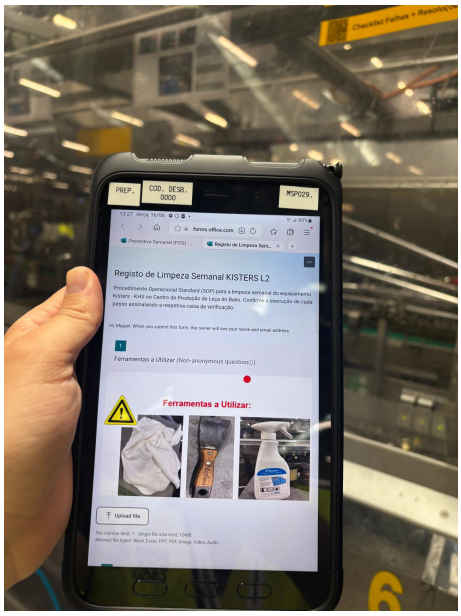


Figure 5.10: Digital submission form (Microsoft Forms) displayed on the industrial tablet, detailing the autonomous cleaning requirements.

5.2.5 Industry 4.0 Perspectives: Smart Factories and Voice Assistance (RealWear)

Although the implemented countermeasures successfully stabilized and optimized the cadence of the weekly preventive routine, the continuous improvement cycle inherent to this project does not terminate with this iteration. As a short-term Future Work objective, the roll-out of these workflow restructuring and document digitalization methodologies is envisioned for the remaining periodicities of the SAP maintenance plan (from monthly to annual schedules). However, the strategic technological roadmap defined for the production lines aims to transcend mere process optimization, projecting the maintenance infrastructure into the paradigm of Smart Factories, in the Industry 4.0.

The core axis of this technological evolution focuses on elevating the maintenance technician to the concept of the Connected Worker. To mitigate the aforementioned ergonomic and usability barriers imposed by capacitive tablets in harsh workshop environments, a transition toward wearable technology is envisioned, anchored in Assisted Reality solutions using industrial-grade devices (e.g., RealWear technology).

Unlike immersive Augmented Reality, which projects 3D images overlaying the real field of view, potentially inducing cognitive overload or obscuring kinetic hazards on the shop floor, assisted reality projects the Microsoft Forms tasklist, electrical schematics, and SOPs onto a high-resolution micro-display strategically positioned in the technician's lower peripheral vision. This hardware is intrinsically engineered to clip onto standard Personal

Protective Equipment helmets, ensuring eye and cranial protection without compromising comfort. A preliminary demonstration of this hardware integration within the production environment is illustrated in Figure 5.11, highlighting the device's compatibility with standard safety gear and its unobtrusive adaptation to the operator's line of sight during machine inspection.



Figure 5.11: Demonstration of the use of Assisted Reality technology integrated with Personal Protective Equipment on the Kisters KHS machine (line 2), focused on hands-free usability.

Interaction with the data infrastructure will operate under a strictly hands-free regime, with navigation and checklist validation entirely governed by voice commands. Considering that bottling lines operate under high acoustic pressure, frequently exceeding 85 dB, the success of this interface relies on microphones equipped with advanced industrial active noise cancellation algorithms, ensuring accurate interpretation of vocal commands.

Within a Smart Factory context, this cyber-physical architecture will not merely act as a workaround for dirty touchscreens. It will exponentially elevate occupational safety by allowing the technician to keep both hands free to handle tools or maintain the vital three points of contact when intervening in elevated or confined structures. Concurrently, it will maximize intervention efficiency and data record compliance, enabling maintenance metrics collection and document consultation to occur in absolute symbiosis with manual labor, entirely eliminating mechanical interruptions.

5.2.6 Comparative Analysis and Validation of Results: The Before vs. After Impact of Implementation

The practical and methodological culmination of the engineering countermeasures developed in this project is unequivocally reflected in the comparative analysis of KPIs before and after the shop-floor reengineering process. As discussed in the initial diagnosis (Section 5.2.1), the original state of the Kisters KHS wrap-around packer was characterized by an unsustainable scheduling bottleneck. The simultaneous requirement of 4 hours of autonomous cleaning and 8 hours and 20 minutes of specialized preventive maintenance demanded a continuous planned downtime of 12 hours and 20 minutes, colliding frontally with the maximum 8-hour window established by the PPC department.

The introduction of the dynamic maintenance frequency matrix based on the P-F Curve and resource leveling radically altered this scenario. By fragmenting and distributing slow-wear operations across the three optimized weekly variants, the specialized weekly workload was compressed to a stable average of 3 hours and 13 minutes.

In parallel, the development and deployment of the visual Standard Operating Procedure for Autonomous Maintenance converted the once chaotic cleaning routine into a linear, standardized process, reducing execution time from 4 hours to a consolidated 51 minutes without any loss of effectiveness. The combined sum of these improvements reduced the total required intervention time to 3 hours and 13 minutes, generating a comfortable safety margin of 4 hour and 47 minutes within the 8-hour production window.

The impact of this temporal optimization was immediately reflected in the failure rates and equipment reliability in the weeks following implementation, as summarized in Table 5.2.

Table 5.2: Comparative matrix of operational and logistical indicators before and after the implementation of the engineering solutions.

Metric / Parameter	**Initial State (Before)**	**Optimized State (After)**	**Operational Impact**
Autonomous Cleaning Time	4h 00m	0h 51m	79% reduction via visual *SOP*
Weekly Preventive Maintenance	8h 20m	2h 22m	Task leveling (*Heijunka*)
Total Required Time	**12h 20m**	**3h 13m**	**Successful fit into PPC window (< 8h)**
Micro-stoppages due to Blinded Sensors	High frequency (Chronic)	Close to zero	Stabilization of nominal line speed
Failure Frequency of Critical Components	Recurrent breakdowns	Drastic reduction (Compliant inspections)	Increase in Mean Time Between Failures (MTBF)
Mean Time to Repair (MTTR)	High (Motion and search waste)	Linear minimization	Point-of-Use access (Kanban and QR Code)

Eliminating maintenance delays broke the cycle of asset deterioration. Following the introduction of new operational controls, we observed a drastic reduction in chronic micro-stoppages caused by sensor blinding.

The systematic application of approved cleaning agents and microfiber cloths, as mandated by the new Autonomous Maintenance Standard Operating Procedure, effectively prevented the accumulation of dust and hot-melt residues, ensuring the stability of the Siemens automation architecture.

Similarly, the failure rate of critical components, specifically chain lugs, roller carriages and feed combs, registered a significant decrease. With rigorous weekly inspections carried out within the PPC window, shop-floor teams can now intercept functional failures systematically, replacing components in a state of preventive degradation during planned stops.

Finally, the introduction of Point-of-Use Kanban racks and QR-codes drastically compressed the Mean Time to Repair by eliminating motion waste. While these initial results are highly promising, they should be interpreted with caution. Given that the observation period was limited to June 12–26, 2026, these findings serve as an early validation rather than a definitive conclusion. Ongoing data collection is essential to capture a broader range of failure scenarios and to confirm the long-term sustainability of these reliability gains.

5.3 Information Architecture and SharePoint

5.3.1 Historical Context and the Need for Cyber Resilience

Historically, all the factory's technical information relating to the Production department was concentrated in the Production SharePoint. This information repository played an important role in supporting operations on the factory floor, particularly in minimizing unplanned internal breakdowns. This repository contained all critical operational engineering documents and documents to support maintenance.

The database included all equipment specifications and technical manuals, 2D layouts of production lines, standard operating procedures for each piece of equipment, a list of problems for each piece of equipment and their respective solutions, instructions for the correct execution of preventive maintenance, electrical and pneumatic diagrams, and risk maps for the prevention of workplace accidents.

The centralization of information allowed operational teams to have a single reliable source.

However, the company suffered a cyberattack across several areas of the company about three years ago. The recorded event caused a serious gap in the company's digital ecosystem, resulting in the almost total loss of internal documentation in the production department. Internally, the sudden loss of the technical and intellectual history accumulated over several decades created an immediate information void, leaving the operation

and maintenance teams without the necessary documentation tools for decision-making and preventive maintenance. The technicians' experience was essential to control this gap and mitigate its effects.

Thus, the organization activated disaster recovery protocols.

Focusing on the production department, the "filling" (operation), maintenance, and manufacturing areas needed to build a new database to replenish the lost data, something that was achieved by collecting manufacturer manuals and extracting technical knowledge from the most experienced technicians and operators.

During an initial contingency phase, in which the speed of information gathering was the immediate priority, the newly generated documentation was allocated in an improvised manner to internal Microsoft Teams folders, by area (Figure 5.12).

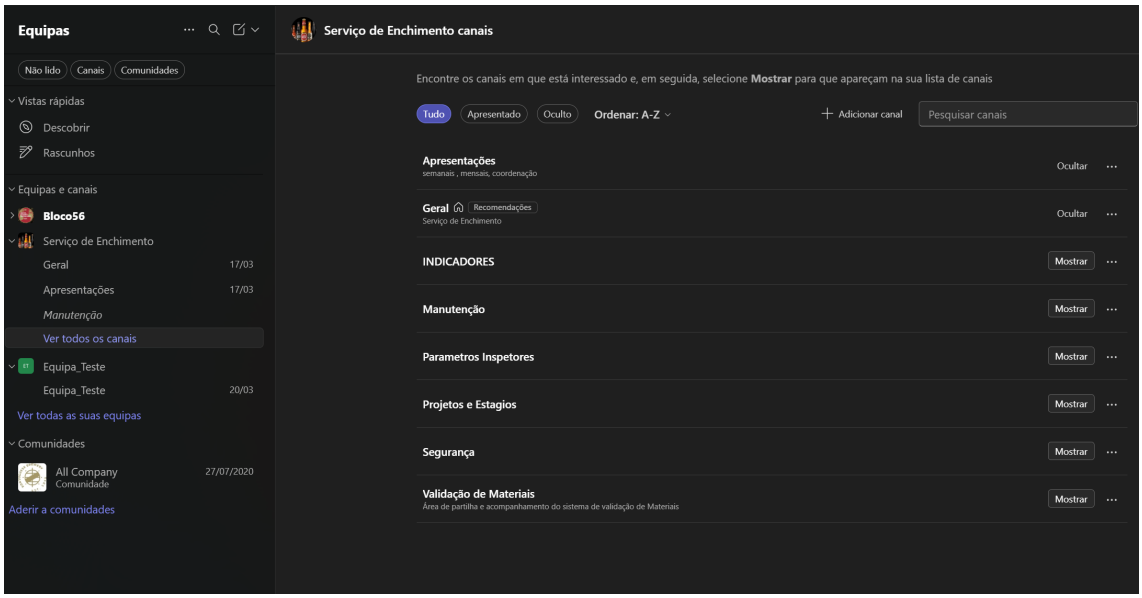


Figure 5.12: Ad-hoc documentation repository architecture within Microsoft Teams.

Although the temporary solution was vital to re-establish an initial database of urgent data, the model proved to be informal and de-internalized, which raised challenges of robustness and cyber-resilience, aligned with audit requirements and the Industry 4.0 paradigm.

5.3.2 Limitations of the Transitional Model and the Strategic Advantages of SharePoint

Although the database in *Microsoft Teams* software effectively fulfilled the purpose of immediate emergency storage, the increasing maturity and need for digitization of the factory, as well as the need for regular and compliant audits of the company, exposed the limitations of the current configuration.

From a data management perspective, Microsoft Teams is fundamentally a horizontal collaboration tool.

As a main shortcoming, in an industrial environment, the inserted documents do not have a well-defined hierarchy, and access to documents is usually easier.

The system, in general, allows all members of a given channel to share the same privileges to view, edit, and delete files.

This easy horizontal access makes secure control of different versions impossible, causing the risk of document overlap and loss of data alignment. On the factory floor, the existence of several versions for a given procedure is a significant problem, mainly in terms of safety procedures or lubrication risks.

The vulnerabilities presented by *Microsoft Teams* made the transition to the new SharePoint Production urgent. SharePoint was created to safeguard data integrity, based on 5 main pillars of information control:

- **Granular Permissions:** Enables Role-Based Access Control policies. The software ensures that only authorized engineers and technicians can edit and add master documents, restricting operator access to viewing only, thus mitigating the risk of accidental data deletion.
- **Centralized Taxonomy:** Acts as a robust corporate intranet. To facilitate document location and prevent loss, the platform organizes information in a logical tree structure, subdivided by department and production line.
- **Absolute Traceability:** The system automatically records every interaction, identifying who opened, edited, or downloaded the file, along with the date and time stamp. The created history is important to ensure that documents are compliant during internal and external audits.
- **Automated Workflows:** The software allows for hierarchically divided approval cycles. A new Standard Operating Procedure can only be published and thus made available to the production line after digital validation by both the managers of each area and the Quality department, ensuring only the presence of official and approved documents in the system.
- **Secure External Sharing:** External sharing allows external entities, such as auditors or KHS technicians, to access specific folders, in isolation and for a limited time, through URL links. Technical documentation can thus be shared without compromising the security of the internal database.

5.3.3 Hierarchical Taxonomy and Database Segmentation

The new *SharePoint* architecture for production was designed for structural simplicity and horizontal scalability. The goal is to build a reliable, future-proof database capable of

adding operational information stored in *Microsoft Teams* and meeting the needs of the production line.

Industrial asset management practices follow a top-down information taxonomy, which is a requirement for company alignment. At a macro level, the Production *SharePoint* was initially structured and divided around the three main areas responsible for supporting Operations: Production, Maintenance, and "Filling" (Operation) (Figure 5.13). A separate root library was created for each action area in order to avoid data conflicts and ensure the retrieval of information and documents through direct hyperlinks.

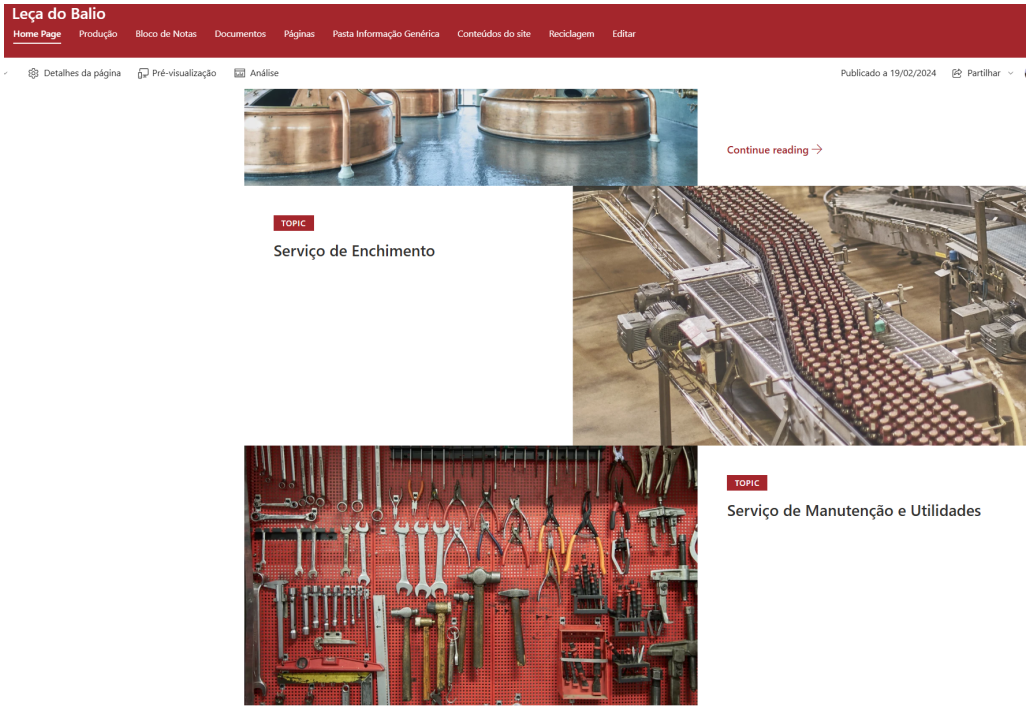


Figure 5.13: Production SharePoint interface showing the structural separation by sub-department libraries.

Within each library, the architecture is branched into two main macrofolders where all backup documents are stored. The first folder, called "Miscellaneous Information," acts as a central repository for loose data, such as videos and photos. This folder stores high-resolution photos of mechanical components, explanatory videos of operational procedures, and other useful visual resources. The inclusion of this library with multimedia content allows for the optimization of operational page loading times. The second folder created, called "Workstation," is where the system core and the database accessed daily by operators are located.

The page presents a topological taxonomy, digitally following the asset tree and showing the actual physical layout of the factory. It is sequentially divided by production line (Line 1 to the Tin Line). Subsequently, each line is hierarchically subdivided by individual mechanical equipment per production flow. SharePoint's structure is organized so

that, during document consultation, the operator and technician can directly and digitally map all the information that sequentially replicates the operation of the production line, thus ensuring that the transition to a digital system occurs without interference or loss of production time during problem solving.

5.3.4 Equipment Structuring and Document Integration (Quality and Operations)

By analyzing in detail a specific level of SharePoint in Production, using the KHS wrapping machine from Line 2 as the main case study, the information architecture was rigorously designed based on a centralized portal for all the company's internal knowledge. The goal was to consolidate all the tools needed to intervene, perform maintenance, and troubleshoot equipment in a single digital space. Finally, the information is dynamically distributed across 3 directories:

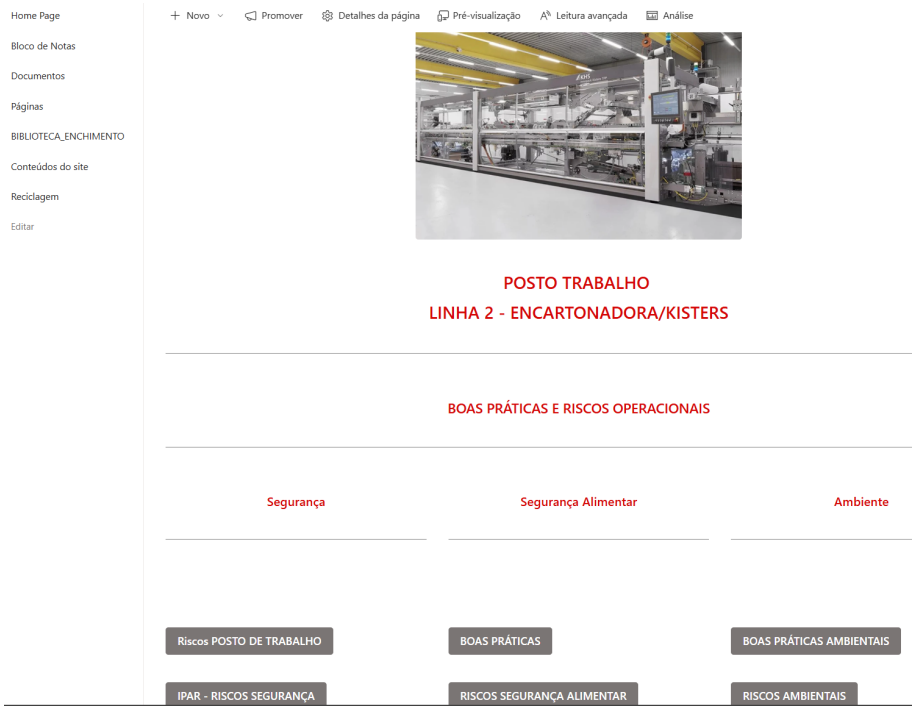


Figure 5.14: Internal hierarchical structure of the Line 2 KISTERS equipment in SharePoint.

- **Problem Solving:** The folder functions as an active diagnostic interface, actively interacting with the operator. It features direct hyperlinks to the PowerApps application for intuitive problem solving (developed in subchapter 5.1). Centralizing access to this tool allows the maintenance technician to have constant support for real-time decision-making, directly helping to reduce Mean Time To Repair during unexpected events.

- **Preventive Maintenance Guide and Tasks:** SharePoint fills existing gaps between tactical planning and operational execution. Specifically, it contains supporting information and direct links to the Weekly Preventive Maintenance Guide, using structured forms in Microsoft Forms software (detailed in subchapter 5.2). The maintenance guides are centralized, allowing inspections to be followed sequentially by the technician and, in the event of an anomaly, facilitating the collection of reliable data on the machine's technical condition.

- **Autonomous Cleaning and Autonomous Maintenance:** In line with TPM principles, the folder related to weekly cleanings aims to assist and empower operations teams.Internally, the folder stores digital forms to support the weekly cleaning routine, as well as operational procedures and visual matrices to support autonomous maintenance (discussed in Chapter 6), which are essential for preserving the company's core assets.

Internally, it is necessary to ensure that the created repository is in full compliance with the regulatory requirements of ISO 9001, particularly from the perspective of Knowledge Management and Quality Engineering.

The original files of all operational procedures are protected in an isolated area of the quality department's digital system, thus guaranteeing all document control standards of the production department. In this way, the Production SharePoint only presents secure hyperlinks to the origin of these files.

The adopted digital strategy ensures that operators and technicians on the production line only access the most recent formally approved version, completely eliminating the risk of outdated information, duplicate documents, or tasks performed according to non-existent or revoked standards.

The practical result of this knowledge integration is exemplified in Figure 5.15, which shows the physical allocation of the finalized Standard Operating Procedures directly on the Kisters machine frame. This configuration guarantees that, even in scenarios of temporary lack of digital connectivity or mobile device unavailability, the standardized procedures remain accessible at the point of use (gemba), ensuring the continuity of the autonomous maintenance routine.



Figure 5.15: Physical posting of the Standard Operating Procedures (SOPs) for Autonomous Maintenance on the Kisters machine.

5.3.5 Cyber-Physical Interfaces (QR Codes) and Future Work Roadmap

The main factor that motivated the immediate creation of the "Workstation Documentation" directory was to enable the creation of a digital-physical interface between the operator and SharePoint using QR codes. From the perspective of Process Engineering and Lean Manufacturing, the time spent by an operator or technician manually searching for documents in complex folder structures represents a chronic waste of movement and processing.

To eliminate this gap, URLs were generated to access the optimized folders created (Figure 5.16). The corresponding QR codes were printed using a thermal transfer printer, using heat to melt and transfer the ink from a ribbon to the ribbon surface. The ribbon was cut and positioned on the Kisters frame.

Therefore, the installed tapes guarantee a high-impact logistical shortcut and serve as a mechanism for preventing information errors. By scanning a QR code with a tablet or smartphone, the user avoids spending time searching for the necessary information. Thus, depending on the QR code accessed, they can instantly access a range of critical information, including preventive maintenance documents, troubleshooting guides, and Operational Procedures for Autonomous Maintenance. The created configuration thus ensures a precise and immediate response to the factory's urgent needs.

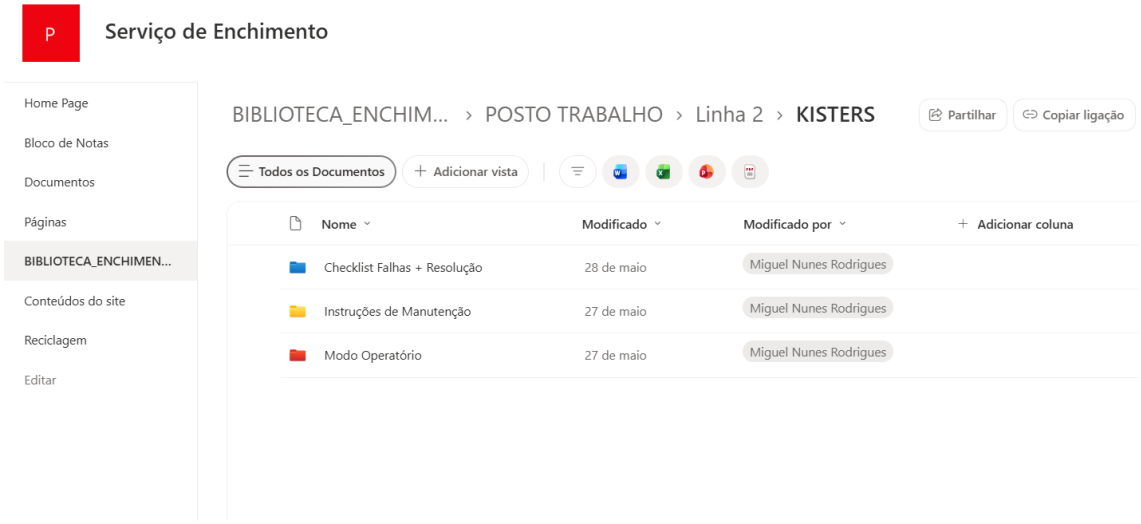


Figure 5.16: Direct view of the Workstation Documentation accessed via QR Code on the shop floor.

Although the initial implementation successfully demonstrates a Just-in-Time information flow, allowing the operator to access the right document at the exact moment of use, this is currently only the foundation of a much broader ecosystem.

Therefore, the strategic steps and work to be performed in the future to advance the project will require a deeper and more multifunctional expansion of the existing database. In the short and medium term, it is expected that digital segmentation for each machine will increase to include functional tabs focused on QHSE.

The horizontal expansion will thus integrate environmental records such as good Practice Manuals and dynamic mapping of operational risks, specific data on Personal Protective Equipment for use in maintenance tasks, laboratory self-monitoring parameters (such as chemical dosages and disinfection times), specifications and sizing of packaging materials, standard procedures, and historical records for deep cleaning validation.

Chapter 6

Autonomous Maintenance Implementation and Cyber-Physical Systems (CPS) Integration

6.1 Operational Execution: Field Deployment

Following the methodological framework defined in Chapter 3, this chapter details the physical implementation of Autonomous Maintenance measures on the Kisters case-packing machine. After establishing the strategy based on the PDCA cycle, the subsequent focus is on the transition from planning to execution, specifically addressing the shop floor constraints that previously obscured operator autonomy, namely the lack of standardized knowledge, unavailability of tools at the point of use, and organizational resistance.

6.2 Workplace Ergonomic Engineering: 5S Methodology and *Kanban* Systems

With the knowledge barrier successfully overcame through visual documentation, the focus of this dissertation redirected toward workstation architecture, aiming for the elimination of localized logistical inefficiencies. Historically, an immaturity in the operational maintenance process was observed, arising from systemic factors: a deficit in technical training, a lack of ownership regarding machine downtime, and the absence of replacement parts near the equipment. Through the lens of the *Lean Manufacturing* philosophy, an operator's movement to search for a tool or spare part in the central workshop constitutes an elementary waste of time.

To eradicate this non-value-added workflow and foster autonomy in troubleshooting, the 5S Methodology - a foundational tool of *TPM* - was deployed, with a particular emphasis on the *Seiton* (Set in Order) pillar. This pillar postulates that maximum efficiency is achieved when there is a place for everything, thereby minimizing searching time. The engineered solution was materialized through the conceptual design of modular physical supports to implement two proximity *Kanban* systems at the point of use.

The rigorous selection of the components to be integrated into these *Kanbans* was not arbitrary, but rather based on a balanced matrix of engineering criteria and risk management: high-wear components with high turnover rates were selected, alongside with parts that require low substitution complexity, and components with a low unit cost to mitigate the financial risk of loss or improper use. By empowering the Production team with these local resources, the specialized Maintenance team is liberated to focus on high-value-added preventive tasks, directly driving a targeted reduction in the MTTR.

6.2.1 Architecture and Content of Proximity Kanbans

The initial *Layout Assessment* phase required the analysis of multidimensional constraints: the supports could not pose an ergonomic risk, had to avoid collisions with the machine's kinematic envelope, and needed to withstand environmental sanitation operations. The ideal location identified was on the faces of the Kisters KHS cartoning machine's metallic safety guards, dividing the system into two substructures:

- ***Kanban* 1 (Forming Zone):** Allocated on the bordering metallic wall between the forming and folding modules. It houses the transfer combs and their respective fastening screws. It likewise integrates the electronic IoT prototype (detailed in subchapter 6.3) developed to enable rapid visual stock identification without interrupting the production cycle. This is a critical premise, since the opening of the safety doors triggers the safety interlocks, forcing an immediate stop of the servomotors.
- ***Kanban* 2 (Wrapping Zone):** Positioned within the folding and film-wrapping zone. It contains the roller carriages used in the transfers between modules and the folding pads, with their respective fixings. These pads play a crucial kinematic role in the mechanical folding of the cardboard flaps around the bottles, a high-precision process that occurs immediately after the hot-melt glue extrusion into the blanks' grooves.

The three-dimensional CAD (*Computer-Aided Design*) modeling of the supports was executed using *SolidWorks* software. The design methodology focused on structural rigidity and user intuition (Figure 6.1). The structure of *Kanban* 1 features slots designed with tight clearance tolerances, acting as mechanical locking elements that dissipate kinetic energy and mitigate the resonant longitudinal vibrations of the machine chassis.

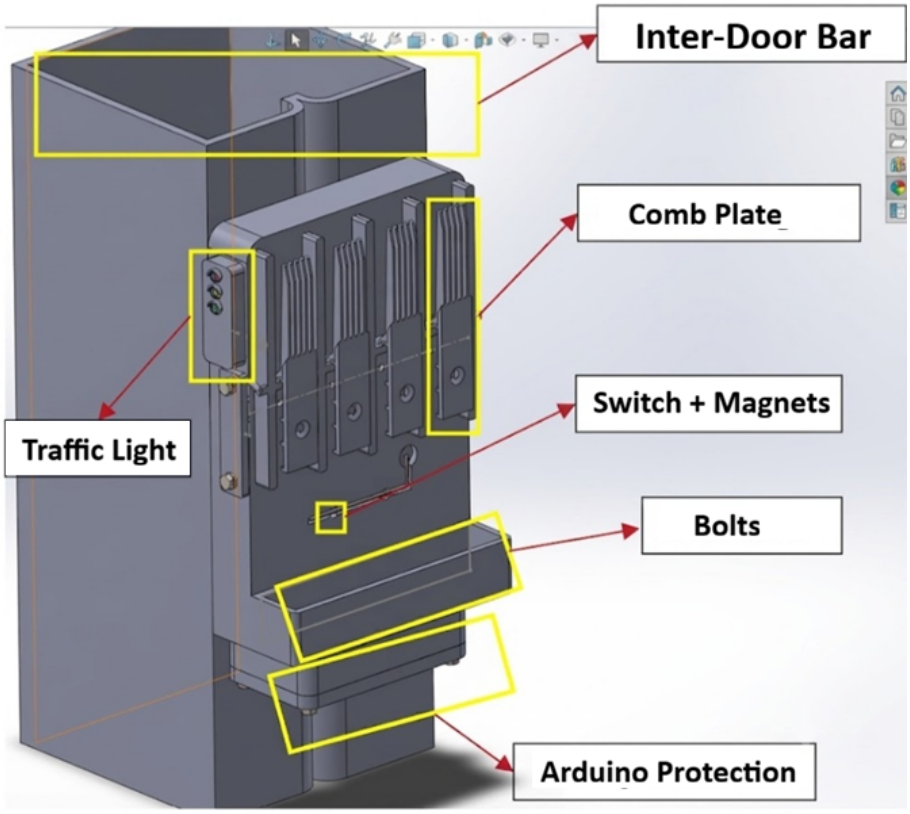


Figure 6.1: Three-dimensional modeling of the *Kanban* system support 1.

In a practical demonstration of *Poka-Yoke* (error-proofing) mechanisms, the model integrates a specific slot for the FESTO 4 mm Allen key diameter. To avoid mechanical fits prone to frictional wear, a magnetic retention system utilizing cylindrical Neodymium magnets of $\emptyset 8 \times 4$ mm was selected. The magnetic holding force ensures a high safety factor against vibrational acceleration peaks, guaranteeing that tools will never drop onto the machine's spindles or gears, which would otherwise precipitate a catastrophic failure or the loss of the tool.

This virtual approach assured dimensional and geometric compatibility prior to physical materialization. The final outcome can be observed in Figure 6.2. The 3D-printed support is already seamlessly secured to the machine's metallic chassis, housing all predefined critical elements in a standardized layout.



Figure 6.2: Physical implementation and point-of-use demonstration of the *Kanban* 1 system support on the Kisters cartoning machine, showing the housing of the feed combs, conical screws, and the retention of the intervention tool.

Appendix A.4 details the exploded view of the L2 *Kanban* system, highlighting the arrangement of the infrared sensors, the integration of the Arduino board, and the mounting system of the traffic light module.

Although the implementation of the electrical part of *Kanban* was delayed due to time constraints, the mechanical part achieved the initially set objective.

6.2.2 Operational Circuit for Material Replenishment

The efficacy of a physical *Kanban* system depends entirely on the robustness of its supporting logistical workflow. The engineered operational circuit governs the communication and the *Pull* logistical flow between the Filling Line, the Workshop, and the Central Warehouse, operating within a closed-loop cycle of four stages, as outlined in the flowchart of Figure 6.3.

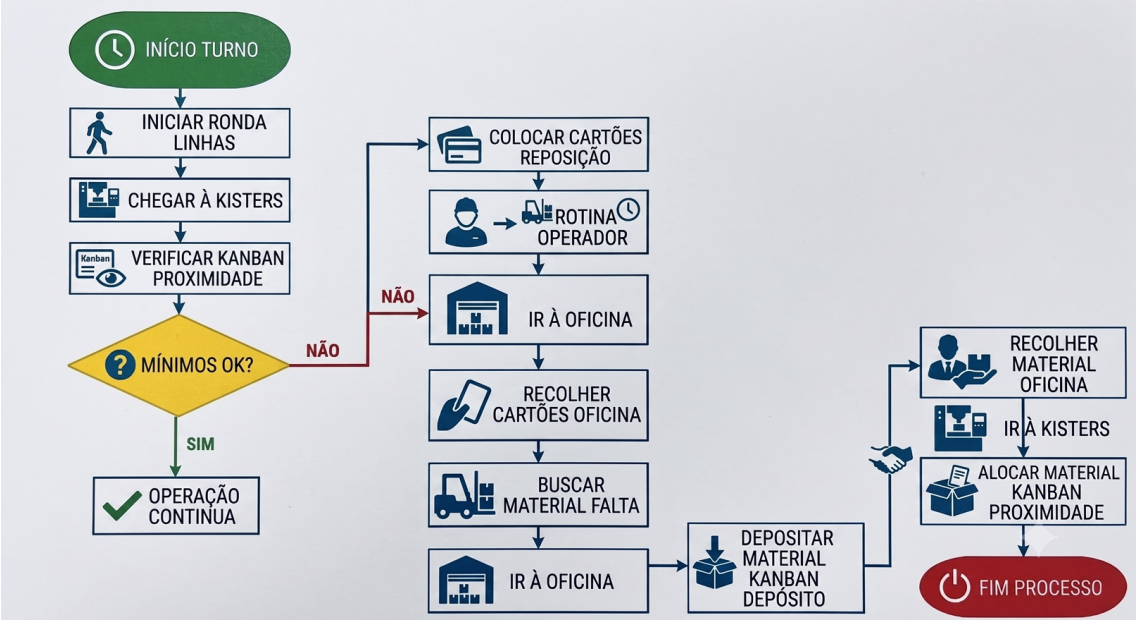


Figure 6.3: Flowchart of the operational circuit and material replenishment routine of the proximity *Kanban* system.

The operational cycle is standardized into the following phases:

1. **Consumption and Signaling (Filling Line 2):** The process is triggered when the operator detects an abnormal wear or failure. Upon consuming a replacement part available in the proximity *Kanbans*, the operator removes the respective "Kanban Card" (replenishment signal) and places it on their auxiliary desk. At the end of the shift, the Team Leader collects all activated cards.

2. **Transition Point and Request (Workshop):** The Team Leader moves to the Workshop, which acts as the logistics transition hub, and deposits the collected cards onto the Central *Kanban* Board.

3. **Preparation and Dispatch (Central Warehouse):** On a strict 48-hour schedule, the Logistics Technician from the Central Warehouse checks the board in the Workshop. After quantification of the requirements, the Warehouse executes the picking of the requested parts and dispatches them back to the Workshop.

4. **Reception and Replenishment (Cycle Closure):** The new parts are deposited into the Workshop's Inbound Box. At the beginning of each shift, the responsible Team Leader collects these components, transports them to the Filling Line, and performs the physical replenishment into the machine supports during a window of opportunity (planned stoppage). This step ensures that the *Kanbans* return to their optimal inventory levels, sustainably closing the logistical loop.

6.3 The Digital Lean Paradigm: IoT Inventory Prototype (Cyber-Physical Systems)

Although the mechanical implementation of the *Kanban* resolves *Point-of-Use* access, its physical location inside the acrylic guards introduced a new process inefficiency.

To visually inspect the inventory level of the spare parts, operators and logistics teams were forced to open these safety doors. This mechanical action trips the safety interlock devices, cutting power to the servomotors and resulting in an immediate stoppage of plant production. Halting a high-cadence production line solely for inventory verification constitutes a glaring inefficiency and a paradox of traditional *Lean* management.

To overcome this limitation, the present project elevated the state of the art of the system into the realm of *Digital Lean* by integrating Industrial Internet of Things principles into the monitoring of wear components. An intelligent electronic inventory control system was designed and assembled, structured as a Cyber-Physical System, which fuses the physical and digital (real-time data feedback) dimensions.

The computational architecture is orchestrated by an 8-bit ATmega328P microcontroller, embedded within an Arduino Uno R3 prototyping platform. The system adopts a solid-state, non-contact optical sensing topology, superseding vulnerable mechanical limit switches, which would undergo accelerated degradation (wear and tear) due to cyclic actuation and susceptibility to moisture accumulation. A matrix of reflective infrared sensor modules (TCRT5000) was deployed, housing an IR light-emitting diode and an adjacent phototransistor. These elements are mechanically aligned with the guide channel of each transfer comb. When the mechanical component is in its housing, it reflects the infrared radiation back to the phototransistor, generating an analog variation in the output voltage. The prototype circuit is represented in Figure 6.4.

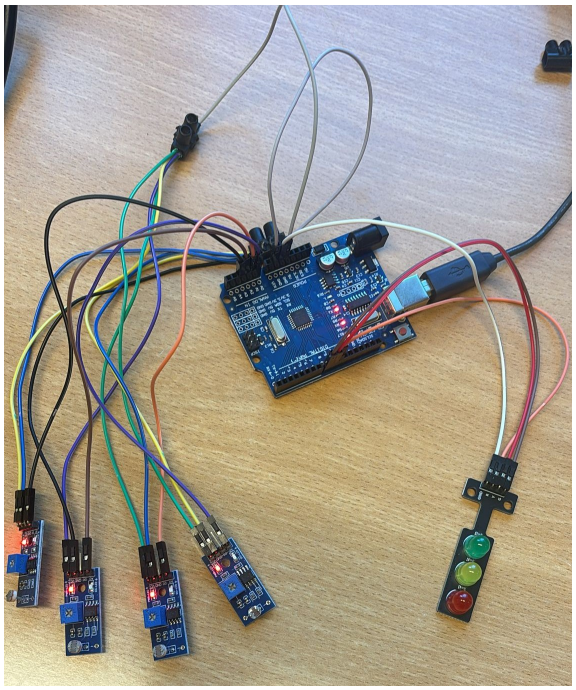


Figure 6.4: Cyber-Physical System Prototyping. On the left, the TCRT5000 optical sensor array for mechanical Kanban detection; in the center, the Arduino Uno R3 microcontroller; on the right, the triple-signaling LED traffic light module for inventory status feedback.

The *firmware*, developed in C/C++ language, executes a continuous conditional sampling loop. To ensure signal stability in environments characterized by high harmonic vibration, the appended code integrates a dynamic triggering threshold and debouncing algorithms, successfully ignoring transient noise. The logical inference of the inventory status culminates in the actuation of power transistors that control a triple-signaling LED traffic light module, installed on the exterior of the acrylic guard:

- **Green LED Activated (Nominal State):** The system detects the presence of 3 to 4 transfer combs inside the housing. Therefores, the production line operates with no risk of disruption due to a lack of accessories.
- **Yellow LED Activated (Alert Point):** The microcontroller gauges the presence of only 2 combs. This state triggers the *Reorder Point*, visually signaling to supervisors the need to plan replenishment during the next scheduled stoppage.
- **Red LED Activated (Critical State):** Imminent or effective stockout (1 or 0 combs). This state requires urgent logistical intervention to prevent extended downtime (*Extended Downtime*).

The validation of the electrical design was consolidated through the routing and single-line schematics within the open-source software *KiCad E.D.A.* (Appendix A.5). The prototype successfully demonstrated the unequivocal value added by digitization to the

internal supply chain. Architecturally, the module is currently stabilized to transition from a benchtop prototype into industrial-grade hardware, through the scaling of voltage regulation circuits (*Buck Converters*) capable of interfacing directly with the 24 VDC bus provided by the Siemens-Kisters machine's power supply.

6.4 Manufacturing Optimization through Additive Manufacturing

The transition from digital models (CAD) to the physical materialization of the *Kanban* supports was heavily constrained by the budgetary and scheduling boundaries inherent to maintenance engineering. Producing customized components, such as Jigs and Fixtures, in unit series through traditional machining (CNC milling of aluminum or polyacetal blocks) would impose several weeks of lead times and prohibitive operational costs. To bypass this operational inertia, Additive Manufacturing technology was embraced, specifically the Fused Deposition Modeling process.

3D printing within modern industrial environments ceases to be merely a rapid volumetric validation tool and establishes itself as a reliable method for production-grade tooling. The material selection underwent rigorous engineering scrutiny. The use of PLA was rejected due to its low glass transition temperature (susceptible to thermal deformation) and its impact brittleness. Instead, PETG filament was selected. PETG offers superior toughness, excellent interlayer adhesion, and outstanding chemical resistance against hydrocarbons and aggressive sanitation agents routinely deployed in the beverage industry.

In Appendix A.6, the manufacturing preparation and the configuration of slicing parameters within the *Bambu Studio* software are referenced.

The parametric optimization of the three-dimensional slicing, executed in the *Bambu Studio* software, aimed to maximize the ratio between structural integrity and printing time/cost. A strict infill density of 15% was specified. To counteract the directional anisotropy typical of the FDM process (tensile strength orthogonal is substantially lower), a Gyroid infill pattern was applied. As an infinite minimal surface free of self-intersections, the gyroid structure yields a quasi-isotropic mechanical strength (uniform across the X, Y, and Z axes), uniquely absorbing unpredictable torsional forces generated by the cartoning machine's kinematics.

Due to the build volume constraints (*Z-height limit*) of the available 3D printer, the total height of the *Kanban* base required the digital sectioning of the model into two halves. The post-processing joint assembly of the printed parts posed a fracture mechanics challenge. For the chemical inter-part bonding, a high-density cyanoacrylate-based adhesive coupled with an aerosol activator was utilized, promoting instantaneous polymerization and the creation of cross-linked chains that impart structural rigidity to the joint.

Finally, the fastening of the *Kanban* supports onto the machine's oscillating metallic safety guards required the exclusion of intrusive mechanical fasteners. For this purpose,

Loctite 406 instant adhesive was applied, which is a low-viscosity cyanoacrylate adhesive specifically formulated for bonding plastics and elastomers. This adhesive stands out due to its near-instantaneous polymerization and the formation of a high-strength structural joint, ensuring absolute adhesion between the PETG panels and the metallic substrate. The selection of this technical solution enables a clean and permanent assembly, featuring a tensile shear strength that secures the integrity of the assembly against the high-frequency mechanical vibrations typical of the cartoning machine, thereby guaranteeing that the *Kanban* system remains static and seamlessly bonded to the machine frame over time.

6.5 Internal Supply Chain Engineering and Operational Digitalization

The mechanical implementation and autonomous maintenance would represent transient solutions had they not been anchored upon a robust internal supply chain. A production system centered on Autonomous Maintenance fails, comprehensively, when the responsibility for requesting, transporting, and bureaucratically managing consumables falls upon the same technical team that should be focused on equipment intervention. To insulate operations from this burden, the logistical workflow was restructured in accordance with the *Pull* production paradigm of the classic *Kanban* system, abolishing the inefficiencies inherent to stochastic *Push* models.

The engineered *Supply Chain Loop* integrates a high degree of interdepartmental coupling, divided into three functional phases:

1. **Stochastic Parameterization and Safety Stock:** In the first instance, the data extracted by the Python model (Chapter 4) regarding the actual consumption rate of the joints and transfer combs was cross-referenced with the lead times of external suppliers. This matrix enabled the analytical redefinition of the Safety Stock Limit within the Central Warehouse, ensuring that the service level remains inviolable against unpredictable peaks of fatigue failures.

2. **Decentralized Trigger and Kanban Pull:** The Production Team Leader, during tactical supervision and equipped with real-time visual information provided by the electronic IoT traffic light, monitors inventory levels at the Point-of-Use. Upon approaching the predefined critical threshold, the supervisor removes a physical Replenishment Kanban Card, positioned in the lower slot of the PETG support, and inserts it into a centralized collection board. The card acts solely as a visual movement order.

3. **Milk Run Logistics and ERP Synchronization:** Without requiring phone calls or hierarchical procedures, a dedicated internal logistics operator performs a periodic route (*Milk Run*), collects the activated cards, and immediately processes the

material issue transaction within the integrated ERP management system, operating under the SAP MM module. Subsequently, the same distributor physically replenishes the *Kanban* on Lines 1 and 2, closing the logistical loop seamlessly for the factory's technical team.

As the culmination of this vanguard industrial ecosystem, the project absorbed corporate transformation directives focused on eliminating paper support. Relying on printed dossiers and manuals within the physical environment of a beer filling line constitutes a technological incongruity and a quality management risk. In fact, pages degrade rapidly due to the condensation, the lubricant splatters and the sanitizing fluids, invariably leading to the consultation and practical application of obsolete guidelines.

The three new Standard Operating Procedures were hyperlinked within a central *Cloud* repository. As the final link to the user, highly durable and universal QR codes were generated and affixed to the Operation Mode Panel and the panels of the Kisters KHS cartoning machine.

In the event of a comb or roller failure, any operator equipped with a service tablet or industrial smartphone can, within a fraction of a second, perform an optical scan and directly access the immutable and always updated digital version of the repair instructions.

Chapter 7

Mechanical Re-engineering and Quality Control

This chapter explores the physical engineering interventions designed to eliminate two of the most critical mechanical bottlenecks in the Kisters packaging lines. The approach is twofold: firstly, a mechanical re-engineering solution is developed to prevent kinematic failures caused by internal hot-melt adhesive contamination. Secondly, a quality control Poka-Yoke mechanism is designed, supported by Finite Element Analysis (FEA), to intercept external non-conforming packaging materials before they disrupt the machine's synchronized workflow. Together, these interventions physically sustain the reliability gains intended by the digitalization strategy.

7.1 Mechanical Solution Development: Redesign and Optimization of the Hot-Melt Gluing System

The core operational constraint addressed in this chapter is the chronic and uncontrolled accumulation of hot-melt industrial adhesive on the machine's kinematic tools and articulation rollers. Due to the rapid solidification and high bonding strength of this thermal adhesive, recurrent leaks act as a severe abrasive and locking agent, leading to premature mechanical jamming, accelerated component wear, and forced line stoppages. Consequently, this persistent failure mode demanded an urgent, targeted redesign intervention focused on *Kaizen* and long-term asset reliability.

To ensure a robust and sustainable resolution, the problem was approached through the Process Engineering and Operations Management. Rather than merely applying corrective maintenance patches, the intervention was structured around a rigorous Root Cause Analysis to identify the systemic origin of the adhesive dripping. Furthermore, the decision-making process was heavily supported by a comprehensive economic viability

analysis. This financial evaluation was crucial to mathematically balance the capital expenditure required for different mitigation alternatives against the hidden costs of deferred maintenance, spare parts consumption, and lost manufacturing capacity.

Following the analytical phase, this chapter describes the transition from the conceptualization stage to product engineering. It details the precise geometric modeling of a physical containment system in a three-dimensional computational environment (CAD), the material selection tailored to withstand thermal chemical stresses (stainless steel) and the generation of standardized technical drawings for manufacturing to order the part from the stainless steel parts supplier.

Finally, this chapter outlines the physical integration of the custom solution onto the shop floor. It emphases that the SharePoint modifications are only as effective as the organizational processes that govern them, and that the implementation phase also covers the necessary alignment with Total Productive Maintenance principles. This is achieved through the integration of the new SharePoint into the Operations team's Cleaning Maintenance Standard Operating Procedures, ensuring the compliance of the implemented engineering solution.

7.1.1 Problem Diagnosis and Root Cause Analysis

During the systematic monitoring of the equipment Kisters operational behaviour, empirical evidence and maintenance logs corroborated that the chronic accumulation of hot-melt adhesive on the articulation rollers was the primary root cause of their premature mechanical degradation and subsequent jamming.

The historical data revealed an high frequency of corrective interventions required to replace these kinematic sub-assemblies, a recurring failure mode that severely penalized the filling line's OEE.

A comprehensive Root Cause Analysis traced this unwanted adhesive contamination back to the dynamic behavior of the electro-pneumatic solenoid valves. These application modules are responsible for firing the precise hot-melt adhesive beads required to securely seal the cardboard box flaps under high-speed operation. The nominal operational cycle of this hybrid electro-pneumatic system is governed by a high-frequency sequence:

1. PLC transmits a digital command signal to energize the solenoid valve coil;
2. The active energized solenoid redirects the compressed air flow towards the pneumatic cylinder of the applicator head;
3. The pneumatic pressure induces the retraction of an internal needle-piston housed within the heated gluing gun;
4. The displacement of the piston unseats the nozzle, allowing the extrusion of the highly pressurized, high-viscosity molten adhesive onto the target packaging surface.

Under ideal theoretical conditions, the de-energization of the control signal should trigger an instantaneous closure of the internal piston, ensuring a seal and the immediate stoppage of the adhesive flow. However, the system exhibited persistent vertical leakage, through adhesive dripping, as illustrated in the real industrial inspection of Figure 7.1.



Figure 7.1: Visual inspection of hot-melt adhesive accumulation and dripping on the solenoid valve application nozzles.

The RCA identified several concurrent mechanical and fluid-dynamic factors driving this anomaly.

Firstly, these drips stem from incomplete piston seating, which is typically driven by the tribological wear of internal seals, particulate contamination, or mechanical fatigue of the return spring.

Secondary contributing factors include pneumatic hysteresis or micro-leaks within the solenoid block, excessive residual hydraulic pressure trapped in the delivery hoses, and abrasive geometric deformation of the applicator nozzle tip.

Due to the vertical alignment of the machine's architecture, these residual drips fall directly onto the underlying folding zones. Given the rapid thermal cooling gradient of hot-melt adhesive, the molten droplets quickly solidify upon contact with the cooler metallic surfaces of the articulation rollers.

Over successive cycles, this hardened adhesive acts as an abrasive locking agent, inducing excessive mechanical friction, seizing the rotational axes, and ultimately leading to the catastrophic failure of the kinematic assemblies.

As seen in detail in Figure 7.2, the deposition and accumulation of the thermal adhesive occur precisely on the articulation rollers. This dripping contamination is severely exacerbated during the dynamic passage and cyclic motion of the mechanical articulations, at which point these kinematic elements are exposed directly beneath the vertical trajectory of the residual adhesive. The rotational movement of the rollers themselves subsequently spreads the adhesive, while still in its highly viscous fluid state, across the bearing tracks. This action accelerates the mechanical obstruction process, culminating in a localized solidification that ultimately seizes the system.



Figure 7.2: Solidified hot-melt adhesive accumulated on the articulation rollers, illustrating the aftermath of the chronic dripping issue.

7.1.2 Economic Viability Analysis and Impact on Downtime

Resolving this problem required a comparative economic study to evaluate the balance between component replacement costs and production downtime losses. The complete replacement of a solenoid valve module incurs a high unit cost of 2,122.37 €. Given that the machine has 8 independent applicator heads, responsible for gluing the 8 corners of each cardboard box, the annual replacement cost is fixed at Equation 7.1:

$$\text{Current Annual Cost} = 8 \times 2,122.37 = 16,978.96 \text{ €} \tag{7.1}$$

If the organization opted for a quarterly preventive replacement strategy to fully mitigate dripping, the annual financial burden would suffer an unsustainable increase (Equation 7.2) :

$$\text{Projected Quarterly Cost} = 16,978.96 \times 4 = 67,915.84 \text{ €} \tag{7.2}$$

This approach would represent a net annual increase of 50,936.88 €, making it financially unviable for the company's asset management.

On the other hand, corrective maintenance of the damaged articulations also presented a severe impact. Between the second semester of 2024 and the second semester of 2025, 62 failure occurrences were recorded in these components across Lines 1 and 2. Empirical data collected from the mechanical maintenance teams showed that exactly half of these failures (31 occurrences) were directly caused by hot-melt contamination. Considering that each articulation has a replacement cost of 293.27 €, the accumulated direct cost in

spare parts totaled (Equation 7.3):

$$\text{Direct Parts Cost} = 31 \times 293.27 = 9,091.37 \text{ €} \tag{7.3}$$

More critical than the direct cost of the components is the logistical impact associated with downtime. Each intervention to replace a damaged articulation requires a MTTR of 90 minutes. Multiplying this indicator by the 31 annual occurrences caused by the adhesive yields the totalized impact on the line's production capacity (Equation 7.4):

$$\text{Accumulated Downtime} = 31 \times 90 = 2,790 \text{ min} = 46.5 \text{ hours} \tag{7.4}$$

The loss of 46.5 annual hours of operation in a high-cadence filling line represents a massive opportunity cost, fully justifying the development of a local engineering solution.

7.1.3 Solution Development: CAD Modeling and Technical Design

To solve the problem without incurring the prohibitive costs of quarterly solenoid valve replacements, a mechanical protection and retention system was designed. The solution was based on the introduction of retention plates installed below the solenoid valves and bolted to the machine frame, designed to intercept and contain vertical adhesive drips before they reach the kinematic components. The underlying philosophy was to implement a localized, non-intrusive physical barrier capable of enduring the harsh dynamic environment of the packaging line without compromising the machine's primary kinematic envelope.

The development process began with a careful dimensional survey inside the wrap-around packer, measuring the operational clearances and distances between the solenoid valve nozzle and the moving mechanisms. This phase was vital, since any dimensional deviation exceeding the allowable tolerances would cause mechanical interference with the cardboard folding zone, leading to constant collisions. Using precision metrology tools, the spatial constraints and interference zones were mapped out, ensuring that the protective barrier could be retrofitted within the tight confines of the Kisters KHS chassis without disrupting the high-speed folding of the box flaps.

Once geometric viability was validated, the three-dimensional prototype was developed using SolidWorks software. The top protection plate was designed collectively with a truss support structure, ensuring stability against structural vibrations (inherent to cyclic packaging machinery) and facilitating direct drainage, as illustrated in the 3D model in Figure 7.3. The truss geometry was optimized to distribute mechanical stresses evenly, preventing fatigue failure from continuous operational movement.

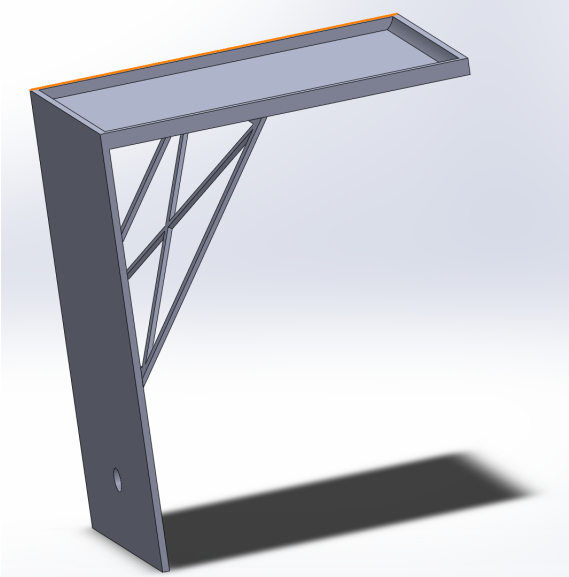


Figure 7.3: Three-dimensional CAD modeling of the top protection plate and truss support structure.

Subsequently, the technical detailing and modeling of the bottom base of the retention system were completed. Figures 7.4 and 7.5 display the isometric and bottom perspectives of this component, highlighting the drilling designed for rigid fixation to the Kisters KHS chassis. Counterbored holes and machined channels were incorporated to allow micro-adjustment during installation, accommodating small deviations in the existing framework.

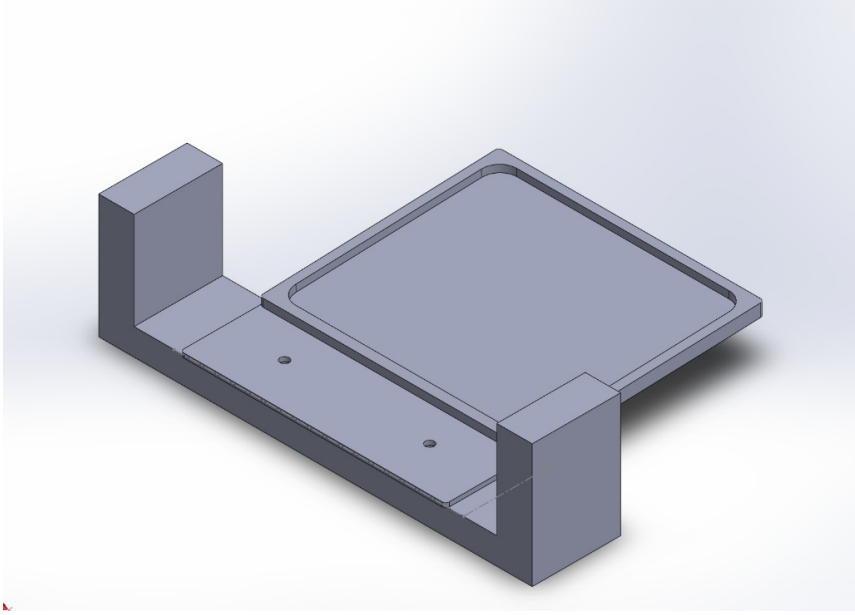


Figure 7.4: Isometric perspective of the CAD model of the retention system bottom base plate.

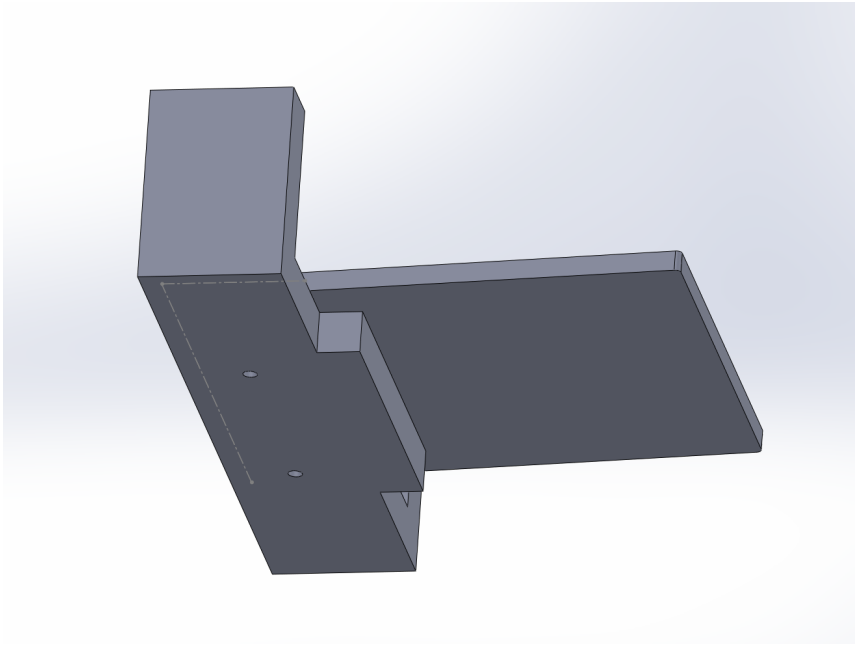


Figure 7.5: Bottom perspective of the CAD model highlighting the mechanical positioning counterbores and channels.

Following the approval of the virtual models, standardized technical drawings were generated for manufacturing. The material selected for all components was Stainless Steel (AISI 304), ensuring the mechanical strength needed to resist against the high temperatures of the hot-melt glue, frequently above 160°C, and preventing oxidation corrosion during the factory's chemical wash cycles. Staniless Steel AISI 304 was also chosen for its excellent toughness, resistance to thermal distortion, and superior corrosion resistance against aggressive industrial detergents used in daily sanitation protocols.

The detailed drawings of the top plate, the support truss, and the bottom base are documented in Figures 7.6, 7.7, and 7.8, respectively, detailing tolerances, bend radius, and surface finishes.

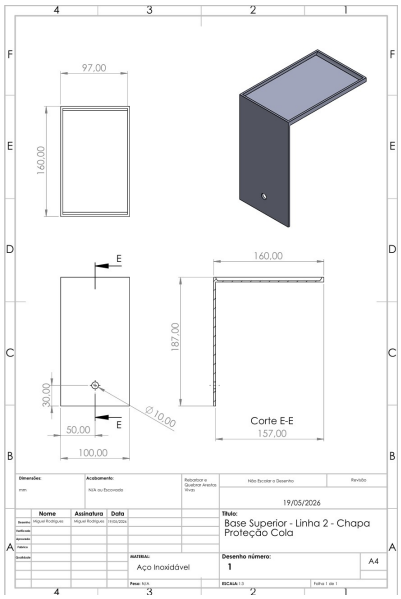


Figure 7.6: Dimensioned technical drawing of the top protection base geometry against adhesive.

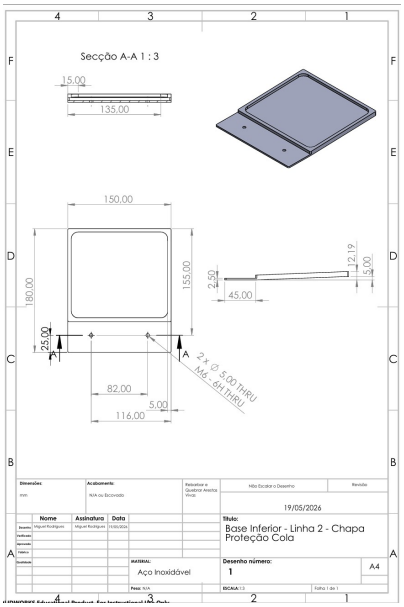


Figure 7.7: Technical drawing and dimensional specifications of the mechanical reinforcement truss structure.

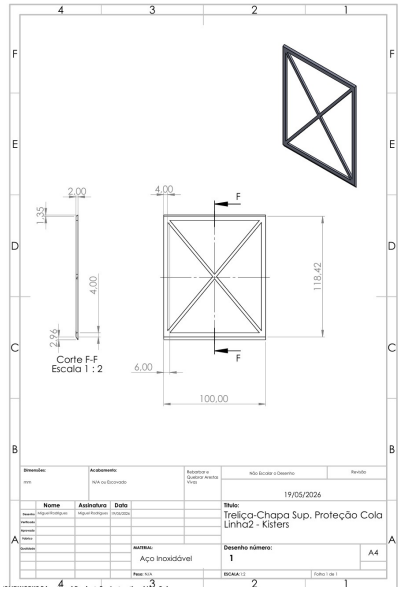


Figure 7.8: Dimensioned technical drawing of the bottom base plate with standardized fixation drilling.

The engineering files were sent to an external supplier specialized in laser cutting and precision metalworking. The manufacturing and physical replication process of the plates took approximately 3 weeks, guaranteeing high dimensional accuracy and minimal kerf deformation via CNC laser processing. In parallel, metric fixation bolts (A2-70 stainless steel) and respective nord-lock or spring washers were acquired to prevent loosening under operational vibration, successfully completing the assembly and physical integration of the project on the Line 2 shop floor.

7.1.4 Final Implementation and Integration on the Factory Floor

The physical implementation and installation of the retention plates were successfully carried out during the weekly preventive maintenance downtime, following the execution of the planned cleaning and preventive tasks. The integration phase of the new plates had the hands-on support and technical collaboration of an experienced maintenance technician, which ensured compliance with the application's stringent safety protocols and precise mechanical alignment, according to the specific characteristics of the Kisters machine.

Initially, during the physical shop-floor integration of the two ordered plates, specific spatial limitations were identified regarding the tray format. The manufacturing design for the smaller tray and the corresponding adjustment of the lower solenoid valve associated with it requires a dimensional precision of the plate that is impossible to guarantee, as the plate could lightly scrape against the articulations and cause severe damage to the assembly. Consequently, it was necessary to repurpose this same acquired plate to achieve the previously defined protective function. Therefore, the execution was planned for the two upper glue applicator valves (bimodal and unimodal).

Therefore, a custom structural adaptation was conceptualized. A secondary support bracket was fabricated to allow for rigid lateral fixation to the Kisters structure using two CHC M6x20 bolts. The bracket was subsequently welded using a coated electrode to the stainless steel plate, positioned exactly vertically beneath the glue nozzle. The adapted assembly will thus effectively intercept the vertical dripping of the glue. Figures 7.9, 7.10, 7.11 and 7.12 illustrate in detail the mechanical assemblies of the two final retention plates and their physical integration into the equipment.



Figure 7.9: Frontal perspective of the implemented retention system on the dual top valve, showcasing the welded support bracket and CHC M6x20 bolts.



Figure 7.10: Rear perspective of the dual top valve assembly, detailing the vertical alignment of the retention plate beneath the applicator nozzles.

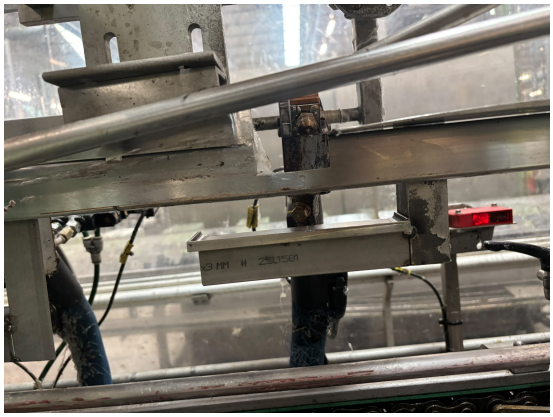


Figure 7.11: Frontal view of the retention tray adapted for the single top valve, highlighting the necessary spatial clearances.



Figure 7.12: Rear view of the single top valve setup, emphasizing the rigid fixation to the Kisters machine structure.

To ensure that the continuous improvement is effectively maintained, it was necessary to establish a formal autonomous cleaning routine for the two plates. As such, on a monthly basis, the operators will clean the accumulated glue from the retention plates. To perform the cleaning, the CHC M6x20 fixing bolts must be unscrewed, thus allowing

the safe extraction of the bracket. After removing the accumulated glue, the plates are refastened, allowing the machine to resume normal operation.

7.1.5 Cleaning Standardization and Operational Impact Assessment

The introduction of a physical retention barrier successfully resolves the immediate risk of kinematic roller contamination. However, it inherently introduces a secondary operational requirement by demanding a disciplined maintenance routine to prevent overflow and excessive adhesive accumulation on the retention plates themselves.

To ensure this does not become an appellant failure point, a standardized intervention procedure was formally instituted within the Operations team's Total Productive Maintenance framework, specifically under Autonomous Cleaning Maintenance routines.

Routine inspections and cleaning of the retention plates are scheduled on a monthly basis. Essentially, this intervention does not require dedicated downtime; however, the intervention is carried out within the scheduled technical time already allocated for preventive maintenance and detailed weekly cleaning of the machine. The mechanical design prioritizes rapid, tool-less or low-tool accessibility. The plates are detached simply by unfastening standard metric bolts with a manual hand wrench.

To guarantee safety and prevent contamination of the primary packaging zone, the plates are removed from the machine perimeter and cleaned on a designated workbench. The maintenance protocol requires the use of Nordson cleaning solvent alongside industrial scraping spatulas to safely strip away the solidified adhesive layers without damaging the stainless steel substrate. Once cleared of residue, the assemblies are reinstalled and rigidly torqued to specification. The structured autonomous maintenance tasks are summarized in Table 7.1.

Table 7.1: Autonomous Maintenance routine for the hot-melt retention system.

Frequency	**Action / Task**	**Tools & Consumables**	**Responsible**
Weekly	Visual inspection of plates for adhesive dripping	None (Visual check)	Operator
Monthly	Removal, solvent cleaning, and reinstallation	Hand wrench, Nordson solvent, industrial spatula	Operator and Maintenance Team
Biannually	Structural integrity and bolt thread wear check	Feeler gauge, torque wrench	Maintenance Technician

To analytically validate the engineering intervention, it is necessary to quantify the financial and productive impact of the downtime previously consumed by corrective maintenance on the kinematic articulations. Over the reference period, hot-melt contamination

forced 31 articulated joint replacements, each demanding an average of 90 minutes of corrective downtime, culminating in 46.5 lost production hours.

To establish a baseline for the plant's manufacturing capacity, the historical average OEE of the line was calculated using operational records from two consecutive periods, yielding 55.5% and 56.4%:

$$\text{OEE}_{\text{average}} = \frac{55.5 + 56.4}{2} = 55.95\% \tag{7.5}$$

Given that the high-cadence bottling line operates at a nominal production capacity of 60 000 bottles per hour, incorporating the baseline OEE yields an effective production throughput of:

$$\text{Effective Production} = 60\,000 \times 0.5595 = 33\,570 \text{ bottles/h} \tag{7.6}$$

Consequently, the volume of unrealized production during the 46.5 hours of inactivity caused directly by adhesive-induced failures is calculated as:

$$\text{Lost Production} = 33\,570 \times 46.5 = 1\,561\,005 \text{ bottles} \tag{7.7}$$

This production deficit of approximately 1.56 million bottles represents a severe economic setback. To comprehensively assess this impact, the loss was modeled under two distinct commercial scenarios, summarized in Table 7.2:

- **Scenario A – Net Contribution Margin:** Evaluating the loss solely through direct cash flow impact, where each unit carries a contribution margin between €0.05 and €0.15, the immediate fluid loss stands between **€78,050** and **€234,151**.
- **Scenario B – Factory Gate Sales Value:** Under a gross wholesale revenue perspective, where each bottle is valued between €0.30 and €0.60 at the factory exit, the unrealized revenue fluctuates between **€468,302** and **€936,603**.

Table 7.2: Financial impact of unrealized production due to downtime.

Modelling Scenario	**Unit Value (€)**	**Lower Limit (€)**	**Upper Limit (€)**
Scenario A: Contribution Margin	0.05 – 0.15	78,050	234,151
Scenario B: Factory Gate Sales	0.30 – 0.60	468,302	936,603

In summary, this low-cost mechanical redesign functioned as a highly effective physical *Poka-Yoke* device. By intercepting and neutralizing adhesive dripping at the source, the design completely eliminated the annual expense of €9,091.37 previously wasted on replacing stuck joints. In addition, it protected the organization against a productivity loss equivalent to €230,000.

7.2 Quality Control Integration: Mitigation of Non-Conforming Packaging Materials

7.2.1 Problem Diagnosis: Material Degradation and Kinematic Impact

In high-speed packaging lines, equipment reliability is inextricably linked to the structural quality of the raw materials. The corrugated cardboard utilized in the Kisters KHS packer must act as both a precise kinematic blank during folding and a robust load-bearing structure during palletization. However, empirical observation on the shop floor reveals frequent deviations from quality specifications, transforming non-conforming packaging into a primary agent of machine failure.

The structural degradation of these blanks is primarily driven by two logistical root causes:

1. **Hygroscopic Softening:** Being inherently hygroscopic, the cellulosic fibers in the cardboard absorb moisture when stored in environments with high Relative Humidity. This disrupts the intermolecular hydrogen bonds, leading to a non-linear reduction in Young's Modulus and macroscopic warpage (Figure 7.13), which impairs the machine's feeding accuracy.

2. **Localized Plastic Deformation (Strapping Over-tension):** Automated pallet strapping often applies tensile forces exceeding the cardboard's transverse compressive yield strength. This concentrated radial pressure causes irreversible plastic buckling of the corrugated medium (Figure 7.14), effectively collapsing the "I-beam" structure of the board and creating a structural hinge that triggers jams within the feeding magazine.



Figure 7.13: Batch of cardboard blanks exhibiting severe macroscopic warpage at the upper layers due to hygroscopic softening and lack of structural support.



Figure 7.14: Visible creasing and structural web collapse caused by excessive localized contact pressure from polymeric strapping bands.

These defects are significantly more pronounced in tray formats, which utilize lower grammage and lower-profile flutes to optimize costs, resulting in a lower Area Moment of Inertia (I) and reduced mechanical resistance to deformation.

When these compromised blanks enter the Kisters KHS packer, they disrupt the machine's calibrated kinematic envelope. The resulting issues include:

- **Material Waste:** A manual disposal rate averaging 35 blanks per batch for trays, increasing operational costs and logistical clutter.
- **Kinematic Jamming:** Synchronization failures during the upward vertical transfer phase, often leading to off-center bottle positioning.
- **Catastrophic Failures:** Collisions between bottles and the folding mechanism, resulting in glass breakage, prolonged downtime for cleaning, and significant degradation of the line's OEE.

To mitigate this, a *Poka-Yoke* mechanical assessment tool was developed to replace subjective visual inspections with a definitive, physical approval/rejection limit. This tool allows operators to instantly determine if material warpage exceeds the 4% tolerance threshold, ensuring that only conforming batches are processed.

7.2.2 Computational Validation of Packaging: Finite Element Analysis (FEA)

The visual identification of structural creases and tears caused by palletizing tapes required rigorous initial analytical validation in order to transition from a qualitative observation, based on the operator's visual perception, to a rigorous standard quality control.

To this end, a numerical simulation model was developed using Abaqus FEA software.

The main goal was to model the stress state induced in the corrugated cardboard caused by the force imposed by the polymeric tapes, to qualitatively and mechanically understand the localized damage, and to define the force limit beyond which irreversible plastic deformation occurs.

7.2.2.1 Definition of *Inputs* and Configuration of the Numerical Model

The accuracy and reliability of a finite element model is intrinsically linked to the accuracy of its boundary conditions, contact formulations, and material properties.

The configuration of the developed computational model was structured around four fundamental axes, taking into account the effects of large deformations (geometric nonlinearity activated by the NLGEOM parameter):

- **Geometry and Contact Interactions:** The model was simplified to focus exclusively on friction at the localized contact, thus optimizing the computational cost of the model.The model involves three solids: the *Top Support* (modeled as an analytical rigid body, simulating the cumulative inertial weight of the packaging protection stacked on the pallet), the *Corrugated Cardboard* (deformable body), and the *Plastic Strap* (deformable body). The nonlinear interaction between the tape and the cardboard surface was defined using the *Surface-to-Surface* contact algorithm. A penalty formulation was employed to solve the normal contact equations, along with

a Coulomb friction model for tangential behavior, assuming a kinetic friction coefficient (μ) estimated at 0.3 (a standard value of the polymer-cellulose interface tribology).

- **Material Properties and Failure Criterion:** Although corrugated cardboard has a sandwich panel structure, with a flat outer layer and a corrugated inner layer, inhibiting highly orthotropic behavior microscopically, a macroscopic elastoplastic homogenization model was assumed for the present cross-contact study. Based on the supplier's technical data sheets (DS Smith and Saika) and literature for equivalent single-wall corrugated board, the macroscopic transverse compressive yield strength was established conservatively at approximately **2.5 to 3.0 MPa**. Thus, it was concluded that the critical structural failure, the origin of permanent bending, occurs when the equivalent Von Mises stress exceeds this yield limit within the model. Visually, the failure represents the point of instability where the inner walls of the cardboard undergo localized plastic buckling.
- **Boundary Conditions and Loading (*Loads and BCs*):** The cardboard model was constrained at its lower degrees of freedom, fixed in Z-axis translation, to simulate the perfectly rigid support provided by the wooden pallet base. The load was introduced gradually through a tensile force imposed on the cross-sections of the plastic strap. The baseline value of this load - the primary input - was not assumed theoretically. The applied tensile load was empirically determined on the shop floor using a calibrated strap tension gauge, yielding a baseline residual tension of **650 N** from non-conforming batches.
- **Mesh Discretization and Convergence (*Meshing*):** To mitigate bending-induced shear locking inherently associated with C3D8R elements in thin structures, the mesh was configured with **multiple elements across the thickness**, and enhanced hourglass control algorithms were activated within the ABAQUS solver. The mesh density was subjected to a prior convergence study, being substantially refined in the direct contact zone with the strap to guarantee the precise capture of stress concentrations without incurring numerical singularities.

7.2.2.2 Analysis of Results and Mechanics of Hidden Failure

Figures 7.15 and 7.16 illustrate the spatial distribution of the Von Mises stress gradient after the full application of the simulated load. It is emphasized that the simulation was processed with a unitary deformation scale factor (*Deformation Scale Factor: +1.000e+00*), indicating that the displacements and strains observed in the post-processed model reflect the physical reality of the phenomenon, without any visual extrapolation or exaggeration.

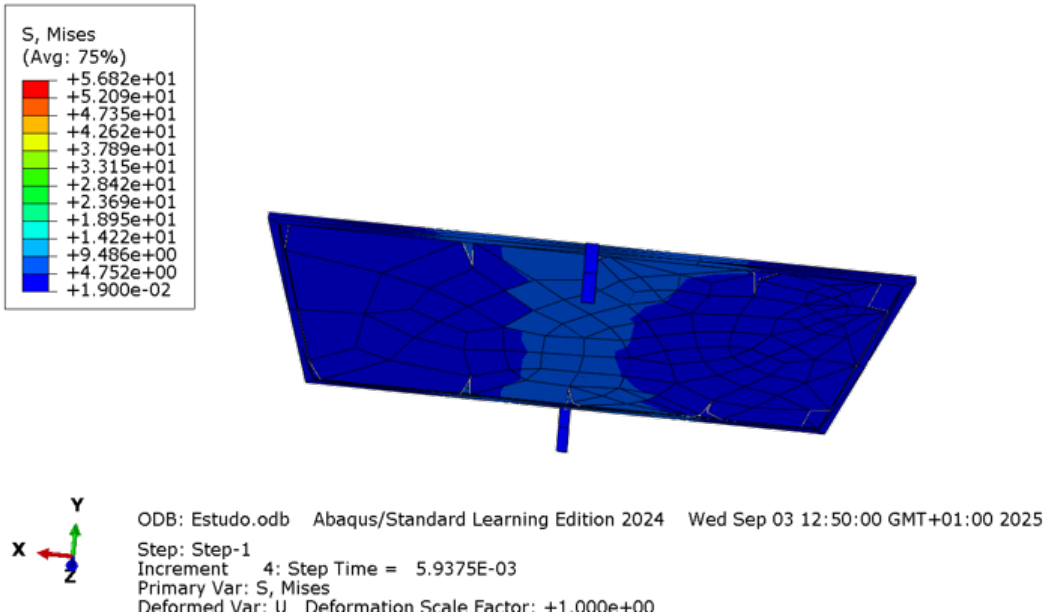


Figure 7.15: Von Mises stress distribution in the complete assembly (Bottom view detailing the support).

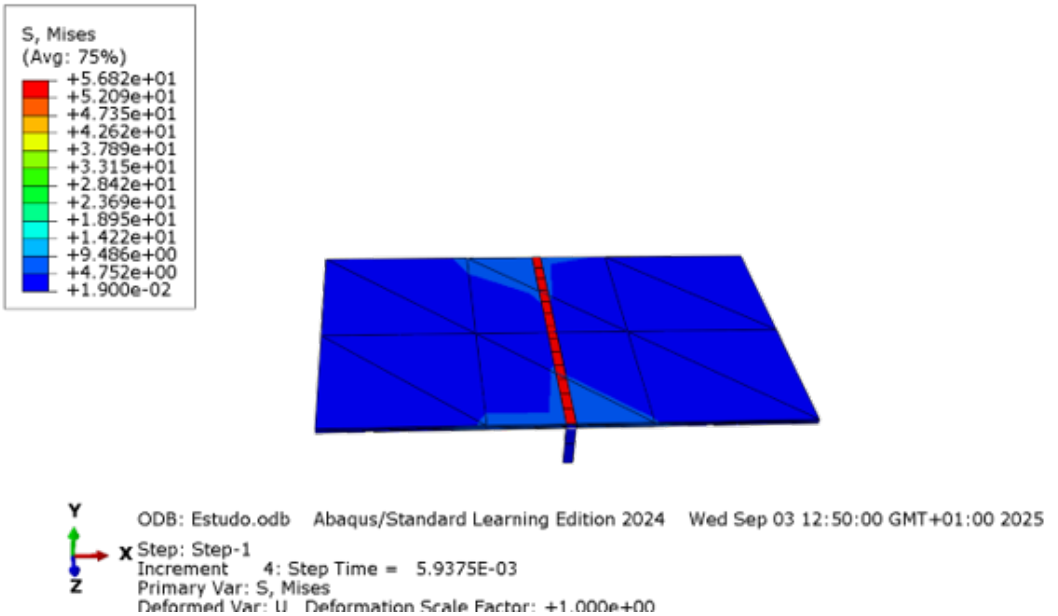


Figure 7.16: Von Mises stress distribution across the entire assembly, highlighting the constriction (Top view).

A detailed analysis of the perspectives with the strap hidden (Figures 7.17 and 7.18) reveals a severe stress concentration bulb directly beneath the polymeric area of incidence. In the models configured with the loads measured from the damaged batches, ABAQUS reported critical Von Mises stress peaks in the order of 6.02 MPa (regions highlighted in red).

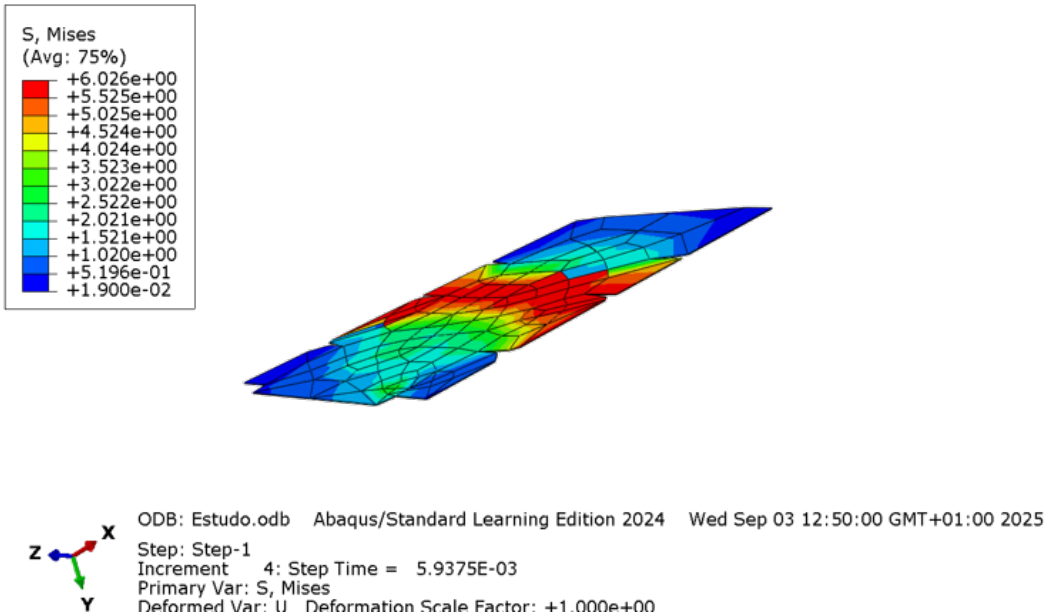


Figure 7.17: Geometric isolation of the card highlighting the propagation of local stresses (Peripheral view).

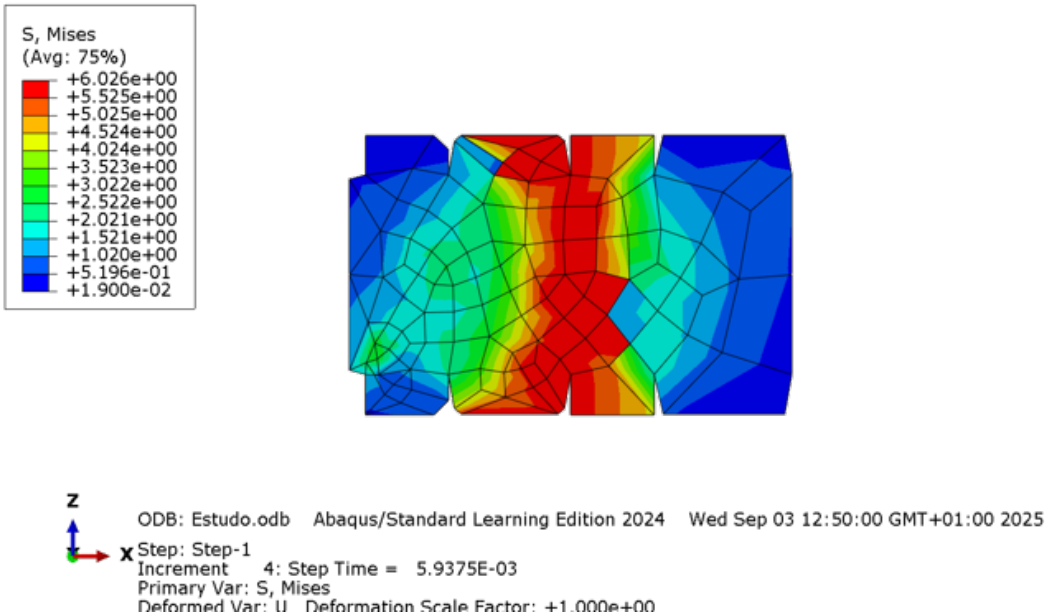


Figure 7.18: Card isolation demonstrating the extent of the collapse in the transverse plane (Top view).

Considering that the characteristic transverse yield strength for the cardboard grammages under study is positioned significantly below this value of 6.02 MPa, the simulation unequivocally proves that the force exerted by the strapping machines operates violently outside the material's elastic zone. The mechanical consequence of this extreme stress state is an internal structural collapse: by crushing the corrugation flutes, the cardboard

loses its "I-beam" effect, characterized by a drastic reduction in the section's moment of inertia). This localized core collapse structurally compromises the board's Area Moment of Inertia, acting as an instability point that justifies the excessive sagging that inevitably leads to critical jams within the Kisters machine's feeding magazine.

7.2.2.3 Supply Chain Optimization: Implementing *Data-Driven* Actions

The ultimate value of this FEA modeling was not confined to a phenomenological diagnosis; instead, it acted as the central axis of a strategic negotiation leverage for the Quality and Procurement departments of the *Super Bock Group*. Translating the mechanical failure language (MPa) into adjustable parameters on the supplier's equipment enabled a highly assertive and scientifically irrefutable Quality Audit approach.

The corrective implementation process unfolded across three distinct phases:

1. **Computational Determination of the Maximum Operational Limit (T_{max}):** Through an iterative parametric optimization process within the ABAQUS model, the strap's tensile force was incrementally reduced until the peak Von Mises stress in the cardboard stabilized comfortably below the yield strength. Applying an appropriate safety factor tailored to transportation logistics ($SF = 1.25$), this study translated into a maximum tension limit, defined by the variable Z Newtons, to be applied to the strapping band.

2. **Presentation of Evidence and Demand for Corrective Actions:** Backed by the FEA simulation report and the statistical logs of rejections (physical *Poka-Yoke* system), a Non-Conformance Report was issued and directed to the suppliers.

3. **Procedural Change at the Source and Follow-up:** Faced with the computational proof, the logistical partners were compelled to recalibrate their processes. Consequently, they adjusted the strapping machines' torque wrenches, integrating a new Upper Control Limit (UCL). For specific scenarios where reducing the strap tension compromised the pallet's static stability during road transport, a mandatory safeguard was introduced: the application of **rigid edge protectors** along all corners. This countermeasure substantially increases the contact force dissipation area, preventing the local pressure from exceeding the cardboard's yield strength.

In summary, this intervention reflects the high efficacy of translating advanced computational methods into pragmatic manufacturing problem-solving, driving the reliability of the Line 2 packaging machine through the rigorous control of upstream physical variables at the very source of the supply chain.

7.2.3 Kinematic Impact on the Kisters Packer

When the Kisters KHS wrap-around packer is calibrated for a specific SKU during a format changeover, the mechanical guides, transport belts, and feeding chains are set to precise

geometric tolerances. The machine operates on a highly synchronized continuous-motion principle, processing dozens of cycles per minute. In this high-cadence environment, timing, spatial positioning, and material predictability are critical aspects. The introduction of cardboard blanks with pronounced warpage that exceeds these nominal clearances immediately disrupts the machine's kinematic envelope, triggering a cascade of detrimental operational scenarios:

- **Material Waste and the Hidden Cost of Poor Quality:** When operators detect severe deformation during pallet opening, they are forced to manually triage and reject the compromised blanks. Empirical data collected on the shop floor indicates an average disposal rate of 35 individual blanks per lot for tray formats, and 22 blanks per lot for box formats. Each pallet typically contains 1000 boxes or trays per batch. Beyond the direct purchasing cost of the scrapped cardboard, this phenomenon introduces hidden operational costs. The manual sorting process severely disrupts the operators' Standard Operating Procedures, diverting their attention from critical machine monitoring tasks. Furthermore, the accumulation of rejected material poses logistical challenges on the shop floor and directly contradicts the organization's Lean Manufacturing and sustainability targets.

- **Kinematic Jamming and Servomotor Overloads:** The cardboard model underwent a restriction in the lower degree of freedom, fixed in the translation of the Z-axis, in order to simulate the rigid support provided by the base of the wooden pallet. The load was introduced gradually derived from a tensile force imposed on the lower section of the plastic strap. The reference value of this load (650N) was not assumed theoretically, it was determined empirically at the supplier Saika using a calibrated strap tension gauge, performing a statistical sampling of the actual residual tension present in the non-conforming batches received in the warehouse.

- **Synchronization Failure and Catastrophic Glass Breakage:** The most serious malfunction occurs during the upward vertical transfer phase from the cardboard warehouse to the folding module of the equipment, where the cardboard conveyor belts are located. The deformation that occurs during palletized cardboard storage alters the geometric profile of the cardboard, causing the back edge to lift or fold unevenly. In the forming module that is positioned after the folding module, the glass bottles are programmed to be correctly positioned and at the exact time they are scheduled to be placed in the box. If the box is incorrectly positioned or has gaps or geometric errors, the bottles collide off-center with the box and, at the moment the box is folded, the bottles break.

- **OEE Degradation:** The increase in Mean Time to Fault Diagnosis is a result of the initial diagnostic time, fault clearance, cleaning of broken glass, and resetting the machine's zero position coordinates. Ultimately, this localized fault creates a

bottleneck, limiting upstream and downstream operations, thus impairing the OEE of the entire filling line.

7.2.4 Mechanical Solution: *Poka-Yoke* Conceptualization

A visual physical assessment tool was designed and built for implementation in the cardboard delivery area (standard rejection criterion imposed by the quality department), in order to mitigate damage resulting from non-conforming raw materials in the Kisters equipment. The project developed was based on the principles of Lean Manufacturing.

These principles require the solution to be perfectly integrated into the existing machine structure, requiring a very significant capital investment and not introducing ergonomic restrictions or possible delays in the operator's standard workflow.

The Kisters cardboard delivery warehouse has a roller conveyor driven by a servomotor. The initial section of the rollers on the conveyor is not motorized, thus there is a "dead zone" used exclusively for buffer accumulation before the cardboard feeding cycle is active. The previously existing static area on the machine was identified as strategically the ideal location for integrating the *Poka-Yoke* device, thus creating an efficient initial check and sorting point upstream of the machine's active conveyor.

The assembly is physically composed of a plate made of a lightweight aluminum alloy, which was selected primarily for its excellent strength-to-weight ratio and also for its high corrosion resistance. The plate is mechanically coupled to the adjustable side guide for card delivery, ensuring that it moves mechanically in an integral way with the system during format adjustments. In order to guarantee maximum universal versatility for all SKUs, it is necessary to accommodate up to the maximum capacity of the largest SKU, 974 millimeters long by 615.72 millimeters wide (corresponding to a format of 35 bottles x 20 cl).

Therefore, the plate was designed with a longitudinal split connected by means of a low-profile metal hinge. The specifically constructed design allows the plate to be folded and retracted, avoiding spatial interference with the operator's work area and the machine structure, essentially during format changes. The assembly is rigidly fixed using three ISO 4762 M6x20 screws, efficiently securing and dampening operational vibrations. The interaction of the mechanism with the rollers and sliding guides was modeled in 3D CAD and is shown in Figures 7.19 and 7.20.

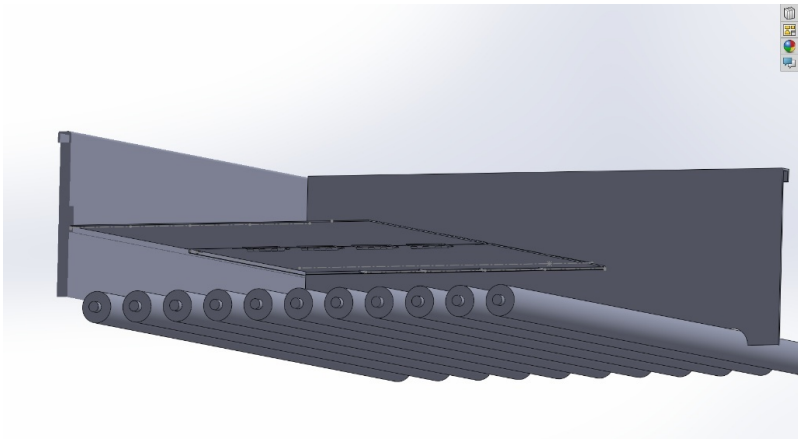


Figure 7.19: CAD model of the aluminum assessment plate in the extended, operational position.

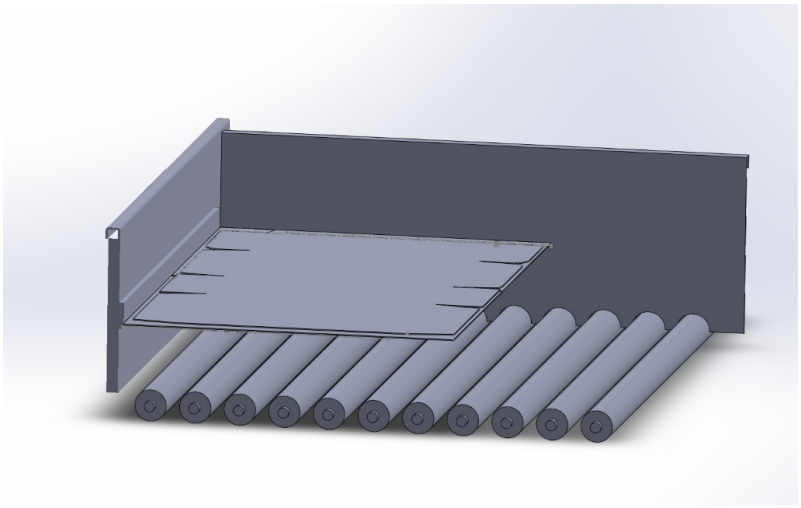


Figure 7.20: CAD model of the plate in the folded position via mechanical hinge, accommodating spatial constraints.

The measuring and evaluation ruler of the system is presented on the rear reference plane of the plate. The rectangular verification plate, also called fixed visual ruler, is installed in the space between the adjustable guide and the fixed edge of the loader (marked in blue in Figure 7.21). The plastic plate is coated with Teflon tape, calibrated with delineated markers that represent the maximum permissible warping curve (4%).

The setup created for the production line functions similarly to standard gauges used in modern production lines throughout the brewing industry (e.g., Carlsberg factories in Polonia). Figure 7.22 highlights in blue the prototype location of the visual check ruler.

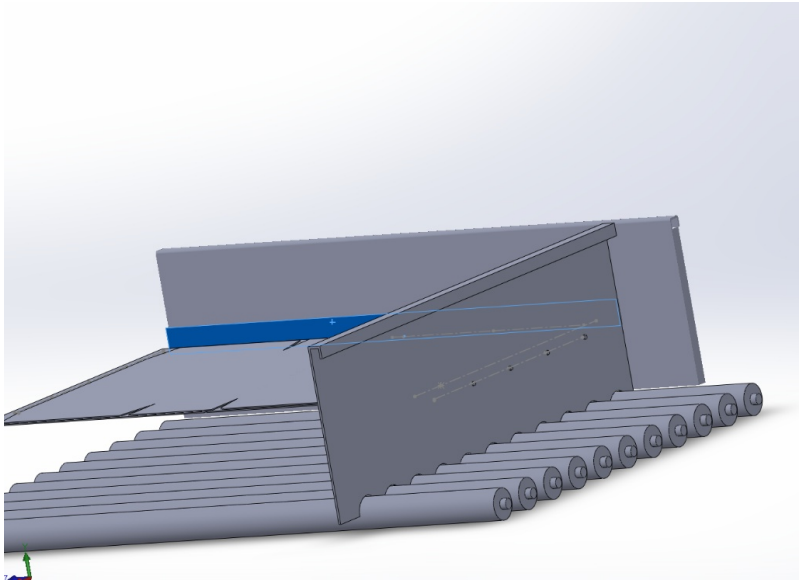


Figure 7.21: Highlight of the fixed datum plane where the Teflon-lined visual warpage gauge is strategically located.

The maximum permissible percentage of internal buckling is 4% and is calculated internally using the measurement procedure that can be found in Appendix A.8.

Finally, the technical drawings of the prototype plate and hinge were sent to the supplier for manufacturing and machining, and future work will proceed with its installation.

The installation of the parts on the equipment will be carried out as soon as they arrive from the supplier.

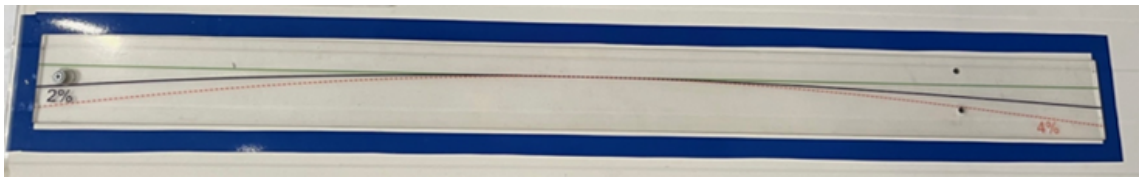


Figure 7.22: Measuring rod used for checking maximum allowable bending (Kisters equipment)

The economic losses resulting from damaged packaging during transport, extremely tight batch securing straps, and consequent damage to boxes and trays, have thus become a relevant aspect to be considered and explored. In fact, the number of boxes per pallet varies depending on the product manufactured; however, the most common is 1000 boxes/trays per pallet.

After analyzing 8 sample pallets of each type, it was noted that, on average, they had 35 damaged pieces (trays) or 22 (boxes) (Table 7.3).

Given the data sharing restrictions imposed by the company, it is assumed that 1000 pallets of boxes and 1100 pallets of trays are purchased per month (on each production

line). That being said, the costs resulting from the purchase of non-conforming material are presented in equations 7.8, 7.9, 7.10, 7.11, 7.12 and 7.13:

Table 7.3: Input variables for monthly packaging damage volumes and costs.

Product	**Pallets/Month**	**Damaged/Pallet**	**Unit Price (Example)**
Boxes	10,000	22	1 cent
Trays	11,000	35	2 cents

The general formula for calculating the monthly cost resulting from non-conforming material is defined as:

$$\text{Total Cost} = \text{Number of Pallets} \times \text{Damaged per Pallet} \times \text{Unit Price} \tag{7.8}$$

1. Cost Equation for Boxes

Assuming the unit cost for a damaged box is $C_{\text{box}} = 1$ cent:

$$\text{Cost}_{\text{boxes}} = 22 \times 10,000 \times 1 = 220,000 \text{ cents} \tag{7.9}$$

Converting to Euros (dividing by 100):

$$\text{Cost}_{\text{boxes}} = 2,200 \text{ €/month} \tag{7.10}$$

2. Cost Equation for Trays

Assuming the unit cost for a damaged tray is $C_{\text{tray}} = 2$ cents:

$$\text{Cost}_{\text{trays}} = 35 \times 11,000 \times 2 = 770,000 \text{ cents} \tag{7.11}$$

Converting to Euros (dividing by 100):

$$\text{Cost}_{\text{trays}} = 7,700 \text{ €/month} \tag{7.12}$$

Final: Total Monthly Economic Loss

The combined global monthly cost across this production line is calculated as follows:

$$\text{Cost}_{\text{Total}} = 2,200 + 7,700 = 9,900 \text{ €/month} \tag{7.13}$$

7.2.5 Standardization and Quality Assurance Integration

The implementation of the mechanical visual inspection tool and its use was complemented by the formalization and definition of a new Standard Operating Procedure, integrated into the factory's Autonomous Operation database.

In summary, at the initial moment when the operator loads a new pallet sequentially, the operator slides two samples positioned above the batch onto the aluminum plate. Visually, the operator compares the natural curvature induced by gravity of the cardboard with the standard Teflon reference lines. This method allows the operator to instantly determine whether or not the material is within the machine's operational tolerances.

The physical intervention and check-up eliminates human subjectivity, replacing previously existing qualitative guesses with a binary and definitive "Pass/Fail" criterion.

If the curvature exceeds the standard operational critical limit, the samples considered non-conforming will be systematically separated and rejected before entering the machine. Fundamentally, operators must record the exact number of rejected samples, indicating their respective labels for batch tracking.

The data must be sent to the quality department and will be compiled into a standardized tracking Excel spreadsheet at the end of each shift by the operations team leader.

The structured protocol allows for effective data collection that transforms an existing operational problem into a measurable and traceable measure. The protocol also allows the *Super Bock Group* to transition from reactive to proactive supply chain management.

By using the data collected in daily Excel spreadsheets, the Quality department has the power to formally notify suppliers (DS Smith and Saika) of the existence of significant anomalies in Non-Conformance Reports. The strategy to be implemented not only allows the company to formulate commercial claims in order to recover financial losses associated with the waste of non-conforming material, but also forces suppliers to implement Corrective and Preventive Actions in their factories, also driving continuous improvement in their internal practices, particularly in the specific areas of strapping, storage, and logistics of cardboard pallets.

Chapter 8

Tribological Study and Kinematic Stability in the Transfer Plate: Methodological Formulation

8.1 Problem Identification and Operational Impact

In order to continuously optimize Line 2, after a detailed analysis of the failure history, critical bottlenecks were identified in the transition between the forming module and the folding module of the Kisters case packing machine. The constant occurrence of braking and subsequent breakage of glass bottles on the transfer plate was identified as one of the most serious failure modes of the equipment.

After consulting the records extracted from the internal SAP system (as shown in Figure 4.6), seventeen occurrences associated with this mechanical bottleneck were recorded in the time frame between the second half of 2024 and the second half of 2025 (one calendar year). Considering that, in the seventeen recorded occurrences, each intervention required an Average Repair Time of seventy minutes, the accumulated impact resulted in:

$$\text{Total Stop Time} = 17 \times 70 = 1190 \text{ minutes} \approx 19.8 \text{ hours} \tag{8.1}$$

The loss of approximately 20 hours of active production, as can be seen in equation 8.1, justified the start of a Root Cause Analysis.

The empirical physical evaluation of the equipment by the maintenance technician revealed that the problem lies in the tribological contact interface on the surface of the passage plate. Visual and tactile inspection revealed that both the support and the sliding plate, constructed of stainless steel with a black polytetrafluoroethylene (Teflon) coating, showed severe degradation due to the constant wear imposed by the passage of the bottles. The delamination of the Teflon tape and the abrasive wear of the Teflon coating (Figure 8.1) significantly increased the local kinetic friction coefficient of the plate, causing dynamic

instability of the passage and also causing the bottles to tip over during their high-speed movements (Figure 8.1).

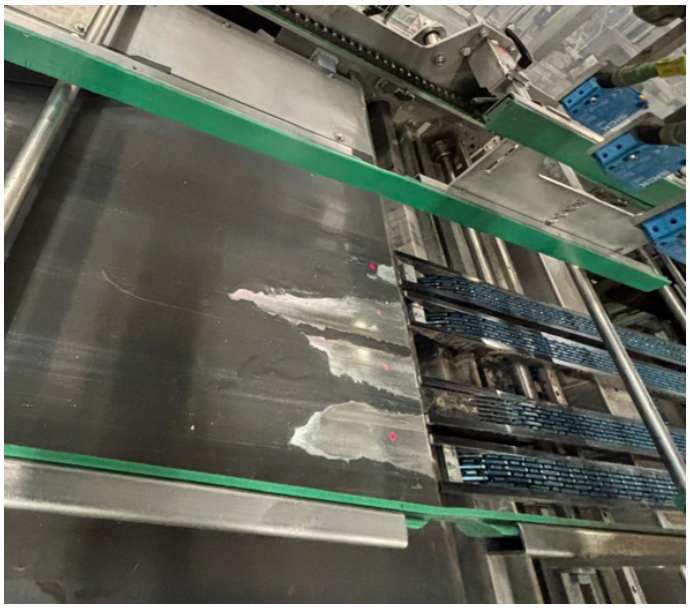


Figure 8.1: Visualization of the feed plate on the KISTERS machine, showing severe wear of the lining and damage to the adjacent feed combs.

To model the problem, it is necessary to collect real operational data. For this, it is necessary to attach a digital dynamometer to a standard bottle to measure the actual drag force on the production line. This allows us to obtain the real value of the coefficient of friction between the glass and the Teflon-degraded coating.

8.2 Analytical Stability Calculation: Center of Gravity (CG)

Line 2 processes three distinct references of glass bottles (0.20 cl, 0.25 cl, and 0.33 cl). In order to ensure that the future Finite Element Analysis (FEA) study focuses on the most critical scenario (Worst-Case Scenario), each Center of Gravity (CG) was characterized for each SKU.

Therefore, an analytical approximation model was assumed, in which the glass bottle is treated as an axisymmetric solid body of revolution, exhibiting a homogeneous mass distribution due to the constant glass thickness along the bottle.

Due to the circular symmetry of the bottles, the coordinates of the CG along the X and Y axes (horizontal plane) should not be accounted for in the center of gravity, since they are located exactly on the central axis of revolution of the bottles.

Consequently, the only determining variable for the stability analysis against tipping is the height of the center of gravity (h_{CG}) along the Z axis. Therefore, in order to overcome the complex geometry of the bottle, the profile was discretized and divided into 5 primitive sections (Zones 1 to 5), as shown in Figure 8.2.

- **Zones 1, 3, and 5:** Approximated as cylindrical geometries.
- **Zones 2 and 4:** Approximated as truncated cone geometries.

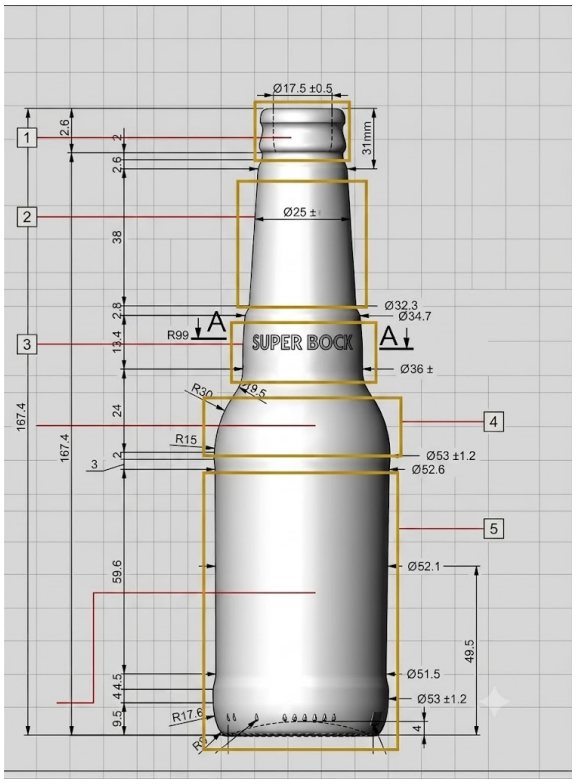


Figure 8.2: Geometric discretization of the Super Bock bottle into 5 primitive sections for analytical calculation.

The calculation height of the gravity center (CG) for each individual section was performed according to the geometric formulations present in equations 8.2 and 8.3, where h represents the section height, R the major radius, and r the minor radius:

$$h_{CG\ (Cylinder)} = \frac{h}{2} \quad \text{(Zones 1, 3 e 5)} \tag{8.2}$$

$$h_{CG\ (Cone\ Truncated)} = \frac{h}{4} \times \frac{R^2 + 2Rr + 3r^2}{R^2 + Rr + r^2} \quad \text{(Zones 2 e 4)} \tag{8.3}$$

Following the physical laboratory measurement of the total masses of each filled bottle using a *Mettler Toledo* digital precision balance, model PB3002-S (0.20 cl = 335.75 g; 0.25 cl = 408.98 g; 0.33 cl = 525.71 g), the theorem of static moments was applied to define the overall height of the Center of Gravity ($h_{CG\ Total}$) of the composite system, according to equation 8.4:

$$h_{CG\ Total} = \frac{\sum(m_i \times h_{CG_i})}{\sum m_i} \tag{8.4}$$

The detailed results (Table 8.1) revealed a critical insight. Although the absolute heights varied, the fundamental parameter for the mechanical instability study is the percentage ratio between the CG height and the total height of the bottle (h_{CG}/h_{Total}).

Table 8.1: Geometric, volumetric, and mass characteristics for the study models.

Parameter	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Total**
			SB_ORIG_0,20			
h (mm)	12,60	40,00	15,40	24,00	77,60	—
R (mm)	13,80	16,15	13,00	26,50	26,50	—
r (mm)	—	13,40	—	18,00	—	—
h_{CG} (mm)	6,30	18,76	7,70	10,49	38,80	**61,51**
Volume (mm^3)	7534,57	27497,71	8172,16	37762,00	171113,04	**252079,13**
Massa (g)	10,04	36,62	10,88	50,30	227,91	—
h_{CG} / Altura Total	—	—	—	—	—	**34,17%**
			SB_ORIG_0,25			
h (mm)	14,10	40,00	11,20	24,50	90,30	—
R (mm)	13,40	16,15	18,25	28,00	28,20	—
r (mm)	—	13,40	17,30	18,25	—	—
h_{CG} (mm)	7,05	18,76	5,50	10,55	45,15	**72,29**
Volume (mm^3)	7949,84	27497,71	11713,14	41749,00	225483,94	**314393,58**
Massa (g)	10,34	35,77	15,24	54,31	293,32	—
h_{CG} / Altura Total	—	—	—	—	—	**32,13%**
			SB_ORIG_0,33			
h (mm)	16,00	46,20	14,10	19,70	111,50	—
R (mm)	13,55	16,95	19,50	29,50	29,50	—
r (mm)	—	13,55	17,50	19,50	—	—
h_{CG} (mm)	8,00	21,39	6,80	8,53	55,75	**91,14**
Volume (mm^3)	9224,19	33877,13	16835,19	37646,00	304683,23	**402265,48**
Mass (g)	12,05	44,27	22,00	49,20	398,18	—
h_{CG} / Total Height	—	—	—	—	—	**40,51%**

The analytical analysis concluded that the **0.33 cl bottle exhibits the highest ratio (40.51%)**, physically justifying why this specific reference experiences the highest rate of instability and toppling along the transfer plate.The comparative positions of the centers of gravity of the different types of bottles are represented in the diagram in Figure 8.3.

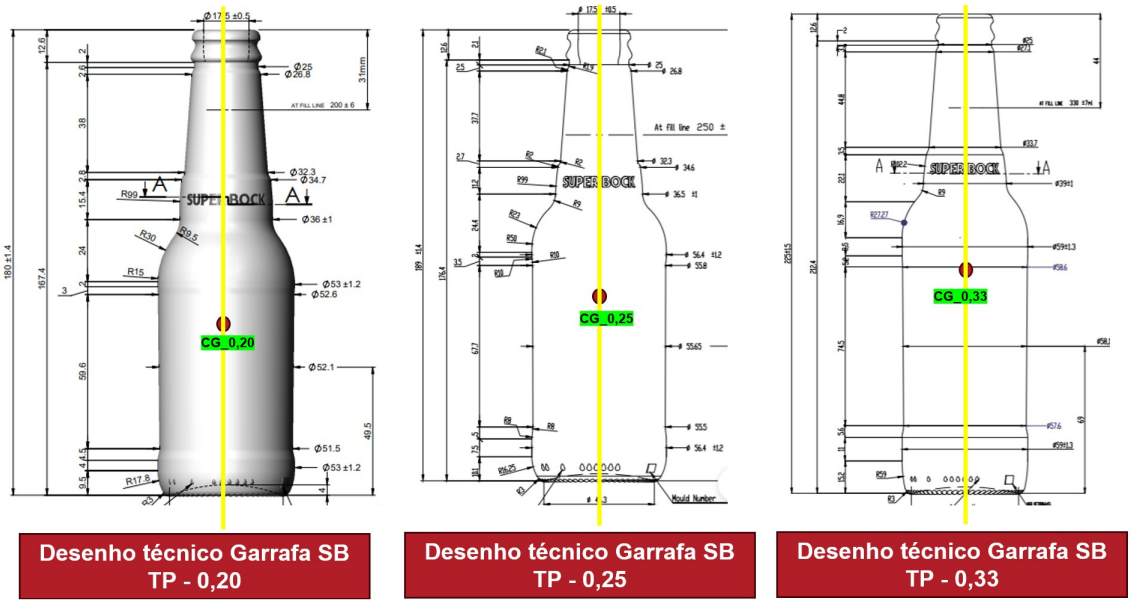


Figure 8.3: Comparative mapping of the Center of Gravity positioning in three geometric variations of bottles.

8.3 CAD Modeling and Three-Dimensional Setup

Once the greater criticality of the 0.33 cl bottle was proven, the initial project began with the construction of a three-dimensional model. Following this, a detailed dimensional survey of the transfer plate, the mounting holes for the plate in the equipment, the lateral alignment guides, and the passage combs was carried out.

To optimize the computational cost of the subsequent simulation, the geometry was simplified (Figure 8.4). Empirically, there are three tracks where greater abrasive wear occurs. Therefore, these tracks were isolated and will be simulated separately.

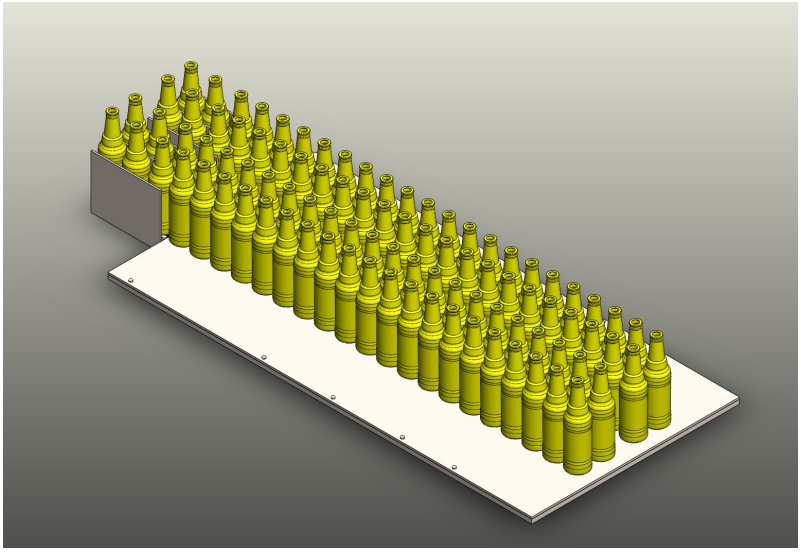


Figure 8.4: Three-dimensional (CAD) modeling of the simplified assembly: transfer plate and die for 0.33 cl bottles.

8.4 Future Work: Tribological Simulation and Materials Optimization

The initial identification of the root cause of the failures in the transition between the forming/folding module and the analytical formulation of the most critical bottle type (0.33 cl bottle) were effectively carried out. However, due to time constraints, advanced numerical modeling and subsequent physical experimental verification of different materials for physical replacement of the passage plate were not achieved in a timely manner. Consequently, the complete execution of a Finite Element Analysis study focused essentially on the wear mechanics of the passage plate is referenced as the main future work to be carried out internally by the company.

To carry out the numerical study, it is proposed that the following methodological and structured sequence be followed for execution in the Abaqus software:

1. **Geometric Simplification and Material Characterization:** 3D CAD modeling should start with a simplified model assembly, restricting computational analysis to only three central strips where the most severe wear was empirically recorded. Subsequently, it is necessary to mechanically characterize the different materials to be tested, namely recording properties such as Young's Modulus, Poisson's Ratio, material density and respective hardness. Initially, this is necessary for the current passage plate, composed of Stainless Steel with Teflon coating, and subsequently for the alternative materials to be tested, namely Polished Stainless Steel and Ultra-High Molecular Weight Polyethylene. The coefficient of kinetic friction between the

lower surface of the glass bottle and each of these test materials should be extracted through controlled practical tests using a digital dynamometer.

2. **Wear Model Formulation and Contact Interactions:** The loss of Teflon thickness over time, due to constant wear, should be simulated by implementing the Archard wear model directly in the contact interaction subroutines of the Abaqus software (Equation 2.1). The interaction type *Surface-to-Surface* must also be defined, where the plate surface assumes the role of *Master Surface*. Finally, the associated friction should be governed by Coulomb's law, parameterized with the previously measured real coefficients.

3. **Mesh Strategy and Boundary Conditions:** In order to optimize the computational cost of the numerical model, the bottles must behave analytically as rigid bodies. In contrast, the sacrificial zone of the plate requires a highly refined discretization using hexahedral finite elements of reduced integration (C3D8R). Activation of the Arbitrary Lagrangian-Eulerian Adaptive Mesh Formula (ALE) is mandatory in order to avoid errors arising from mesh entanglement or severe distortions due to continuous volume loss. A variable vertical force (F_N) must be applied at the center of gravity of the bottles, symbolically representing the individual mass of each bottle combined with the lateral pressure of the accumulation line. In addition, a translation vector must also be added, representing the operational linear feed rate (v) occurring in the KHS machine. Assuming the nominal flow rate limit of the line bottleneck (filling at 60,000 bottles/hour), distributed symmetrically across the three active lanes (in the most critical case, only 3 lanes operate for the maximum filling volume), the linear rate per lane (λ) is derived directly as a function of the flow rate per second (equation 8.5):

$$\lambda = \frac{20\,000}{3600} \approx 5,56\,\text{bottles/s} \tag{8.5}$$

Considering the most critical condition of compact flow, with a maximum diameter of $D_{\max} = 0.059$ m for the 0.33 cl bottle, the continuous linear velocity (v) that must be imposed in the numerical model is calculated in the equation 8.6:

$$v = \lambda \times D_{\max} \approx 5,56 \times 0,059 \approx 0,33 \text{ m/s} \tag{8.6}$$

4. **Time Extrapolation and Results Analysis:** Given that production line 2 has the highest production rate in the company and consequently high hourly occupancy, the simulation cannot be run in real time, according to the machine's operation.

   It is therefore important to adopt a temporal extrapolation strategy (Scale Factor) where the transfer cycle of a reduced set of bottles is simulated, and the solver

multiplies the calculated wear rate in order to represent, in an accelerated way, the degradation equivalent to several months of operation.

The output of this simulation will provide 3D wear depth maps, namely the Wear Depth Maps and contact pressure distribution matrices between surfaces, thus successfully identifying the most critical friction points and the areas most prone to irregular bottle slippage.

In summary, extracting comparative graphs of volume loss over time will provide the Production Department of *Super Bock Group* with the necessary quantitative evidence to justify the upgrade of the final material.

Finally, future work should culminate in an evaluation of the technical-economic relationship, comparing the simulated durability of each material (stainless steel vs. UHMWPE) with their acquisition and machining costs, thus dictating the final solution to be installed in order to minimize operational downtime resulting from said failure.

Chapter 9

Results Analysis and Operational Impact

The main goal of this dissertation was to develop and implement proposals to improve OEE through enhanced reliability. The goal was to shift the group's internal paradigm from a maintenance strategy essentially focused on reactivity, to a proactive landscape for problem-solving, supported by Industry 4.0 tools and applied mechanics. Data collection following the implementation of these improvements allowed for a conclusion regarding reliability and the real impact on the factory floor.

In this chapter, historical operational performance data (OEE) and the evolution of breakdowns are cross-referenced, verifying the viability of the implemented measures.

9.1 Operational Impact: OEE Evolution

The most relevant indicator for measuring success in high-cadence bottling companies is OEE. The initial diagnosis of Line 2 revealed that, up to the implementation phase (January 2026 - May 2026), the cumulative OEE was 55.5%, a value with significant improvement margin (Figure 1.6).

Following the start of structural and procedural improvements on the Kisters equipment (June 2026), the production line's response was assessed. As illustrated in Figure 9.1, the global OEE for the month of June registered an increase of 2%, reaching 57.5%.

Although the timeframe for recording these improvements is short, the 2% growth on a high-cadence production line validates the project's initial premise: that mechanical and logistical stabilization positively impacts the availability and effectiveness of production lines.

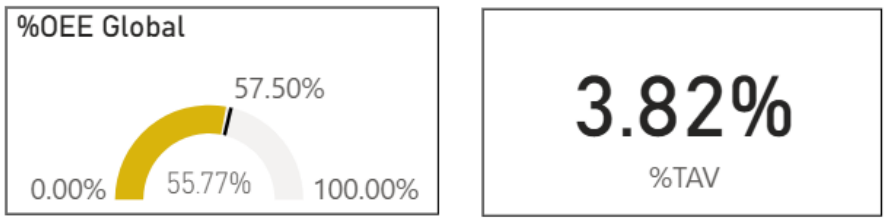


Figure 9.1: OEE indicator value, June 2026 (Line 2)

9.2 Breakdown Analysis and Data Processing

To find a logical justification for the OEE increase, maintenance data for Lines 1 and 2 were collected and processed for June. A total of 62 maintenance orders were recorded, processed taxonomically using the NLP algorithm in Python, detailed in Appendix B.1.

During the analysis, the NLP algorithm identified a critical, high-duration breakdown (servomotor out of position and malfunctioning), which justified 8 maintenance orders with a MTTR of 270 minutes. After meeting with the industrial supervisor and an experienced maintenance technician, it was concluded that this was a sporadic and unique event in the equipment's history. To avoid distorting the effectiveness analysis of routine solutions, this outlier was excluded from the final database, allowing for greater assurance in assessing the equipment's standard behavior and wear.

The success of the improvements was verified via the Criticality Matrix, shifting chronic problems to lower-impact quadrants. The reduction in MTTR is estimated to result from the implementation of the proximity Kanban system (timing combs, plastic fingers, and rollers), as well as the restructuring of weekly preventive maintenance and cleaning routines. The data presented in figure 9.2, shows that:

- **Timing Comb Replacement** went from a MTTR of $\approx$ 120 minutes to just 25 minutes in June (a reduction of $\approx$ 79%).
- **Broken Plastic Fingers** dropped from an MTTR of $\approx$ 90 minutes to $\approx$ 16 minutes (a reduction of $\approx$ 82%).

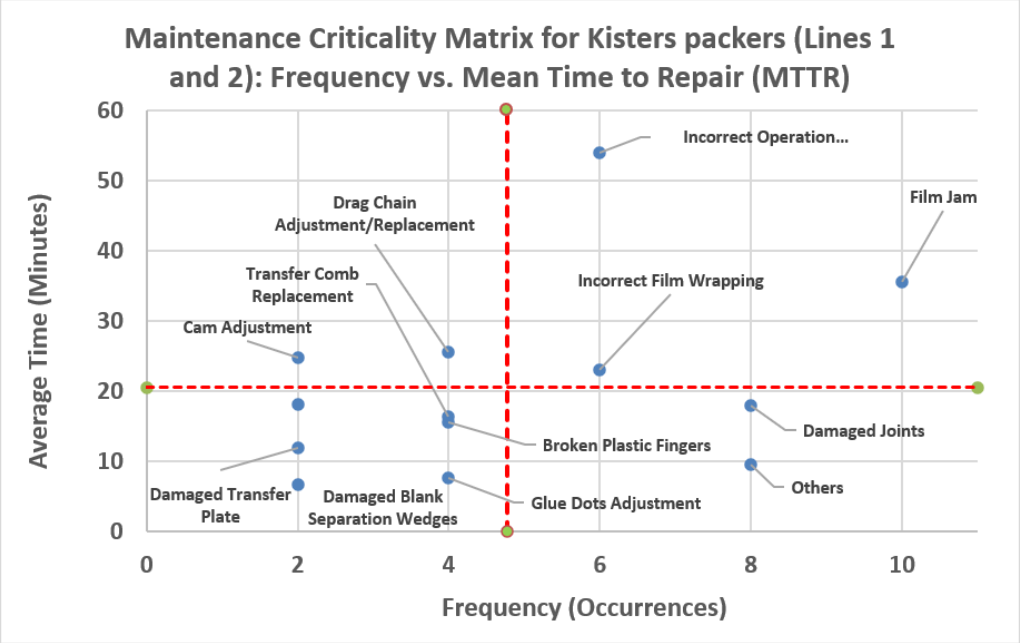


Figure 9.2: Maintenance Critically Matrix for Kisters Lines 1 and 2 (After)

The most impactful case in the study was "damaged articulations". In the previous annual history, the component failed 62 times (an average of 5.16 records per month) with a high MTTR of 83 minutes (Figure 4.6) . In June 2026, 8 occurrences were recorded. Although the frequency during the startup month was not better than the previous average, the MTTR dropped to 18 minutes. The result is that, compared to the previous annual average of 428 minutes of downtime per month (5.16 × 83 min), the total downtime in June was only 144 minutes (8 occurrences × 18 min), representing a 66% reduction in total downtime. This is directly linked to the reduced time required to clean glue leaking onto the articulations, thanks to the addition of retaining plates.

9.3 Longitudinal Analysis and Trend Normalization (2022-2026)

To consolidate the analysis of the interventions number, a comparison was made with the bimonthly history of interventions on lines 1 and 2 since 2022.

The graph presented in Figure 9.3 shows a consistently increasing evolution in the number of interventions between 2023 and 2025. This degradation can be justified by two factors.

Firstly, the high-cadence components have a finite service life, leading to constant damage; second, the limited maintenance budget does not allow for a general replacement of all components during annual overhauls. The period between the 1st and 4th bimester of 2026 was not subjected to detailed comparative analysis as it was a transition phase.

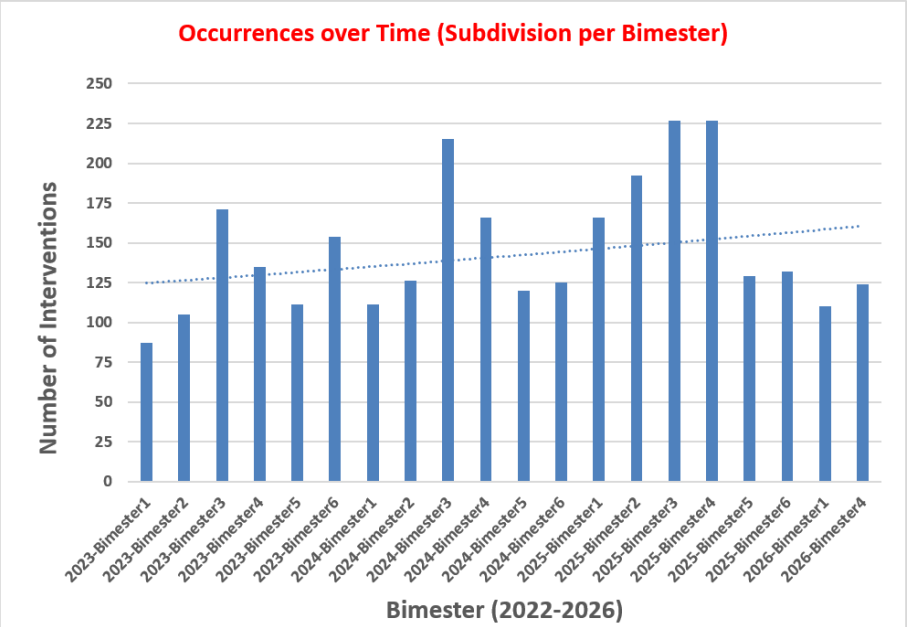


Figure 9.3: Total number of interventions per bimester (2022-2026), Kisters L2

To ensure a more rigorous evaluation, the data for Bimester 4 of the years 2023-2026 were segmented. This segmentation allows for a homologous comparison, given the similarity in operational conditions (production volumes, SKU combinations, etc.).

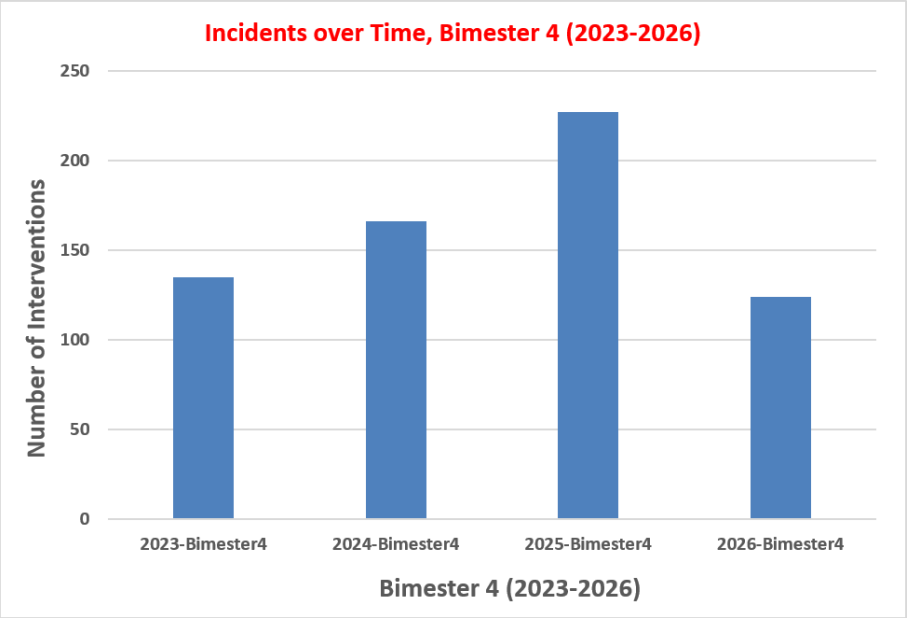


Figure 9.4: Comparative isolated analysis of incidents in Bimester 4, during 2023 to 2026 (Kisters L2).

As detailed in Figure 9.4, a sharp drop in the number of interventions is observable in Bimester 4 of 2026, especially compared to the homologous period of 2025 (the peak of the

graph). It is expected that this decline will help break the trend of equipment degradation felt over the years.

Although the timeframe under analysis is short, the combination of increased OEE and reduced interventions indicates a potential trend of normalization and improvement in operational indicators. It is anticipated that by creating a corporate identity of continuous improvement and maturing the implemented ideas, these indicators will improve transversally across all equipment and production lines.

9.4 Economic Viability: ROI and Payback Period

The engineering interventions implemented were designed not only to restore machine reliability but also to ensure a superior return on investment. The total capital expenditure (CapEx) for the project, covering stainless steel retention plates, the aluminum *Poka-Yoke* assessment tool, 3D printing filaments, and electronic components for the *Kanban* prototype, is estimated at €350.

9.4.1 Annualized Savings and Financial Performance

The financial benefits are derived from both direct spare part cost reduction and the mitigation of production opportunity costs:

- **Direct Maintenance Savings:** The mechanical containment of adhesive leakage eliminated the annual expense of €9,091.37 previously incurred by premature joint replacements (Eq. 7.3).
- **Operational Savings:** The *Poka-Yoke* assessment tool mitigates an estimated monthly loss of €9,900 associated with non-conforming packaging materials (Eq. 7.13).

The project's financial performance indicators are summarized below:

- **ROI (Return on Investment):** Considering the annualized savings and the low implementation cost, the ROI reflects a highly favorable economic performance:

$$\text{ROI} = \frac{(\text{Savings}_{annual} - \text{Investment})}{\text{Investment}} \times 100 \approx 35\%$$

- **Payback Period:** Given the combined monthly impact of nearly €10,000 in avoided losses, the initial investment is recovered in less than one week of full operation, confirming the high financial efficiency of the proposed multidisciplinary approach.

9.5 Reliability and Availability Impact

Beyond the financial metrics, the interventions yielded a significant shift in core reliability indicators. The total downtime for corrective maintenance on critical components was

reduced by 66%, dropping from an average of 428 minutes per month to 144 minutes in June 2026. This abrupt reduction in unplanned stoppages directly reflects an increased Mean Time Between Failures (MTBF) and a higher availability rate, which are the primary drivers for the sustained growth in OEE observed in Figure 1.6.

Chapter 10

Conclusions and Future Work

10.1 Main Contributions and Final Remarks

The development of this dissertation culminated in the conception, testing, and implementation of several multidisciplinary solutions within the scope of Maintenance Engineering and Industrial Asset Management, with a special focus on the optimization of the Kisters case packing machine (Lines 1 and 2). The main contributions achieved include:

- **Data Mining and *Text Mining* (SAP):** Development of a Python algorithm using NLP to extract and structure historical data from the SAP ERP system. The approach ensured rigorous segmentation by module, component, and failure mode, quantitatively defining the critical bottlenecks of the equipment and their respective times.
- **Digitalization of Operational Troubleshooting:** Creation of an interactive application, developed from an operational information survey conducted on the factory floor. By scanning QR codes on the factory floor using tablets or RealWear headsets, technicians and operators can instantly access different troubleshooting guides, specific to each module, thus drastically reducing the time needed to diagnose a given fault;
- **Implementation of Autonomous Maintenance and Additive Manufacturing:** Transfer of low-complexity tasks to Operations teams, with the aid of Standard Operating Procedures. The design and additive manufacturing (3D printing in PETG) of proximity *Kanban* systems allowed for the sustainable transition of tasks with low costs and reduced delivery times when compared to conventional metal machining costs, thus mitigating non-value-adding travel times;
- **Dynamic Optimization of Preventive Maintenance:** Preventive maintenance routines and weekly cleanings were transitioned to the Microsoft Forms platform. Following technical consultation and feedback, the action plans were restructured,

resulting in an average reduction of 79% in the execution time of operations compared to the times initially recorded, allowing the remaining time of the 8-hour weekly window to be used for more critical interventions;

- **Mechanical Failure Mitigation (*Hot-Melt* and Cardboard):** Design and development of deflector plates to prevent damage to pneumatic solenoid valves and high-temperature glue drips from falling onto the equipment. Simultaneously, visual tension analysis of the straps on the pallet identified warping of the cardboard due to excessive tension imposed by the supplier, justifying the creation of a visual inspection system (Go-NoGo) in the cardboard warehouse for rapid sorting of non-conforming batches;
- **Kinematic Modeling and Tribological Structuring:** Determining the worst-case scenario, in which the instability ratio of the bottle on the passage plate is the greatest, through the calculation of the center of gravity (0.33 cl bottle). The subsequent CAD modeling and preliminary planning for the later creation of a Finite Element Analysis (FEA) model, thus establishing the theoretical infrastructure for the future optimization of the friction-minimizing material;
- **Information Management Architecture:** Construction of a centralized internal database, using the SharePoint platform for the Production department, bringing together both all the technical documentation of the equipment and all the procedures that can be used with cross-functional scalability for the Filling, Maintenance and Manufacturing departments.

Finally, the project's execution at *Super Bock Group* demonstrated the practical viability, within an industrial context, of converging classic mechanical design principles, Lean/TPM waste elimination tools, and emerging technologies of the digital transition related to Industry 4.0. In retrospect, the initially defined objectives were surpassed, resulting in an initial transition from a reactive maintenance paradigm to a proactive and autonomous culture.

From a personal and interpersonal development perspective, undertaking the internship in an industrial environment with continuous operation proved to be challenging, yet enriching. The success of engineering projects related to continuous improvement essentially requires firm leadership and change management, which must initially be grounded in rigorous mathematical or computational robustness.

Daily and proactive communication with line operators, maintenance technicians, and factory managers demanded resilience, empathy, and adaptability.

The creation of a positive impact from the implemented solutions was only achieved thanks to the receptiveness and strong mutual collaboration established with all areas of the production department, thus proving that technology is only maximized when the

people who operate it are properly instructed, listened to, and integrated into the decision-making process.

In conclusion, the dissertation fulfills its fundamental purpose. It allows the use of the methodological rigor and scientific research of the Faculty of Engineering of the University of Porto, acquired over the years, in solving complex industrial problems, thus leaving a more organized, efficient, and reliable culture within the *Super Bock Group*.

10.2 Research Limitations

The most impactful logistical and technical challenges were primarily due to the difficulty in translating theoretical models and computational tools into an industrial context under pressure and in constant change. Identifying time constraints proved to be essential to define the scope of the study and in the engineering decisions adopted for each context.

Therefore, the main limitations identified are described below, structured by areas of intervention.

10.2.1 Information Systems, Data Quality, and the Human Factor

Extracting historical maintenance data from SAP revealed inconsistencies between initial reports made by operators, often written in unstructured free text, and subsequent technical reviews performed by maintenance technicians (Chapter 4). To prevent statistical distortions caused by incorrectly written technical terms or omission of relevant information, it was necessary to develop a NLP infrastructure in Python for database normalization. In addition to data reliability, the introduction of new digital tools faced initial resistance in the change management field, such as the low completion rates of relevant operational surveys. The lack of technical knowledge thus required direct and hands-on information gathering from maintenance and operations technicians to ensure a deep understanding of the entire process. Finally, the different software involved in the project (SAP, SharePoint, Python, PowerApps) and the time constraints inherent in the final project completion limited the implementation of new technologies, restricting, for example, the integration of RealWear glasses into preventive maintenance routines.

10.2.2 Logistical Implementation Constraints

The pace of implementing improvements on the factory floor was constrained due to physical and operational limitations encountered during the internship. During the development of the *Kanban* system (Chapter 6), although the electronic prototype successfully validated the effectiveness of the concept, its final integration into the case packing machine revealed specific internal constraints. The permanent configuration and location require a more robust electrical system and adequate industrial protection to support rigorous cleaning procedures, such as high-pressure washing, which the initial prototype developed

could not support. Regarding the development of a prototype using additive manufacturing, the development of 3D printed parts internally at the company successfully mitigated the need to resort to third parties. However, the requirement for high structural density of the manufactured PETG parts required long printing times, often exceeding 13 hours per component. The time and technological limitations imposed technically scaled logistical pauses to complete the final assemblies, dictating the pace of implementation.

Finally, the transition to digital methods and the physical production of the developed project faced immediate logistical barriers. The initial rigorous collection of geometric measurements encountered production and part allocation constraints, specifically the difficulty in scheduling the timing of planned machine stoppages, given that they were uncertain and dependent on the progress of production. The obstacles encountered were gradually overcame thanks to continuous awareness efforts and strategic operational concessions, ensuring the necessary data collection without significantly interrupting the production flow of the production lines.

10.2.3 Challenges in Computational Modeling (FEA)

The numerical simulation model presented the most demanding challenges, namely in relation to mathematical abstraction and non-linear convergence of the model (Chapters 7.2 and 8). In modeling the structural collapse of the cardboard, the main obstacle was the dynamic variability of the forces present in the pallet storage strap. To prevent the arbitrary adoption of a static value, a unit load was applied, allowing the model to function as an analytical tool for qualitative prediction of behavior. In addition, the physical contact between the strap and the cardboard caused pronounced geometric non-linearities and infinite stress peaks, which initially caused the model to diverge. Stabilizing the calculation requires rigorous calibration of the Contact Control between the surfaces. As a result, the obtained value of 6.02 MPa should be conceptually interpreted as a stress concentration factor, proving that the specific geometry of the cardboard amplifies the induced stress.

In parallel, the tribological study on wear in the passage plate established severe computational and experimental constraints. The simulation of continuous material loss inherently involves distortion of the model mesh, which requires highly complex adaptive formulations, such as the Arbitrary Lagrangian-Eulerian (ALE) method. The computational difficulty was further accentuated by the empirical difficulty of parameterizing and defining dynamic friction during real-world production line operating conditions, as well as accurately determining the exact center of gravity of the 0.33 cl bottle. A strategic methodological decision was necessary to mitigate the difficulties encountered. Instead of extracting potentially erratic numerical results, the focus was deliberately directed towards creating an analytical and kinematic foundation. The approach taken ensured that the tribological configuration and kinematic calculations were solidly defined, serving as a reliable basis for the company's future iterations.

10.3 Future Work

This dissertation justifies the implementation of Lean methodologies and typical Industry 4.0 development tools in the two most critical production lines of the *Super Bock Group*, achieving positive results in mitigating operational bottlenecks.

However, similarly to the philosophy of continuous improvement, the work developed is the beginning of a path towards further maturation and application in new filling lines. Therefore, the main guidelines structured for future work are listed below and are divided by areas of intervention:

10.3.1 Digitalization, Information Systems, and *Text Mining*

In the analysis of data acquired by maintenance (discussed in Chapter 4), although the developed Python code has superficially bypassed unstructured information, upstream action is necessary to categorically normalize the different failures. Therefore, restructuring the manual data entry layout in the SmartPlant software is suggested, segmenting by categories such as module, component, and failure mode, before the final data migration to the SAP software. This parameterization will require maintenance operators and technicians to generate more concise and standardized reports, ensuring that the information arrives "clean" for more detailed extraction and analysis.

Simultaneously, the database created on the SharePoint platform (subchapter 5.3) proved to be a useful initial prototype for the maintenance and operations areas. As a future objective, this architecture should be centrally designed and scaled to all areas of the production department at the Leça do Balio plant, thus integrating Manufacturing, Utilities, and General Maintenance services into a single knowledge-sharing ecosystem.

10.3.2 Assisted Reality and the Evolution of Visual SOPs

The visual platforms and Standard Operating Procedures developed (subchapter 5.2.5) represent a solid foundation. However, they need to be supplemented with more complex diagnostic information as well as other difficult-to-detect failures. Currently, there is a limitation in the SAP ERP structure that prevents the direct integration of clickable links and images into Work Orders. In order to implement an immediate resource solution, QR codes that can be read using tablets were adopted, a solution whose objective was effectively achieved.

However, considering that the company will benefit from future SAP software updates, it is expected that this technology will allow the use of hands-free Assisted Reality systems, with RealWear glasses across the production lines by maintenance technicians on the factory floor.

10.3.3 Inventory Management Automation (Cyber-Physical Systems)

The implementation of proximity *Kanbans* (Chapter 6) ensured the execution of Autonomous Maintenance for routine operations. As the next defined technological leap, a study should be carried out on converting the current electrical prototype into a Cyber-Physical Inventory System, in order to monitor the need for replacement parts in real time.

By integrating presence sensors into the *Kanban*, it will be possible to verify the consumption of parts in real time (for example, pass-through combs) and, if necessary, automatically trigger alerts for parts replenishment directly to the central warehouse, thus ensuring Just-in-Time logistical replenishment without human intervention in the process.

10.3.4 Longitudinal Validation of Maintenance Plans

The new Preventive Maintenance and Cleaning routines (Chapter 5.2) demonstrated a positive trend of improvement. However, the test period (four weeks) is statistically insufficient for an absolute determination of their effectiveness. Future work recommends a more extensive and comprehensive study, capable of cross-referencing availability indices with variable metrics such as different SKUs processed, variations in production volume, and audits to verify the correct daily execution of maintenance and preventive maintenance by operators and technicians. Once its viability is proven, the process should be expanded to integrate annual reviews, end-of-shift cleaning, and monthly preventive maintenance.

In the specific case of premature wear of pneumatic solenoid valves (Chapter 7.1), future work should focus on identifying the root cause of defects rather than limiting the study to immediate symptomatic mechanical mitigation. Therefore, a Root Cause Analysis should be conducted to map and define the temporal degradation curve of these components, culminating in a Cost-Benefit analysis compared to alternative intervention methods. The impact of stress reduction on the joints should also be analyzed over a broader time frame.

10.3.5 Upstream Quality and Physical Barrier Implementation

The project for the physical evaluation of *Poka-Yoke* to mitigate cardboard deformation (Chapter 7.2) is now transitioning to the completion phase. At this time, the order for the manufacture of the aluminum plate and the acquisition of the mechanical hinge have been placed. The polymeric verification tool has already been manufactured according to the aforementioned standards. The improvement requires more than just a *Poka-Yoke* model, also needing a supply chain-focused approach. The non-conforming materials collected should be used to pressure suppliers to reduce the tension of the straps for securing cardboard on the pallet within an acceptable limit. Internally, operators should

adopt the routine of quick sorting of cardboard in the created system, thus rejecting non-conforming batches and reporting material losses to the Quality Department, in order to continuously minimize the occurrence of machine breakdowns.

10.3.6 Advanced Tribological Simulation

Mitigating the bottleneck caused by broken bottles on the transfer plate (Chapter 8) will require, in the future, the complete execution of the Finite Element Analysis model in the Abaqus software. The study should then follow the following methodological structure:

1. Tribological and mechanical characterization of current stainless steel compared to other alternatives, such as polished stainless steel or UHMWPE.
2. Application of Archard's wear law in a surface-to-surface contact interaction.
3. Modeling of the bottles as rigid bodies, subject to the dynamic equation of continuous linear advance ($v \approx 0.33$ m/s) and formulation of the sacrificial plate with an adaptive ALE (Arbitrary Lagrangian-Eulerian) mesh that guarantees the absence of severe distortions of the C3D8R elements.

A time scale factor must also be applied to design and evaluate, in acceptable computational time, months of use of the plate.

The model will thus provide Wear Depth maps necessary for the Production Department to justify the mechanical upgrade of the plate through cost/durability analysis.

10.3.7 Horizontal Scalability (*Roll-out*)

Finally, it is noted that the physical boundary of this dissertation encompassed the Filling Lines under study. The ultimate future work consists of the *roll-out* of all reliability, *Lean*, and digitalization methodologies proven on these equipments to the remaining production lines and machines of the *Super Bock Group*, standardizing the best operational practices on a corporate scale.

Bibliography

[1] BarthHaas. The barthhaas report: Hops and beer, 2026. Acedido em 04/07/2026.

[2] Autoridade da Concorrência. Relatório de monitorização do setor das bebidas, 2025. Análise estrutural do mercado cervejeiro nacional. Acedido em 04/07/2026.

[3] Armando Leitão. *Manutenção Industrial*. FEUP, Porto, 1991.

[4] Ramesh Gulati. *Maintenance and Reliability Best Practices*. Industrial Press, New York, NY, 2nd edition, 2012.

[5] Cyber-Physical System for maintenance in industry 4.0. Technical report, Diva-Portal, 2017.

[6] Integrating TPM and Industry 4.0 to Increase the Availability of Industrial Assets: A Case Study on a Conveyor Belt. *Processes*, 2023.

[7] Zineb Mouhib, Maryam Gallab, Safae Merzouk, Aziz Soulhi, and Mario Di Nardo. Total Productive Maintenance and Industry 4.0: A Literature-Based Path Toward a Proposed Standardized Framework. *Applied System Innovation*, 8(4):98, 2025.

[8] Condition Monitoring and Predictive Maintenance in Industrial Equipment: An NLP-Assisted Review of Signal Processing, Hybrid Models, and Implementation Challenges. *Applied Sciences*, 2025.

[9] Text-Mining Maintenance Records to Automate the Identification and Grouping of Failure Modes. Technical report, ResearchGate, 2020.

[10] Burak Gunay, Weiming Shen, and Chunsheng Yang. Text-mining building maintenance work orders for component fault frequency. *Building Research & Information*, 47(5):518–533, 2018.

[11] Eli Hahn-Powell. Adapting natural language processing for technical text. *PMC - National Center for Biotechnology Information*, 2023.

[12] Shamsudeen Musa, J. O. Abass, B. N. Obaju, and A. A. Babalola. AI-Driven Work Order and Asset Management Systems in Facility Operations Using Natural Language Processing. *Asian Journal of Research in Computer Science*, 18(8):87–101, 2025.

[13] Natural Language Processing Model for Managing Maintenance Requests in Buildings Publicação: Buildings.

[14] Sungil Hong, Junghyun Kim, and Eunhwa Yang. Automated Text Classification of Maintenance Data of Higher Education Buildings Using Text Mining and Machine Learning Techniques. *Journal of Architectural Engineering*, 28(1), 2022.

[15] Implementation and Improvement of the Total Productive Maintenance Concept in an Organization. *Applied System Innovation*, 2021.

[16] Industry 4.0 Enablers and Lean Manufacturing Tools in Respect of Human Resources. *Sustainability*, 2023.

[17] Lean Approach to Spare Parts Management in a Food Production Company: A Case Study. *SCILTP*, 2022.

[18] Effect of I4.0 Technologies on Lean Manufacturing Practices. In *IntechOpen*. 2023.

[19] Information Design for Small Screens: Toward Smart Glass Use in Guidance for Industrial Maintenance. Technical report, ResearchGate, 2021.

[20] Anna Syberfeldt, Oscar Danielsson, and Patrik Gustavsson. Augmented Reality Smart Glasses in the Smart Factory: Product Evaluation Guidelines and Review of Available Products. *IEEE Access*, 5:9118–9130, 2017.

[21] Emerging Technologies in Augmented Reality (AR) and Virtual Reality (VR) for Manufacturing Applications: A Comprehensive Review. *Manufacturing*, 2025.

[22] A Systematic Review of User Acceptance in Industrial Augmented Reality. *Frontiers in Education*, 2021.

[23] Mapping the Emergent Trends in Industrial Augmented Reality. *Electronics*, 2023.

[24] Industrial applications of AR headsets: a review of the devices and experience. *Light: Advanced Manufacturing*, 2025.

[25] Simulating Wearable Urban Augmented Reality Experiences in VR: Lessons Learnt from Designing Two Future Urban Interfaces. *arXiv preprint*, 2024.

[26] Augmented Reality for Human-Robot Collaboration and Cooperation in Industrial Applications: A Systematic Literature Review. *PMC*, 2022.

[27] Sygnia. From Crisis to Strategy: What ToolShell Taught Us About Enterprise Resilience. Technical report, 2025.

[28] Significant Cyber Incidents | Strategic Technologies Program. Technical report, Center for Strategic and International Studies (CSIS), 2025.

[29] CIOs: tear down the wall between resilience and data security. *CIO Magazine*, 2025.

[30] Planning: Response & Recovery. Technical report, Cybersecurity and Infrastructure Security Agency (CISA), 2025.

[31] Fuller H.B. *Hot Melt Adhesives Troubleshooting Guide*. 2025.

[32] *Glue Module Troubleshooting: Stop Leaks & Drips Fast*. APPLIED Adhesives, 2025.

[33] Melton Valco. *The Hidden Costs of Hot Melt System Downtime: Maintenance Strategies That Pay Off*. 2025.

[34] *5 Tips for Hot Melt Drum Unloader Preventive Maintenance*. Bostik, 2025.

[35] N. Talbi, A. Batti, R. Ayad, and Y.Q. Guo. An analytical homogenization model for finite element modelling of corrugated cardboard. *Composite Structures*, 88(2):280–289, 2009.

[36] Compressive Strength of Corrugated Paperboard Packages with Low and High Cutout Rates: Numerical Modelling and Experimental Validation. *PMC*, 2023.

[37] Crushing of Single-Walled Corrugated Board during Converting: Experimental and Numerical Study. *Energies*, 2021.

[38] Thomas J. Urbanik and Edmond P. Saliklis. Finite element corroboration of buckling phenomena observed in corrugated boxes. *Wood and Fiber Science*, 35(3):322–333, 2003.

[39] Open Source Simulation for Compression Analysis of Corrugated Boards. *Symmetry*, 2025.

[40] Numerical Prediction of Equivalent Mechanical Properties of Corrugated Paperboard by 3D Finite Element Analysis. *Applied Sciences*, 2020.

[41] Analytical Homogenization Approach for Double-Wall Corrugated Cardboard Incorporating Constituent Layer Characterization. *Materials*, 2023.

[42] Full-Field Measurements in the Edge Crush Test of a Corrugated Board—Analytical and Numerical Predictive Models. *Materials*, 2021.

[43] Analysis of Stress and Strain in Sandwich Structures Using an Equivalent Finite Element Model. *International Journal of Engineering and Technology Innovation*, 2021.

[44] Tribological performances of UHMWPE and PEEK under dry sliding conditions against steel and various polyetherimide polymer counterfaces. *Industrial Lubrication and Tribology*, 2025.

[45] A Comprehensive Review of Wear Mechanisms and Mitigation Strategies for Tribological Systems. *Tribology in Industry*, 2025.

[46] Curtis M. Goreham-Voss. Cross-shear implementation in sliding-distance-coupled finite element analysis of wear in metal-on-polyethylene total joint arthroplasty. *Journal of Biomechanics*, 43(9):1674–1681, 2010.

[47] Advances in tribological testing of artificial joint biomaterials using multidirectional pin-on-disk testers. *PMC*, 2013.

[48] Friction and Wear Characterization of UHMWPE in Reciprocating Sliding Contact with Co-Cr, Ti-6Al-4V, and Zirconia Implant Bearing Surfaces. ASTM Digital Library, 2025.

[49] Analytical and computational sliding wear prediction of ultrahigh molecular weight polyethylene UHMWPE in block-on-ring (BOR) tribometer. *Jurnal Tribologi*, 2025.

[50] Liang Yan, Linyi Guan, Di Wang, and Dingding Xiang. Application and Prospect of Wear Simulation Based on ABAQUS: A Review. *Lubricants*, 12(2), 2024.

[51] Finite Element Simulation of Dry Wear of Prosthesis Made of UHMWPE and 316LVM Stainless Steel. *Coatings*, 2024.

[52] K.K. Bose and P. Ramkumar. Finite element method based sliding wear prediction of steel-on-steel contacts using extrapolation techniques. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 233(10):1446–1463, 2019.

Appendix A

Figures and Tables

A.1 Operational Support Documentation

A.1.1 Autonomous Maintenance: Standard Operating Procedures (KISTERS L2)



Figure A.1: Standard Operating Procedures - Replacement of passage combs on Kisters Line 2.

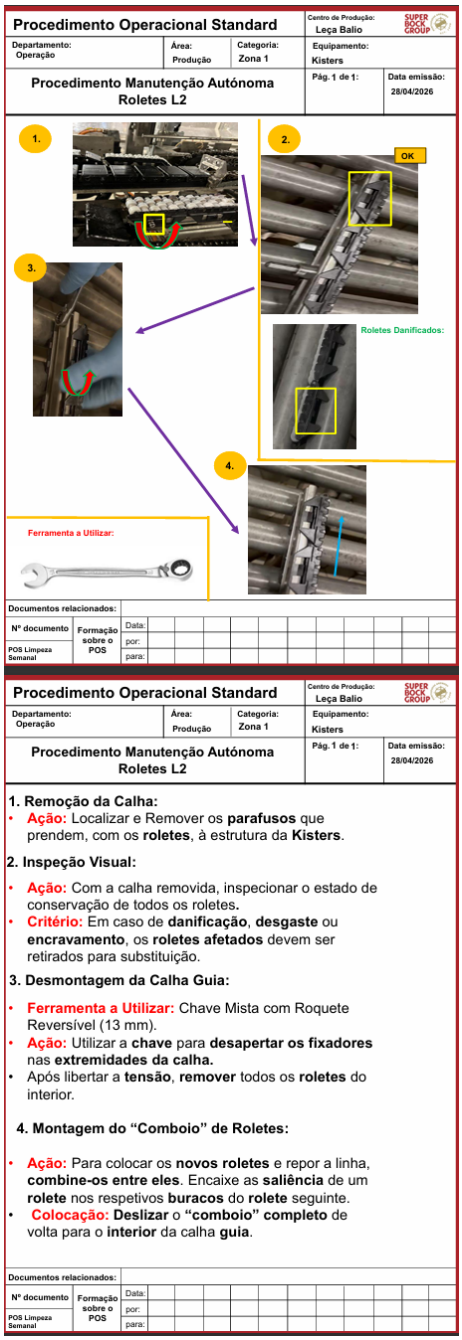


Figure A.2: Standard Operating Procedures - Inspection and replacement of conveyor rollers on Kisters Line 2.



Procedimento Operacional Standard

Centro de Produção: Leça Balio — SUPER BOCK GROUP

Departamento: Operação | Área: Produção | Categoria: Zona 1 | Equipamento: Kisters

Procedimento Manutenção Autónoma Arrastadores Dobradores L2

Pág. 1 de 1: | Data emissão: 28/04/2026

Documentos relacionados:

Nº documento	Formação sobre o POS	Data:
POS Limpeza Semanal		por:
		para:

Procedimento Operacional Standard

Centro de Produção: Leça Balio — SUPER BOCK GROUP

Departamento: Operação | Área: Produção | Categoria: Zona 1 | Equipamento: Kisters

Procedimento Manutenção Autónoma Arrastadores Dobradores L2

Pág. 1 de 1: | Data emissão: 28/04/2026

1. Desaperto de Parafusos:

- **Ferramenta:** Utilizar a **Chave nº10**.
- **Ação:** Desapertar os **parafusos frontais** que fixam o conjunto.

2. Remoção da Chapa:

- **Ação:** Agarrar na chapa e retirá-la puxando-a para cima, libertando-a do suporte principal.

3. Verificar Estado de Limpeza:

- **Ação:** No caso de ser necessário apenas Limpeza, aplicar o **Spray Nordson** nos arrastadores dobradores.
- **Execução:** **Passar o pano limpo** para remover toda a **cola** e **sujidades acumuladas**.

4. Remoção do Arrastador Dobrador:

- **Ação:** Puxar o Arrastador Dobrador para trás, deslizando-o horizontalmente para fora da sua calha de encaixe.

5. Montagem:

- Deslizar o **Arrastador Dobrador** para a frente, recolocando-o na calha.
- Encaixar a **chapa** deslizando-a para baixo até à posição correta.
- Utilizar a **chave nº10** para apertar firmemente os parafusos e fixar o conjunto.

Documentos relacionados:

Nº documento	Formação sobre o POS	Data:
POS Limpeza Semanal		por:
		para:

Figure A.3: Standard Operating Procedures - Folding tractor maintenance routine on Kisters Line 2

A.1.2 Proximity Kanban System: Infrastructure and Automation

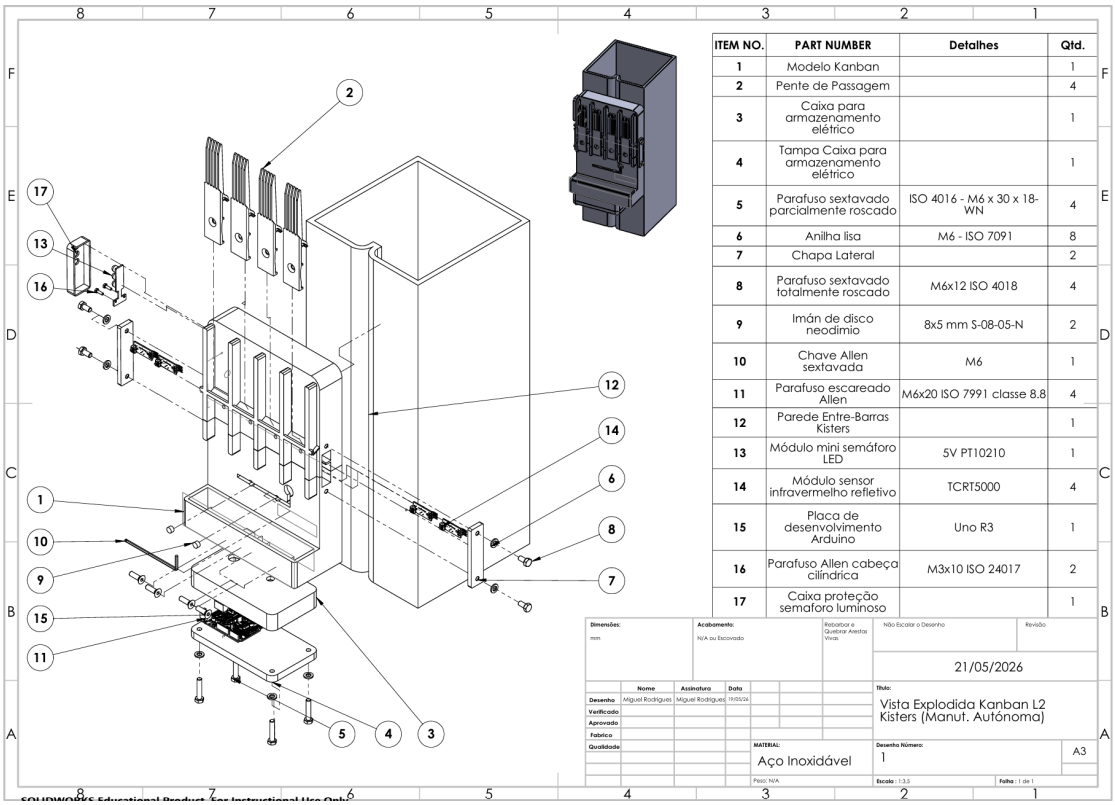


Figure A.4: Exploded view of the Kisters Kanban system support.

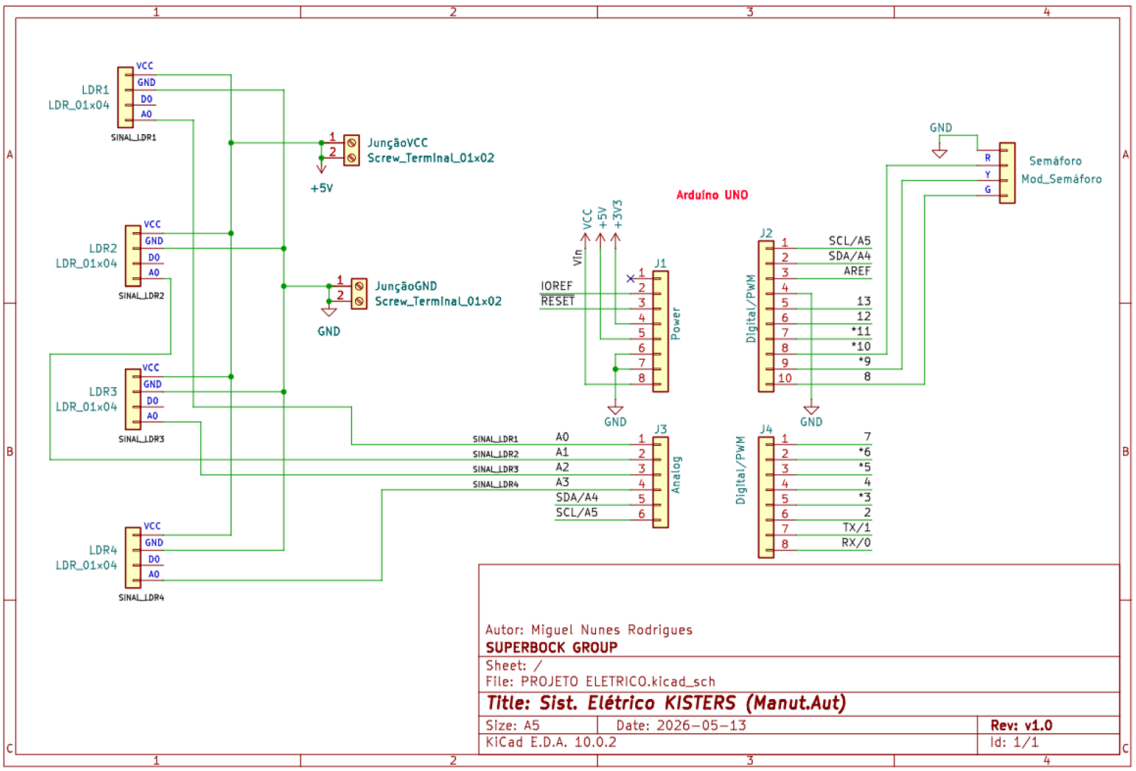


Figure A.5: Electrical topology: Sensor-to-actuator interconnection.

A.1.3 Slicing configurations for Kanban Model 2 production

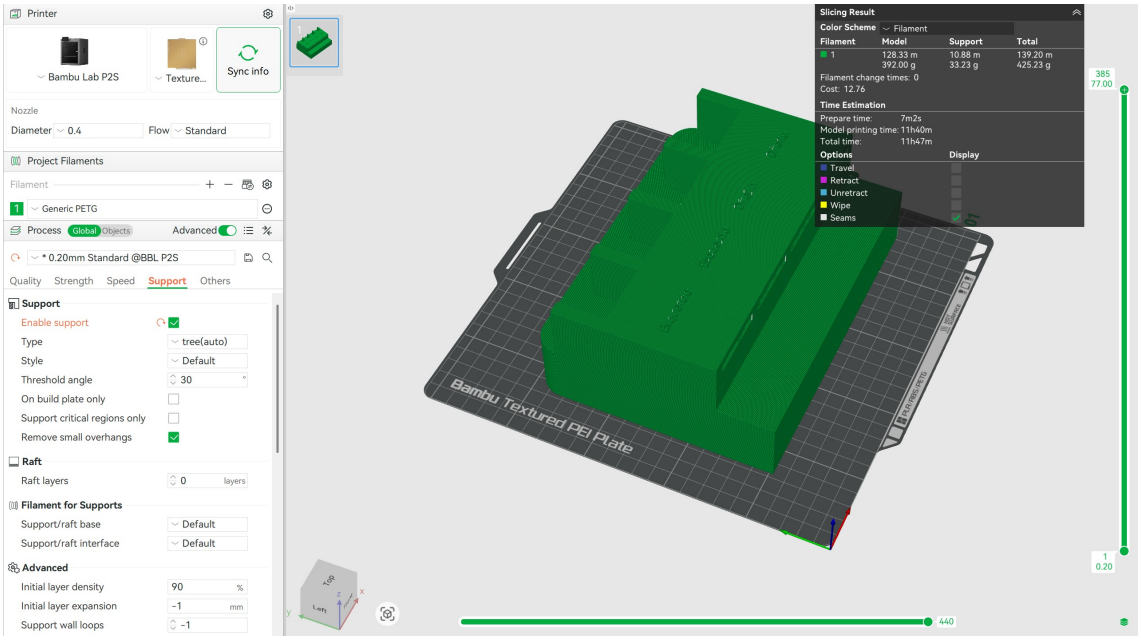


Figure A.6: Preparation for manufacturing and configuration of slicing parameters (Bambu Studio) for the upper zone of the Kanban 2 model.

A.1.4 Digital Preventive Maintenance Interface (Microsoft Forms)

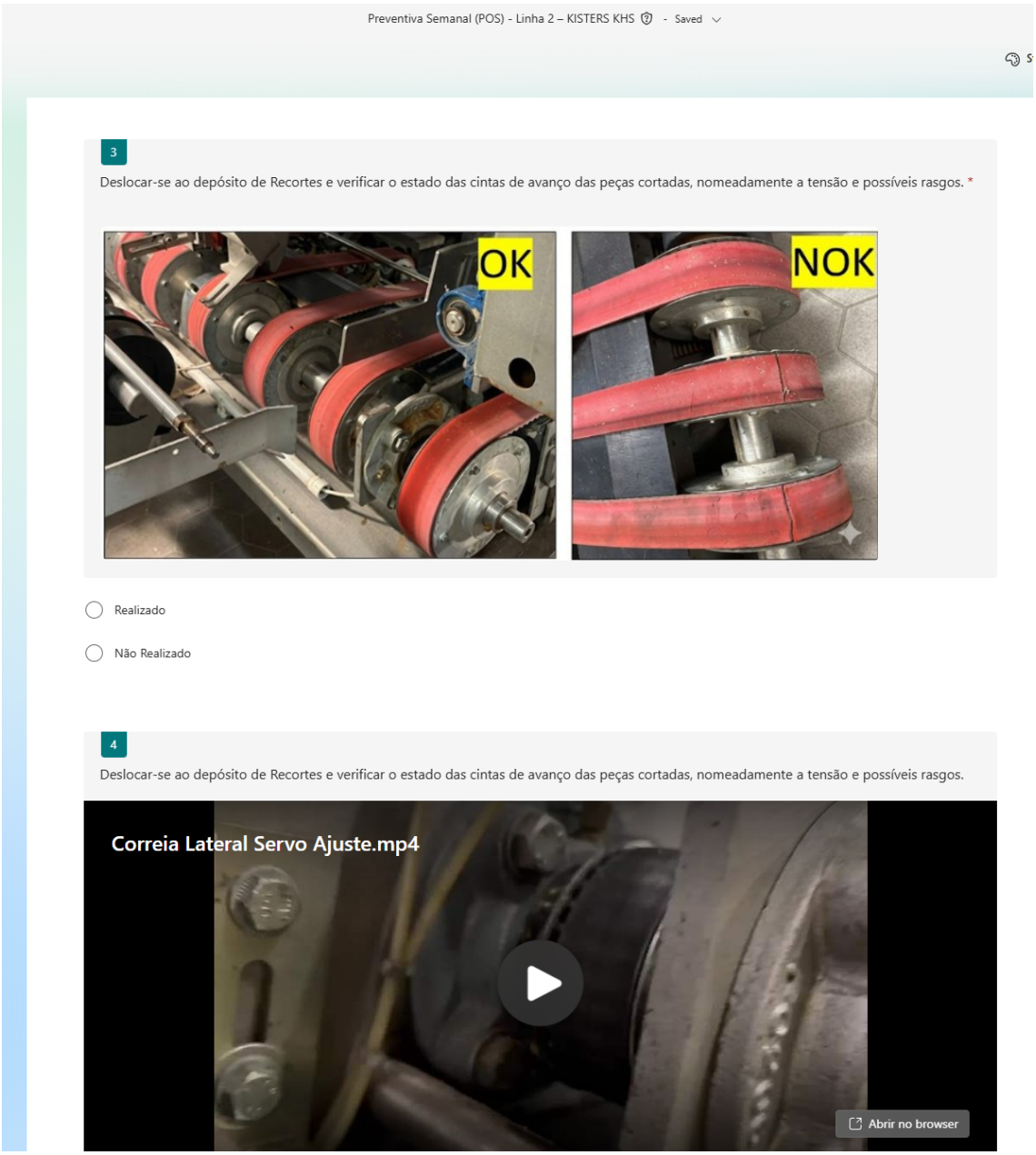


Figure A.7: Mobile view of the digital preventive maintenance interface developed on Microsoft Forms. The platform is accessed via QR Code on the shop floor and features multimedia instructions alongside mandatory validation fields.

A.1.5 Standard Operating Procedure: Ovality Determination

1. Encostar o lado com empeno (ovalizado) sobre uma superfície plana
2. Medir com uma fita a flecha, **x mm**
3. Medir a dimensão total do lado do empeno, **y mm**

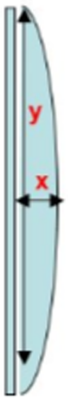


Figura 1

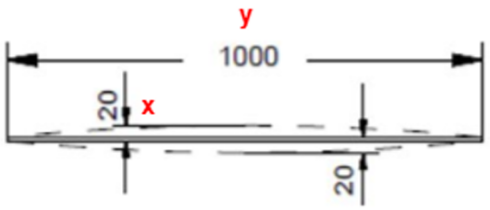


Figura 2

4. Cálculo da Ovalização (%) = (x /y) x 100

Figure A.8: Standard Operating Procedure detailing the specific guidelines, steps, and acceptance criteria for determining ovality in corrugated cardboard packaging.

Appendix B

Codding

B.1 Python code

```
import pandas as pd
from sklearn.feature_extraction.text import TfidfVectorizer
from sklearn.ensemble import RandomForestClassifier

# 1. Ler o ficheiro Excel com o nome EXATO final
caminho_ficheiro = '/content/Linha12_com_tempo_intervencao_teste.xlsx'
df = pd.read_excel(caminho_ficheiro, sheet_name='Sheet1')

# Nomes exatos das colunas
col_texto = 'Texto breve'
col_zona = 'Zona'
col_comp = 'Componente'

print("A carregar e separar os dados...")

# 2. Separar as linhas:
df_treino = df.dropna(subset=[col_zona, col_comp]).copy()
df_vazias = df[df[col_zona].isna() | df[col_comp].isna()].copy()

print(f"Linhas para treinar o modelo: {len(df_treino)}")
print(f"Linhas vazias para o modelo prever: {len(df_vazias)}")

# 3. Preparar o Treino
y_treino = df_treino[col_zona].astype(str) + " - " + df_treino[col_comp].astype(str)
X_treino = df_treino[col_texto].fillna('')

# 4. Converter texto em números e Treinar o Modelo
```

```
vetorizador = TfidfVectorizer()
X_treino_numeros = vetorizador.fit_transform(X_treino)

print("A treinar o cérebro da máquina...")
modelo = RandomForestClassifier(random_state=42)
modelo.fit(X_treino_numeros, y_treino)

# 5. Fazer as previsões para as linhas vazias
if not df_vazias.empty:
    print("A prever as Zonas e Componentes para as linhas vazias...")
    X_prever = df_vazias[col_texto].fillna('')
    X_prever_numeros = vetorizador.transform(X_prever)

    previsoes = modelo.predict(X_prever_numeros)

    # 6. Separar a combinação e atualizar as respetivas colunas
    zonas_previstas = [texto.split(" - ")[0] for texto in previsoes]
    comps_previstos = [texto.split(" - ")[1] for texto in previsoes]

    df_vazias[col_zona] = zonas_previstas
    df_vazias[col_comp] = comps_previstos

    # 7. Injetar as previsões de volta no Excel original
    df.update(df_vazias)

    # 8. Guardar o novo Excel Mágico!
    novo_caminho = '/content/Linha12_Preenchido_Pelo_Python.xlsx'
    df.to_excel(novo_caminho, index=False, sheet_name='Sheet1')

    print(f"\nSUCESSO! O ficheiro foi atualizado e guardado como: {novo_caminho}")
    print("Clica no botão de atualizar as pastas à esquerda para transferires o teu nov
else:
    print("\nNão encontrei nenhuma linha com a Zona ou Componente vazios para prever.")
\label{ap1:Python}
```

B.2 C++ Code

```cpp
/**
 * @file sistema_monitorizacao_luminosidade.ino
 * @brief Sistema de monitorização de luminosidade multi-sensor com feedback visual.
 * @details Implementação não-bloqueante baseada numa máquina de estados finitos (FSM).
 * Incorpora histerese de software para mitigação de ruído analógico nos sensores LDR.
 * @author Miguel Nunes Rodrigues
 * @date Maio de 2026
 */

// ================================================
// DEFINIÇÕES DE HARDWARE E CONSTANTES
// ================================================

const uint8_t NUM_SENSORES = 4;
const uint8_t PINOS_LDR[NUM_SENSORES] = {A0, A1, A2, A3};

const uint8_t PINO_LED_VERDE = 8;
const uint8_t PINO_LED_AMARELO = 9;
const uint8_t PINO_LED_VERMELHO = 10;

// Parâmetros de Calibração do Sistema
const int LIMITE_DETECAO = 500; // Limiar central de transição
const int HISTERESE = 20; // Margem para evitar oscilações no limiar (flickering)

// Temporização do Sistema (Abordagem Não-Bloqueante)
const unsigned long INTERVALO_LEITURA_MS = 100; // Frequência de amostragem (10 Hz)
unsigned long tempoUltimaLeitura = 0;

// ================================================
// ESTRUTURAS DE DADOS E ESTADO GLOBAL
// ================================================

/**
 * @brief Enumeração dos estados possíveis para o módulo de sinalização.
```

```
35  */
36 enum EstadoSemaforo {
37   ESTADO_INICIALIZACAO,
38   ESTADO_NENHUM_ATIVO,
39   ESTADO_PARCIALMENTE_ATIVO,
40   ESTADO_TODOS_ATIVOS
41 };
42
43 EstadoSemaforo estadoAtual = ESTADO_INICIALIZACAO;
44 bool estadosSensores[NUM_SENSORES] = {false, false, false, false}; //
   ↪  Memória do estado de cada sensor
45
46 // ================================================
47 // ROTINAS PRINCIPAIS (SETUP & LOOP)
48 // ================================================
49
50 void setup() {
51   Serial.begin(9600);
52
53   // Configuração dos Pinos
54   pinMode(PINO_LED_VERDE, OUTPUT);
55   pinMode(PINO_LED_AMARELO, OUTPUT);
56   pinMode(PINO_LED_VERMELHO, OUTPUT);
57
58   // Inicialização segura
59   atualizarAtuadores(ESTADO_NENHUM_ATIVO);
60   estadoAtual = ESTADO_NENHUM_ATIVO;
61 }
62
63 void loop() {
64   unsigned long tempoAtual = millis();
65
66   // Execução periódica não-bloqueante
67   if (tempoAtual - tempoUltimaLeitura >= INTERVALO_LEITURA_MS) {
68     tempoUltimaLeitura = tempoAtual;
69
70     // 1. Aquisição e Filtro de Dados
71     uint8_t sensoresAtivos = avaliarSensores();
72
73     // 2. Lógica de Decisão (Máquina de Estados)
```

```
74      EstadoSemaforo novoEstado = determinarEstado(sensoresAtivos);
75
76      // 3. Atualização de Atuadores (Apenas se houver mudança de estado)
77      if (novoEstado != estadoAtual) {
78        estadoAtual = novoEstado;
79        atualizarAtuadores(estadoAtual);
80
81        // Registo da transição para monitorização
82        Serial.print("Mudança de Estado! Sensores Ativos: ");
83        Serial.println(sensoresAtivos);
84      }
85    }
86  }
87
88  // ================================================
89  // FUNÇÕES DE PROCESSAMENTO E CONTROLO
90  // ================================================
91
92  /**
93   * @brief Adquire dados dos LDRs e aplica algoritmo de histerese.
94   * @return O número de sensores que se encontram ativados.
95   */
96  uint8_t avaliarSensores() {
97    uint8_t contagemAtivos = 0;
98
99    for (uint8_t i = 0; i < NUM_SENSORES; i++) {
100     int leituraAnalogica = analogRead(PINOS_LDR[i]);
101
102     // Aplicação de Histerese de Software
103     // Se não está ativo, precisa de descer do limite MINUS a histerese
        ↪ para ativar
104     if (!estadosSensores[i] && leituraAnalogica < (LIMITE_DETECAO -
        ↪ HISTERESE)) {
105       estadosSensores[i] = true;
106     }
107     // Se está ativo, precisa de subir do limite PLUS a histerese para
        ↪ desativar
108     else if (estadosSensores[i] && leituraAnalogica > (LIMITE_DETECAO +
        ↪ HISTERESE)) {
109       estadosSensores[i] = false;
```

```
110       }
111
112       // Contabiliza se o sensor atual estiver no estado ativo
113       if (estadosSensores[i]) {
114         contagemAtivos++;
115       }
116     }
117
118     return contagemAtivos;
119   }
120
121   /**
122    * @brief Mapeia a quantidade de sensores para um estado lógico do
       ↪  semáforo.
123    * @param quantidade Número de sensores ativados.
124    * @return O novo EstadoSemaforo correspondente.
125    */
126   EstadoSemaforo determinarEstado(uint8_t quantidade) {
127     if (quantidade == 0) {
128       return ESTADO_NENHUM_ATIVO;
129     } else if (quantidade > 0 && quantidade < NUM_SENSORES) {
130       return ESTADO_PARCIALMENTE_ATIVO;
131     } else {
132       return ESTADO_TODOS_ATIVOS;
133     }
134   }
135
136   /**
137    * @brief Aciona as saídas digitais correspondentes ao estado atual.
138    * @param estado Estado lógico a aplicar aos atuadores físicos.
139    */
140   void atualizarAtuadores(EstadoSemaforo estado) {
141     // Limpeza de registos (Turn off all)
142     digitalWrite(PINO_LED_VERDE, LOW);
143     digitalWrite(PINO_LED_AMARELO, LOW);
144     digitalWrite(PINO_LED_VERMELHO, LOW);
145
146     // Acionamento específico
147     switch (estado) {
148       case ESTADO_NENHUM_ATIVO:
```

```
149         digitalWrite(PINO_LED_VERMELHO, HIGH);
150         break;
151       case ESTADO_PARCIALMENTE_ATIVO:
152         digitalWrite(PINO_LED_AMARELO, HIGH);
153         break;
154       case ESTADO_TODOS_ATIVOS:
155         digitalWrite(PINO_LED_VERDE, HIGH);
156         break;
157       default:
158         // Tratamento de erro silencioso / fallback state
159         digitalWrite(PINO_LED_VERMELHO, HIGH);
160         break;
161     }
162 }
163
```