

INTERDISCIPLINARY DOCTORAL SCHOOL

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**MONITORING AND OPTIMIZING THE PARAMETERS OF LASER
MICROPERFORATION AND WELDING PROCESSES TO ENSURE THE
NOMINAL FUNCTIONALITY OF THE AIRBAG**

SUMMARY

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SUBJECT AND RESEARCH AREA OF THE DOCTORAL THESIS

The doctoral thesis entitled “Monitoring and Optimization of Laser Microperforation and Welding Process Parameters to Ensure the Nominal Functionality of the Airbag” falls within the field of Industrial Engineering, addressing a topic of major relevance to the automotive industry—particularly in the current context of manufacturing process digitalization and increasingly stringent passive safety requirements for vehicles.

The main objective of this research is the development and implementation of effective methods for monitoring and optimizing the technological parameters involved in laser micromachining and welding processes used in the manufacturing of airbag system components. The thesis proposes an integrated approach that combines experimental methods, mathematical modeling, and statistical analysis to identify critical relationships between process parameters, the materials used, and the quality of the resulting output.

Laser microperforation is a key technological process that ensures the controlled deployment of the airbag upon activation, allowing for the precise rupture of textile or polymeric materials in predefined areas. In this context, the monitoring of perforation quality and the definition of functional tolerances become fundamental to ensuring system reliability. Welding, on the other hand, is employed in the assembly of airbag components, where mechanical strength and sealing integrity are critical parameters. The optimization of these processes aims to reduce defects, enhance reproducibility, and decrease energy consumption—factors that together contribute to improved production efficiency.

The research is conducted within an interdisciplinary framework at the intersection of materials engineering, advanced manufacturing technologies, and industrial automation. High-precision equipment, modern inspection techniques (including optical imaging and integrated sensors), and data processing algorithms are utilized to assess process performance in real time. The thesis also explores the integration of these processes into intelligent production lines aligned with the principles of Industry 4.0.

This doctoral work adds significant value to the enhancement of product quality and safety in the automotive sector, offering concrete solutions for the optimization of critical technological processes. It highlights the importance of applied research in the development of innovative manufacturing technologies and is directed both toward the academic community—by deepening the understanding of the phenomena involved in micromachining—and the industrial environment—by providing practical tools for improving production performance.

INTRODUCTION

The introductory chapter of the thesis provides a well-defined conceptual and practical framework that outlines the foundations of the research on the use of modern micromachining technologies in the automotive industry. Emphasis is placed on laser microperforation and welding processes, both of which are essential to ensuring the performance and reliability of airbag systems. The importance of these processes is highlighted in the context of increasingly stringent international safety regulations and the intensifying technological competition within the automotive sector.

The introduction outlines the main directions of the research, starting from a critical analysis of the current state of technologies used in airbag manufacturing and identifying the limitations of conventional solutions—such as the lack of real-time monitoring, process variability, and the influence of uncontrolled parameters on final product quality. This reveals a pressing need for the development of advanced control and optimization methods that can increase precision and reliability in production.

The thesis proposes the integration of rigorous experimental methods and predictive mathematical models to investigate the influence of technological parameters on the quality of microperforation and welding. Additionally, it seeks to establish a methodological framework for continuous process monitoring using sensors, data processing algorithms, and non-destructive inspection techniques. These efforts aim to enable advanced real-time control systems compatible with the requirements of Industry 4.0.

The introduction defines the specific objectives of the thesis, the research hypotheses, and the applied working methodology, which combines theoretical analysis with practical investigation. Technological and scientific choices are justified, and the usefulness of the research is supported by its direct applicability in high-responsibility industrial processes.

In conclusion, the introduction emphasizes the theoretical and practical value of the thesis, shaping a clear research trajectory oriented toward innovation, safety, and industrial efficiency. This contribution aims to address both academic expectations and real-world industrial needs, strengthening the link between scientific research and the practical implementation of advanced technologies

CHAPTER 1. CURRENT STATE OF RESEARCH IN THE FIELD OF MATERIAL PROCESSING USING LASER TECHNOLOGY

1.1. The Use of Laser Technology in Material Processing

Section 1.1 analyzes the general context and the rationale behind the use of laser technology in material processing applications. It highlights the transition from conventional methods to modern techniques that are faster, more precise, and more energy-efficient, enabling rigorous control of the manufacturing process. Laser technology is presented as a versatile solution applicable to high-precision operations such as cutting, welding, microperforation, and engraving. The argument is made that the use of laser systems in manufacturing has become a necessity rather than an option, particularly in fields where precision, speed, and reliability are critical.

The section also emphasizes the historical development of laser technology, from its first applications in research laboratories to its large-scale industrial implementation. It underscores the evolution of laser sources—from bulky and expensive equipment to compact, high-performance, and scalable systems. The significant role of laser technology in the digitalization of industrial processes and the integration of Industry 4.0 concepts is also highlighted.

This subsection presents concrete examples of laser applications in fields such as electronics, medical technology, aerospace, and the automotive industry, with a focus on the adaptability of the technology to various types of materials: metals, polymers, composite materials, and ceramics. Due to its ability to deliver precisely focused energy at the millimeter scale, laser technology significantly reduces material waste and contributes to the overall energy efficiency of the production process (Figure 1.1).

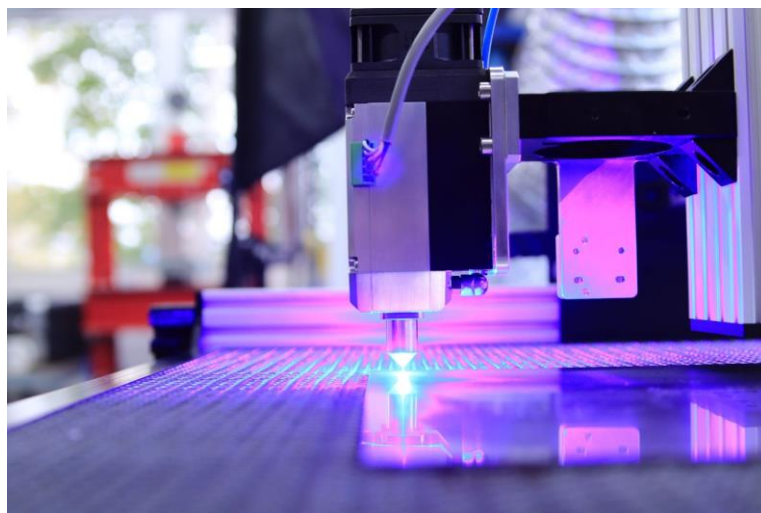


Figure 1.1. Laser-Assisted 3D Printing [WWW3].

The discussion also addresses the importance of standardizing laser-based processes and the applicable regulations concerning operator safety and environmental protection. Finally, the section provides an overview of future perspectives and strategic directions for research and development in the field of laser processing technologies.

1.2. Specific Characteristics of Laser Technology

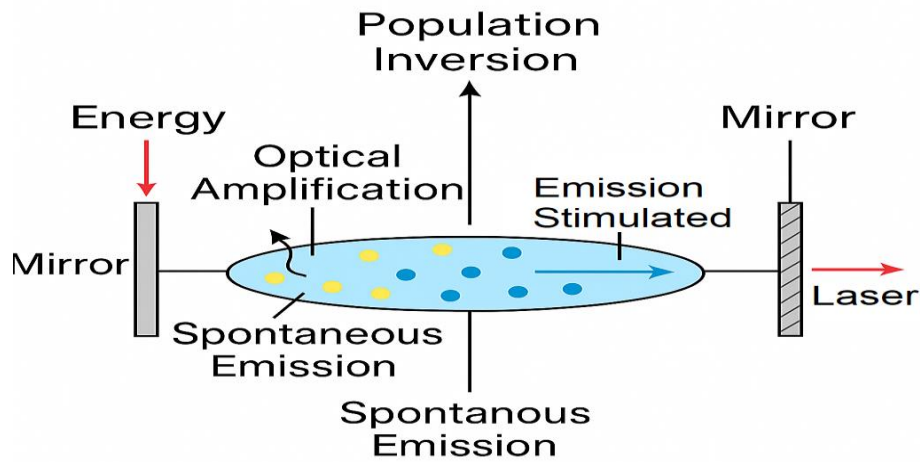


Figure 1.2. Principle of Laser Operation.

Section 1.2 explores the physical and functional characteristics of laser technology, with a focus on the parameters that directly influence processing operations (Figure 1.3).



Figure 1.3. Factors Influencing Laser Selection.

The essential properties of the laser beam—coherence, directionality, monochromaticity, and focusability—are described, along with how these characteristics contribute to process precision. A classification of the main types of lasers used in industrial applications (CO₂, Nd:YAG, and fiber lasers) is provided, analyzing the differences between them in terms of wavelength, energy efficiency, durability, and operating costs (Figure 1.4 and Figure 1.5).

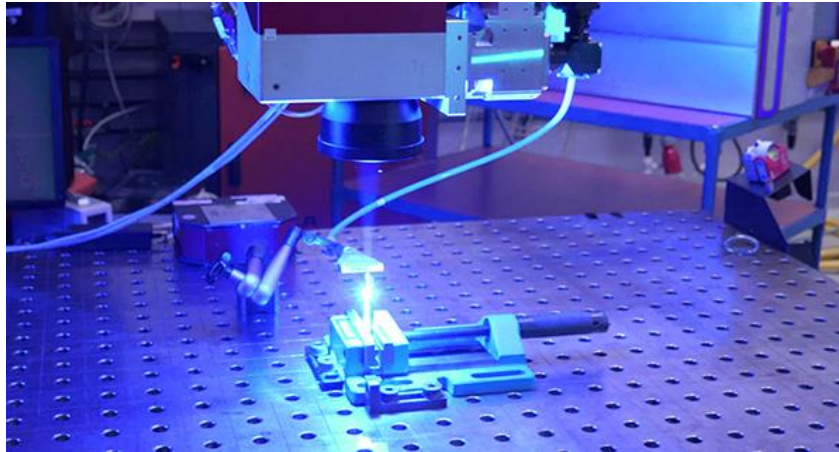


Figure 1.4. Diode Laser Welding [WWW7].

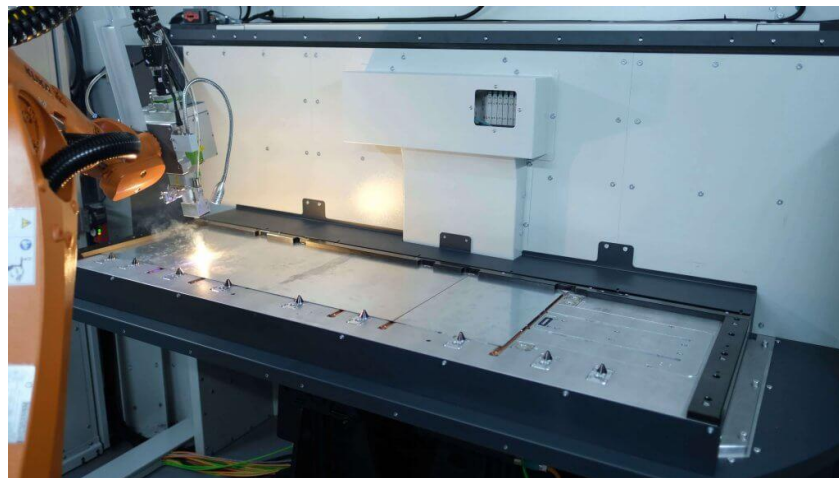


Figure 1.5. Nd:YAG Laser Welding [WWW5].

The general structure of a laser processing system is presented, including the radiation source, the optical guidance and focusing system, as well as the numerical control (CNC) and closed-loop control systems. The principles of beam–material interaction—such as absorption, reflection, and thermal conduction—are discussed, as they determine the processing depth, the extent of thermal influence, and the quality of the resulting surface.

This section also emphasizes the importance of technological parameters such as beam power, scanning speed, pulse frequency, and interaction time. It explains how variations in these parameters can significantly affect the process outcome, and how their optimization is essential to achieving precise and repeatable machining. Examples of industrial scenarios are provided, in which fine control of these parameters directly influences the success of the application.

Additionally, the section outlines the advantages of modern laser systems that integrate optical and sensor-based feedback for real-time process self-regulation. These capabilities enable adaptation to variations in material or working environment, thereby improving the reliability and consistency of industrial processes. In conclusion, Section 1.2 provides a technological foundation for understanding the applicability and complexity of laser processing control.

1.3. Advantages and Limitations of Laser Technology in Material Processing

This section details the strengths and specific challenges associated with the use of laser technology in material processing applications. Among the main advantages are high precision, non-contact processing, reduced heat-affected zones, the ability to work with a wide range of materials, and easy integration into automated systems. These benefits make laser technology a top-tier solution for critical industrial applications where geometric control and surface quality are essential.

Non-contact processing minimizes mechanical wear and eliminates vibrations, leading to extended equipment life and superior control over the final shape. Furthermore, the laser beam can be adapted to the requirements of the application, offering a level of flexibility that is difficult to achieve with other methods. The ability to focus energy enables localized processing with controlled thermal effects, thereby reducing deformations and damage to sensitive materials.

However, laser technology also presents important limitations. The high initial cost of equipment, along with the need for regular maintenance and skilled operator training, can be barriers for small and medium-sized enterprises.

In conclusion, this section provides a balanced analysis between the innovative potential of laser technology and the practical constraints that must be managed to ensure optimal performance in production.

1.4. Current Trends in Laser Technology Research

Section 1.4 presents modern trends in applied laser technology research, highlighting recent advancements and strategic development directions. Emphasis is placed on the shift toward short- and ultrashort-pulse laser systems, which enable high-resolution processing with minimal thermal impact. In addition, the integration of advanced monitoring technologies—based on sensors and artificial intelligence—for real-time process control is underscored.

Another major trend is the full digitalization of laser-based processes through the connection of equipment to intelligent control and data analysis systems (big data, machine learning). This makes it possible to automatically adapt processing parameters based on material behavior, ensuring consistent and predictable quality. Furthermore, increasing attention is being paid to sustainability, emission reduction, and the recycling of processed materials.

A research direction is also emerging in the miniaturization of laser sources and the development of portable systems for mobile industrial applications or operations in confined environments. In conclusion, the section highlights the dynamic, multidisciplinary, and innovation-driven nature of the laser technology field.

1.5. Applications of Laser Technology in the Automotive Industry

This section analyzes the practical applications of laser technology in the automotive industry, with a focus on its contribution to improving manufacturing efficiency and enhancing product safety.

Applications such as welding of structural components, microperforation of airbag materials, precision cutting of metallic or polymeric parts, and marking and engraving for traceability purposes are presented.

Laser welding is employed to join body components and metallic parts of varying thicknesses, offering high mechanical strength and a minimal heat-affected zone. This enables weight reduction of components, contributing to the vehicle's overall energy efficiency. The microperforation of textile materials used in airbags is another essential application, as it ensures a controlled and safe opening at the moment of system deployment.

Laser engraving is used for both decorative and functional purposes on visible or concealed vehicle elements.

The integration of laser processes into automated production lines of major automotive manufacturers is supported by precise process control, flexibility in adapting to various geometries, and reduced cycle time. In conclusion, laser technology proves to be an indispensable tool in the modernization of the automotive industry, supporting innovation, safety, and sustainability.

1.6. Conclusions

The conclusions of Chapter 1 highlight the importance of laser technology in the modern context of material processing, emphasizing its innovative, adaptable, and strategically relevant nature across numerous industrial sectors, particularly in the automotive industry. The analysis of the literature and current applications has demonstrated that the use of laser beams enables high-precision processing operations, with increased energy efficiency and superior control over technological parameters.

Laser technology is characterized by a set of distinct physical and functional features that clearly differentiate it from traditional methods: coherence, directionality, highly precise focusing, and the potential for full process automation. These properties not only expand its range of applicability but also improve the quality of the resulting products.

The chapter also identified a significant set of competitive advantages offered by this technology—such as non-contact processing, adaptability to various materials, and reduction of heat-affected zones—as well as limitations that must be carefully managed, including high equipment costs, process control complexity, and the need for specialized technical expertise.

Recent research trends point to a clear shift toward integrating laser technology into smart production workflows governed by Industry 4.0 principles, where real-time monitoring, data processing, and artificial intelligence play essential roles. This outlines a path toward the sustainable, efficient, and scalable development of these technologies.

In conclusion, Chapter 1 lays the foundation for the need to deepen research efforts focused on optimizing process parameters and integrating advanced control systems in industrial applications, in order to fully leverage the potential of laser technology within the current and future landscape of modern engineering.

CHAPTER 2. OBJECTIVES OF THE DOCTORAL THESIS

2.1. Current Research Trends in Laser Microperforation in the Automotive Industry

Section 2.1 of the thesis focuses on current research trends in the laser microperforation process, with direct applicability in the automotive industry, particularly in the manufacturing of airbag components. It emphasizes the need for strict control over the shape, size, and distribution of perforations, as these directly influence the deployment behavior and efficiency of passive safety systems.

The main research directions presented include the use of short and ultrashort pulse lasers to minimize thermal effects, the development of adaptive scanning strategies, and the integration of optical feedback systems for real-time monitoring of microperforation quality. In parallel, numerical modeling of the process—such as finite element methods—is being explored to simulate beam–material interaction and predict material behavior.

Special attention is given to post-process perforation characterization using optical analysis, electron microscopy, and non-destructive testing techniques to assess quality and compliance with industrial standards. Additionally, the influence of technological parameters—laser power, scanning speed, and pulse frequency—on the perforation quality and thermal impact on the material is analyzed.

The section also highlights the challenges of integrating these processes into automated production lines, particularly regarding perforation uniformity and stable process control under mass production conditions. In conclusion, current research trends in laser microperforation for the automotive sector aim to enhance precision, repeatability, and process adaptability, while simultaneously reducing production costs and environmental impact.

2.2. Delimitation of the Research Domain

Given the complexity of issues associated with laser microperforation in the automotive industry, the delimitation of the research domain is essential to ensure a systematic and objective approach. In this context, the doctoral thesis will focus on the following main research directions:

- Monitoring, control, and optimization of the laser microperforation process for synthetic leather components: analyzing control strategies for laser parameters to improve perforation uniformity;
- Influence of electromagnetic noise levels on the laser microperforation process specific to automotive components: investigating the impact of electromagnetic fluctuations on perforation accuracy and the mechanical performance of perforated materials;
- Study on laser microperforation for integrating sandwich materials in airbag zones using special regimes: testing the compatibility of these materials with laser technology and analyzing the effects on airbag safety and performance;

- Study on the capability of the laser microperforation process in the airbag area: evaluating the precision and efficiency of the manufacturing process under industrial conditions;
- Efficiency and precision of the welding process for automotive components in the airbag zone: analyzing the impact of microperforation on the quality of welds in the airbag guide channel and optimizing process parameters;
- Integration of vision processing systems (VPS) into the control loop of the laser microperforation and welding process: developing and validating a real-time optical inspection system capable of automatically identifying, evaluating, and correcting geometric deviations in perforations, in order to enhance reliability, traceability, and consistency in the quality of the final product.

2.3. Research Objectives

Based on the analysis of the current state of research in the field, as well as a critical review of existing solutions, the following research objectives are proposed:

1. **Monitoring and optimization of the laser microperforation process**
 - Analysis of the influence of laser parameters on perforation accuracy;
 - Improvement of perforation quality, reduction of technological losses, and enhancement of final product reliability;
 - Development of an automated system for real-time parameter monitoring and adjustment.
2. **Investigation of the impact of electromagnetic noise on perforation quality**
 - Determination of the correlation between electromagnetic interference (EMI) intensity and the mechanical performance of perforated materials;
 - Identification of strategies to mitigate EMI effects on the microperforation process;
 - Evaluation of process stability under varying levels of electromagnetic interference.
3. **Integration of sandwich materials in airbag zones for laser microperforation**
 - Experimental studies on the mechanical properties of laser-processed materials;
 - Optimization of laser parameters to ensure precise and safe perforation;
 - Determination of the impact of these materials on airbag safety and performance.
4. **Optimization of the welding process in the airbag guide channel**
 - Evaluation of the influence of microperforation on weld quality;
 - Optimization of welding parameters to ensure a secure and efficient joint;
 - Determination of the perforation process's impact on the structural reliability of the airbag system.
5. **Integration of a Vision Processing System (VPS) into the laser microperforation and welding workflow**
 - Advanced real-time optoelectronic inspection solution;
 - Continuous monitoring of the geometric quality of perforations and welds;
 - Automated identification of dimensional deviations and adaptive correction of process parameters;

- Increased reliability, repeatability, and traceability of the manufacturing process under high-precision industrial conditions.

By achieving these objectives, the doctoral thesis will contribute to the development of innovative solutions for optimizing the laser microperforation and welding processes in the automotive industry, thereby enhancing the reliability and safety of final products.

2.4. Conclusions

Section 2.4 synthesizes the conclusions of Chapter 2 and provides an overview of the current progress and challenges in the field of laser microperforation applied to the automotive industry. It highlights that this technology continues to be a central focus of applied research due to its ability to meet increasingly stringent requirements related to safety, quality, and production efficiency.

The literature review revealed that laser microperforation has established itself as the preferred solution for processing materials used in airbag systems, as it enables high-precision control over perforation geometry, involves no mechanical contact, and produces minimal heat-affected zones. This precision directly contributes to the functional reliability of passive safety systems, which is critical for the high standards of the automotive sector.

The chapter also outlines the main research directions: the use of ultrashort-pulse lasers, the implementation of optical feedback technologies for real-time process control, the development of advanced numerical models for parameter optimization, and detailed characterization of process outcomes. These directions converge toward increasing levels of automation and seamless integration into smart production lines.

In conclusion, Section 2.4 reaffirms the strategic relevance of research in laser microperforation and supports the need for in-depth studies on process optimization in order to ensure the transition to efficient and safe industrial production.

CHAPTER 3. DETAILED ANALYSIS OF THE MICROPERFORATION PROCESS USING LASER TECHNOLOGY

Laser microperforation represents a cutting-edge technology in the automotive industry due to its ability to produce precise and uniform perforations in a wide range of materials, thereby enhancing the quality and performance of vehicle components. This processing method stands out through its excellent control over process parameters, which enables the optimization of functional characteristics of parts and minimizes negative effects on material structure.

In recent years, research has focused on the use of ultrashort-pulse lasers and the integration of artificial intelligence for real-time parameter adjustment, opening promising perspectives for the automation and digitalization of the process. These advances confirm the strategic potential of laser microperforation in the context of sustainable development and smart technologies for the automotive industry.

3.1. Materials Used in the Laser Microperforation Process

The selection of materials used in the laser microperforation process is a critical step in ensuring efficient processing and the production of high-quality final components. The specific properties of each material influence the way it interacts with the laser beam, thereby determining its behavior during perforation. The correct choice of material is essential for achieving clean, precise perforations with minimal impact on material integrity.

Composite materials are becoming increasingly popular due to their high mechanical strength and low weight. However, their laser processing poses significant challenges, as it may lead to delamination, cracking, or thermal degradation. To mitigate these effects, the use of ultrashort-pulse lasers is recommended, as they allow minimally invasive interaction with the material's structure.

(Figure 3.1)

In conclusion, the selection of suitable materials for microperforation must be based on the application's requirements, the optical and thermal properties of the material, and its compatibility with the specific type of laser beam.

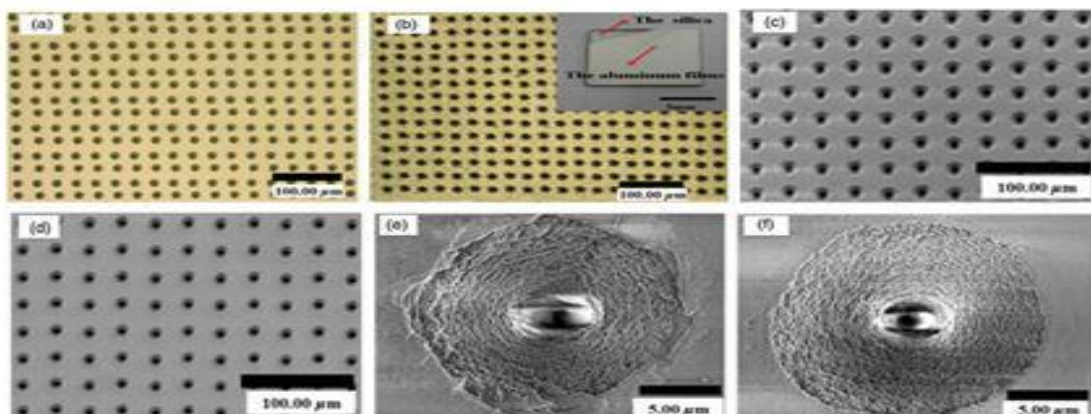


Figure 3.1. Microperforation of Composite Materials [HU20].

3.2. Fundamental Principles of Laser Beam Microperforation

This section explores the physical foundations of the laser beam microperforation process, a complex phenomenon involving the transfer of energy from electromagnetic radiation to solid material. It details how the energy of the laser beam is absorbed by the material surface, causing a rapid increase in temperature that leads to localized melting, vaporization, or sublimation.

In conclusion, a deep understanding of the fundamental principles of laser beam microperforation is essential for process optimization. Precise control of physical parameters and their adaptation to material properties enable the creation of accurate, durable perforations that meet the high standards of the modern automotive industry.(Figure 3.2)

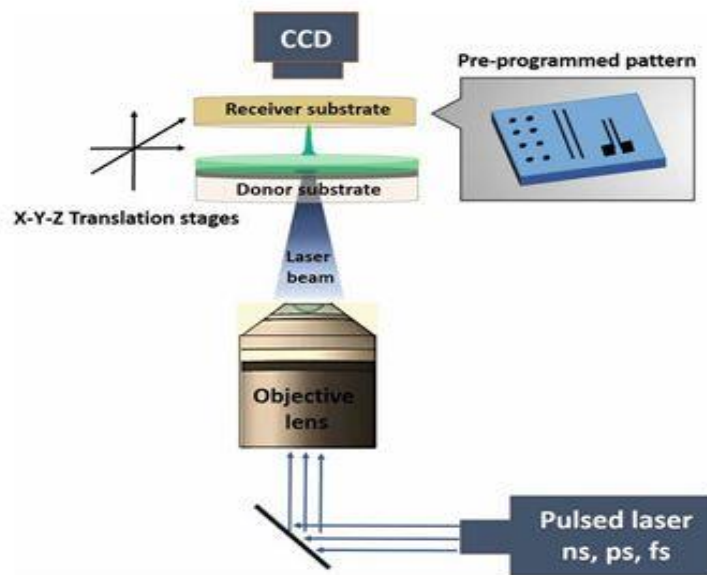


Figure 3.2. Laser Beam Microperforation.

3.3. Types of Lasers Used for Microperforation

This section provides a comparative analysis of the main types of lasers used for microperforating textile materials in automotive applications. It begins with the general classification of laser sources based on the active medium: CO₂ lasers, Nd:YAG lasers (neodymium-doped yttrium aluminum garnet), fiber lasers, and ultrashort-pulse lasers. Each category is presented in terms of relevant technical characteristics such as wavelength, radiation type, and pulse configuration.(Figure 3.3)

Special attention is given to ultrashort-pulse lasers (picosecond and femtosecond), which enable near-surgical precision microprocessing without inducing thermal damage to the material. These systems operate based on photonic ablation rather than thermal mechanisms, meaning no molten zone is formed around the perforation. As a result, higher-quality holes are achieved; however, the equipment is significantly more expensive and requires stringent operational conditions.

In conclusion, the selection of the laser type must be based on the material properties, geometric requirements of the perforations, and available technological conditions. In the context of airbag

microperforation, fiber lasers and ultrashort-pulse lasers have proven to be the most effective in terms of precision, efficiency, and integration into modern production lines.

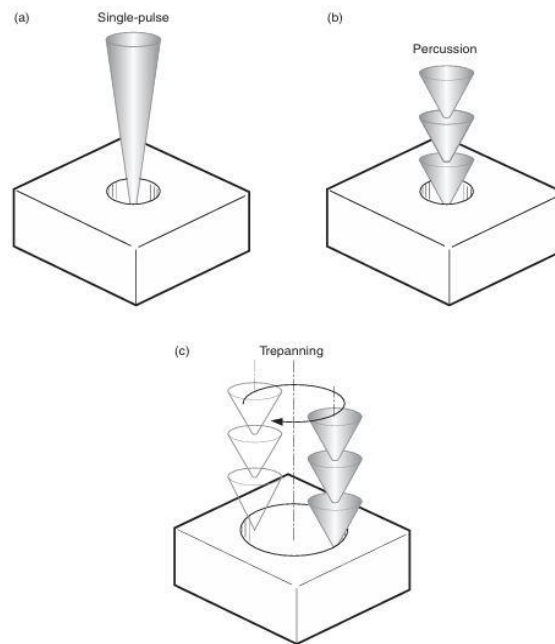


Figure 3.3. Ultrashort Laser Pulses.

3.4. Processing Parameters and Their Impact on the Microperforation Process

This section analyzes the influence of technological parameters on the quality and efficiency of the laser microperforation process. The critical process variables are discussed in detail: laser beam power, pulse duration and frequency, scanning speed, focal distance, and specific energy applied. Each of these parameters plays a fundamental role in determining the size, shape, and quality of the perforation achieved in the textile material.

In conclusion, precise control and proper correlation of processing parameters are essential for maximizing the efficiency of laser microperforation. Understanding the influence of each parameter allows engineers to design robust and efficient processes that comply with modern industrial standards, directly contributing to the reliability of airbag systems.(Figure 3.4)

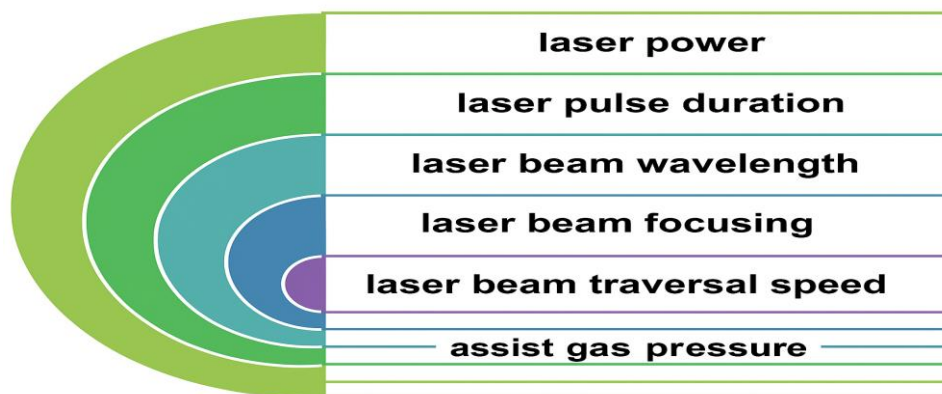


Figure 3.4. Microperforation Process Parameters.

3.5. Experimental Methodologies Applied to Laser Microperforation Efficiency

This section provides a detailed description of the experimental methodology used to assess the efficiency of the laser microperforation process in the context of automotive industry applications. The essential stages of the experiments are presented: material selection, definition of processing parameters, equipment configuration, and test execution. Emphasis is placed on achieving perforations with controlled geometry and predictable behavior under real-world airbag deployment conditions.

Another important aspect covered in this section is the post-process mechanical characterization. The perforated samples were subjected to tensile and tear resistance tests to verify that laser perforation does not compromise the structural integrity of the material. Additionally, accelerated aging tests were performed to simulate the long-term behavior of the processed material.

In conclusion, the adopted experimental methodology enabled a comprehensive characterization of the microperforation process, providing essential quantitative data for the validation and implementation of the technology in airbag manufacturing. The systematic and multidisciplinary approach contributed to the development of a robust analytical and optimization framework, aligned with the stringent requirements of the automotive industry.(Figure 3.5)

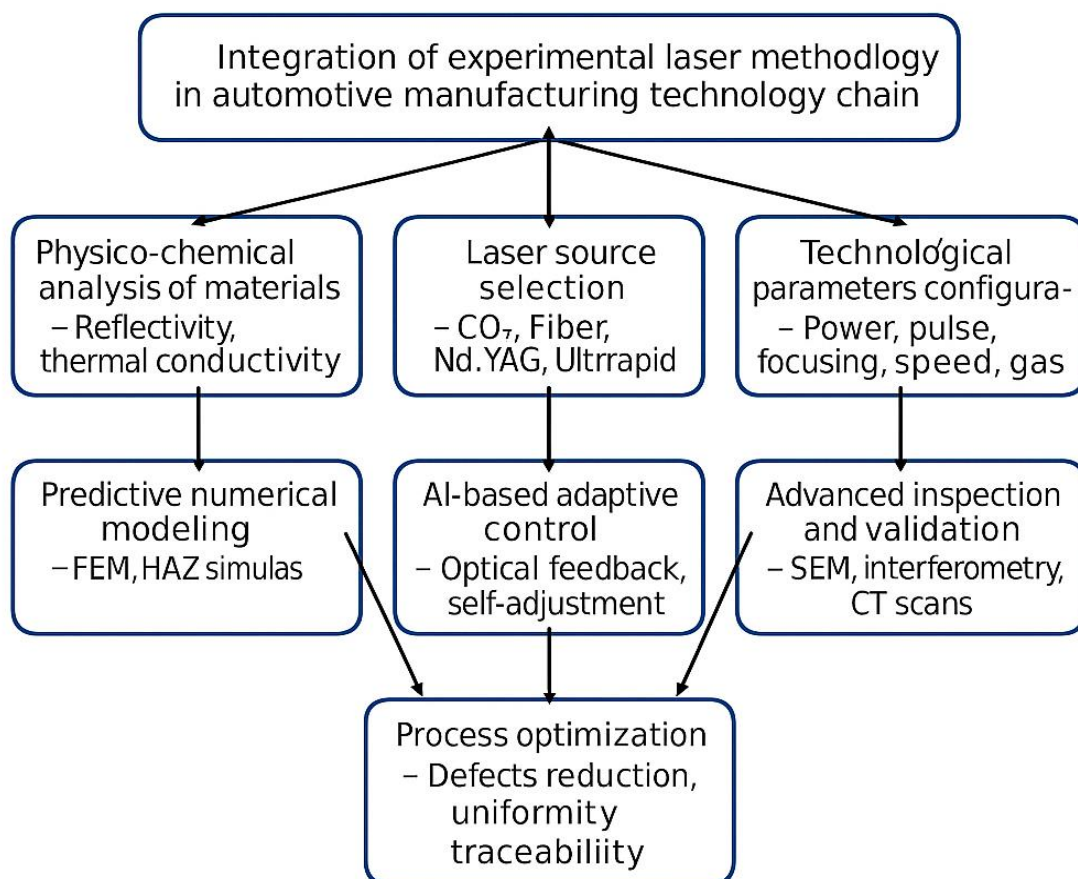


Figure 3.5. Integration of the Experimental Methodology.

3.6. Quality Control Methods in the Laser Microperforation Process

Section 3.6 presents the quality control methods used in the laser microperforation process, which are essential for ensuring the compliance and reliability of the final product. Although the microperforation process is automated and precise, it requires careful quality monitoring to prevent deviations and defects that could compromise the airbag's functionality. Visual inspection techniques, non-destructive methods, as well as quantitative evaluation techniques of the geometric characteristics of the perforations are analyzed.

Particular emphasis is placed on high-resolution imaging analysis, which is used to identify edge defects, shape irregularities, or variations in the diameter of the perforations. These image-based evaluations allow for the detection of minute anomalies that are not visible through standard inspection, ensuring a high level of manufacturing precision.

In conclusion, the integration of modern and efficient quality control methods into the laser microperforation process is essential for validating the technological workflow. Real-time monitoring, automated inspection, and non-destructive analysis provide a robust framework for ensuring the safety and reliability of industrially produced airbag systems.

3.7. Conclusions

Section 3.7 synthesizes the key conclusions drawn from the theoretical and experimental analyses presented throughout the chapter. It confirms that laser microperforation is an efficient, precise, and adaptable technology capable of meeting the demanding requirements of the automotive industry, particularly in the context of airbag manufacturing. It is highlighted that the correct selection of the textile material, in correlation with the process parameters and the type of laser employed, plays a critical role in achieving functionally reliable perforations.

Finally, the chapter emphasizes the multidisciplinary nature of research in the field of laser microperforation: the integration of knowledge from optics, materials engineering, process control, and automotive safety is essential for the development of advanced, reliable, and scalable technologies. The conclusions drawn establish a foundation for future research directions, aimed at integrating artificial intelligence in process optimization and extending the applicability of this technology to other critical automotive components.

CHAPTER 4. ANALYSIS OF THE INFLUENCE OF OPERATIONAL PARAMETERS ON THE LASER MICROPERFORATION AND WELDING PROCESS

4.1 Monitoring, Control, and Optimization of the Laser Microperforation Process for Synthetic Leather Components

Section 4.1 explores the process of monitoring, control, and optimization of laser microperforation applied to synthetic leather components, which are essential elements in the construction of automotive safety systems, particularly airbags. The process involves the precise perforation of the material without compromising the structural or aesthetic integrity of the surface, which requires rigorous control of technological parameters and the integration of advanced real-time monitoring strategies.

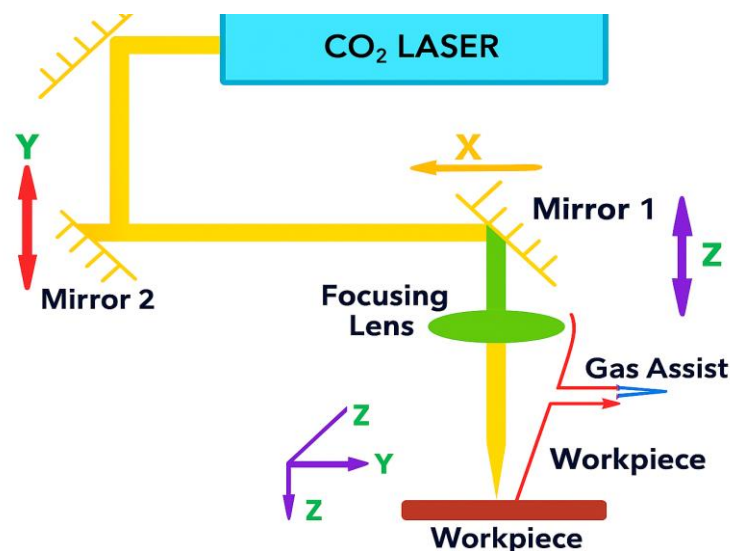


Figure 4.1. Operating principle of the laser.

To achieve this objective, the research analyzed in detail the factors influencing the quality of the perforations: laser pulse energy, pulse duration and frequency, beam geometry, feed rate, and focal positioning. A comprehensive characterization of the interaction between the laser beam and synthetic leather was carried out—this material is characterized by a layered structure and heterogeneous composition, including textile substrates coated with PVC. Such characteristics require a specific approach to avoid burning or visual degradation of the surface.

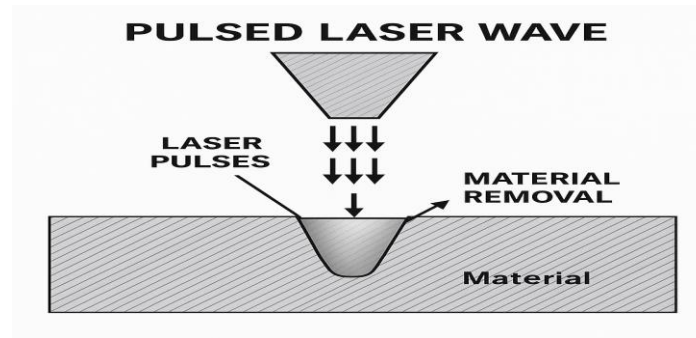


Figure 4.2. Optimal laser microperforation using pulsed wave.

The monitoring process was based on the use of high-resolution optical systems capable of instantly detecting variations in the quality of the perforations. The images captured in real time were analyzed using image processing algorithms, which enable the identification of defects such as incomplete perforations, melted edges, or lack of uniformity. Spectroscopic monitoring of the radiation emitted during the process was employed to assess the level of energy transferred and to detect any deviations from optimal parameters.

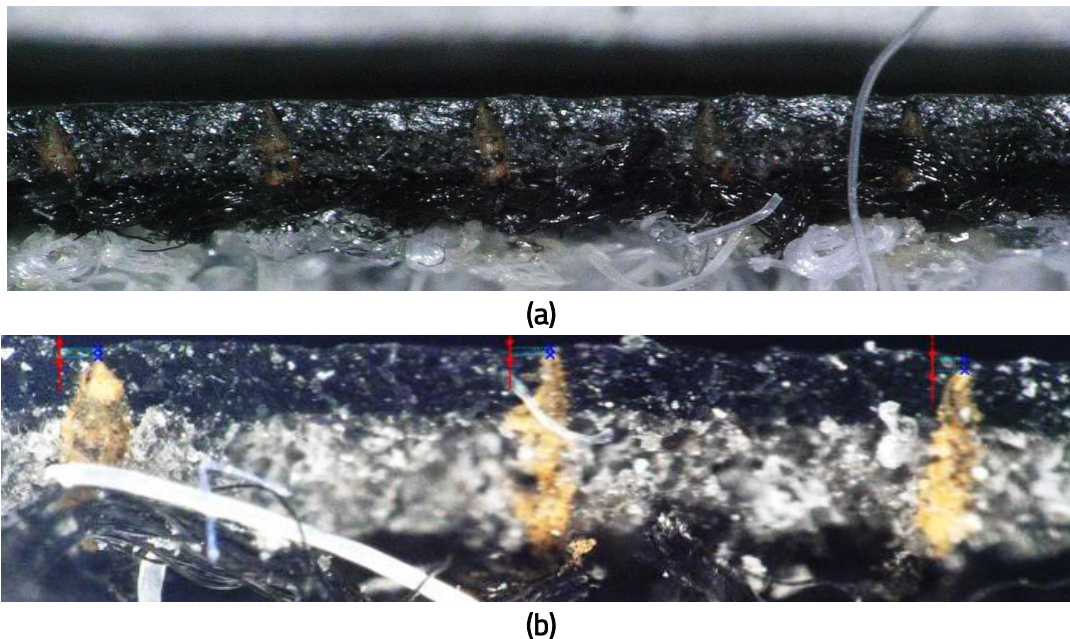
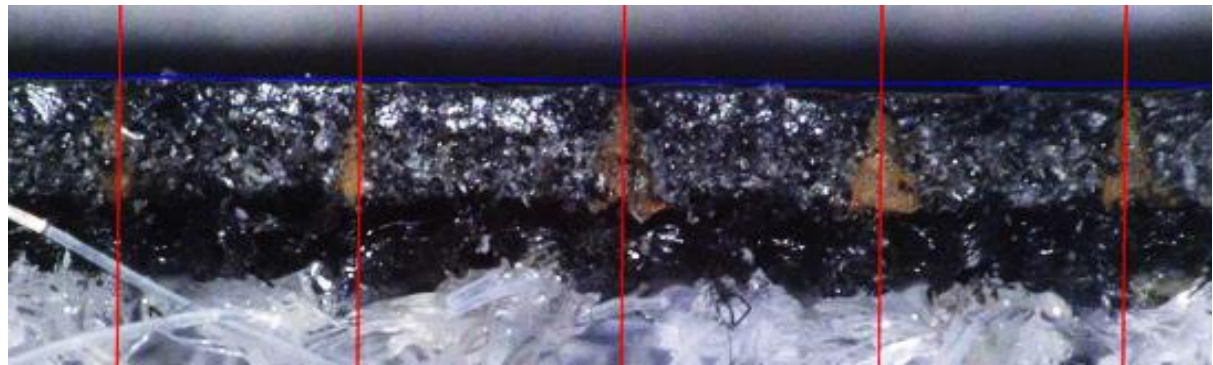
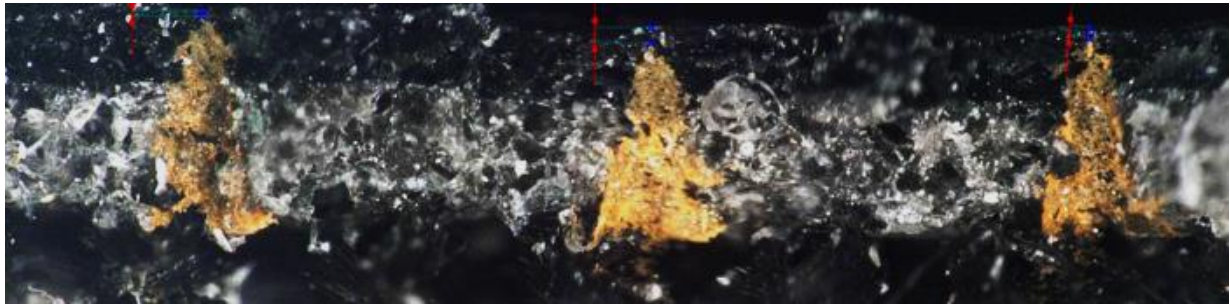


Figure 4.3. Microstructural images of non-compliant parts: (a) micro-holes in the top layer of the material; (b) complete perforation of micro-holes. Scale bar is 500 μm .

The optimization of the process was carried out based on mathematical models developed using factorial experimental designs, regression analysis, and response surface methodology (RSM). These models were used to identify the optimal parameter ranges that ensure a favorable compromise between speed, quality, and energy costs. The results indicated that a specific combination of pulse duration, energy, and frequency leads to high-quality perforations without generating secondary defects.



(a)



(b)

Figure 4.4. Microstructural images of conforming parts: (a) holes in the upper layer of the material; (b) completed microperforation of the holes. Scale bar is 500 μm .

In conclusion, this section emphasizes the importance of rigorous control and advanced optimization strategies for achieving reliable results in the laser microperforation of synthetic leather used in airbag components. The combination of high-precision laser technology with optical monitoring systems and adaptive control algorithms ensures not only the quality and safety of the final product but also enhanced manufacturing efficiency—an essential factor for maintaining competitiveness in the modern automotive industry.

4.2 The Influence of Electromagnetic Noise Level on the Laser Microperforation Process for Automotive Components

Section 4.2 addresses an advanced and relatively new topic in the field of laser processing: the influence of electromagnetic noise on the performance of the microperforation process, particularly in the case of sensitive automotive components such as those in the airbag area. This issue is highly relevant in the context of increased automation and the growing density of electronic equipment in production lines, where multiple sources of interference can impact the stability of the laser beam and the precision of processing.

Furthermore, the impact of electromagnetic noise on optical monitoring systems and sensors used in the process control loop was analyzed. Such interference can lead to erroneous readings and incorrect commands being sent to the laser source, negatively affecting the system's adaptability to material variations and processing conditions.

In conclusion, this section highlights the importance of addressing electromagnetic noise as a major risk factor in laser microperforation applications within the automotive industry. The integration of effective electromagnetic protection strategies is vital for maintaining high process performance, reducing defects, and ensuring the electromagnetic compatibility of the entire production system. These investigations pave the way for the development of more robust and better-shielded laser systems.

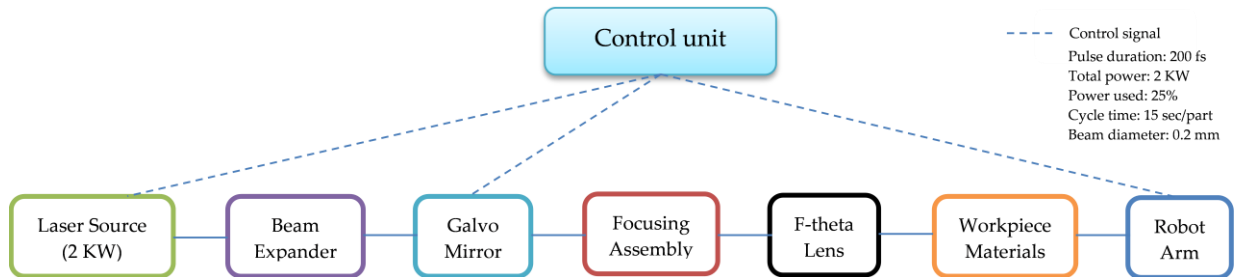


Figure 4.5. Schematic diagram of the experimental setup with robot integration.

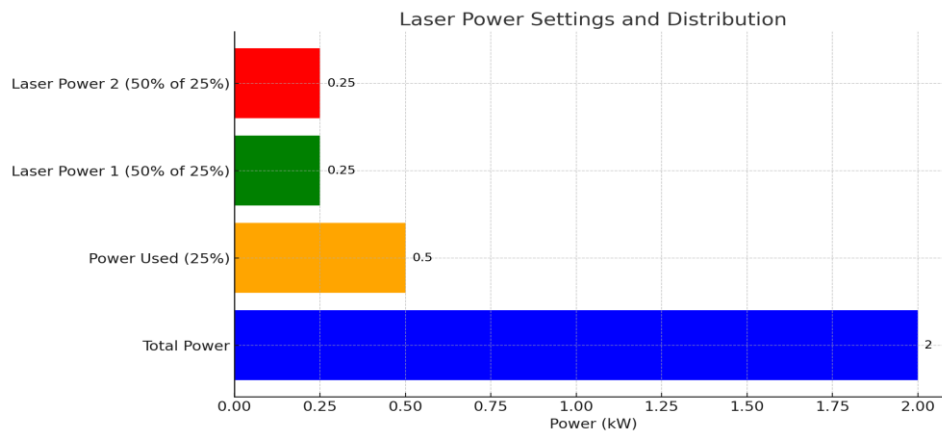


Figure 4.6. Laser power settings and distribution.

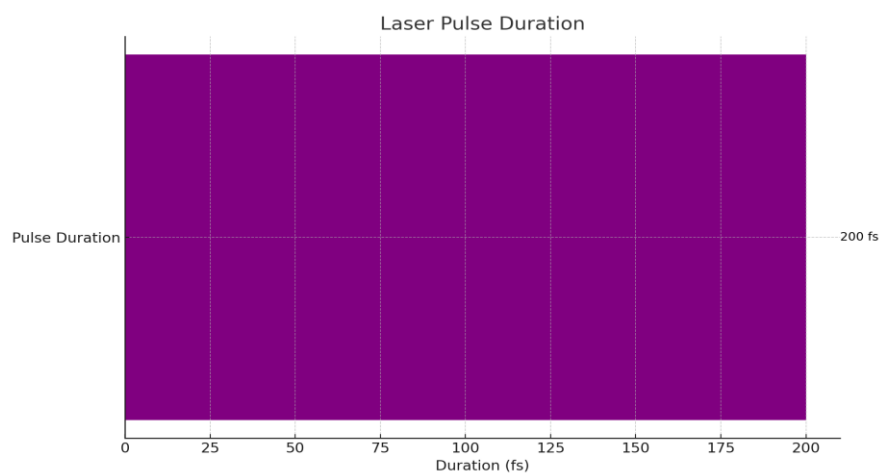


Figure 4.7. Laser pulse duration.

Optical Configuration

The laser optical system consists of f-theta scanning lenses, beam expanders, focusing assemblies, and Galvo mirrors, all designed to operate at the specific wavelengths of CO₂ lasers. These components are essential for the precise control and guidance of the laser beam, ensuring uniformity and accuracy in microperforations.

The laser beam size is controlled through the optical system and can be adjusted to achieve an extremely small focal point, necessary for high-precision processing of textile materials (Figure 4.8). This adjustability is crucial for maintaining the consistency of perforations, reducing the likelihood of thermal deformation or mechanical imperfections.

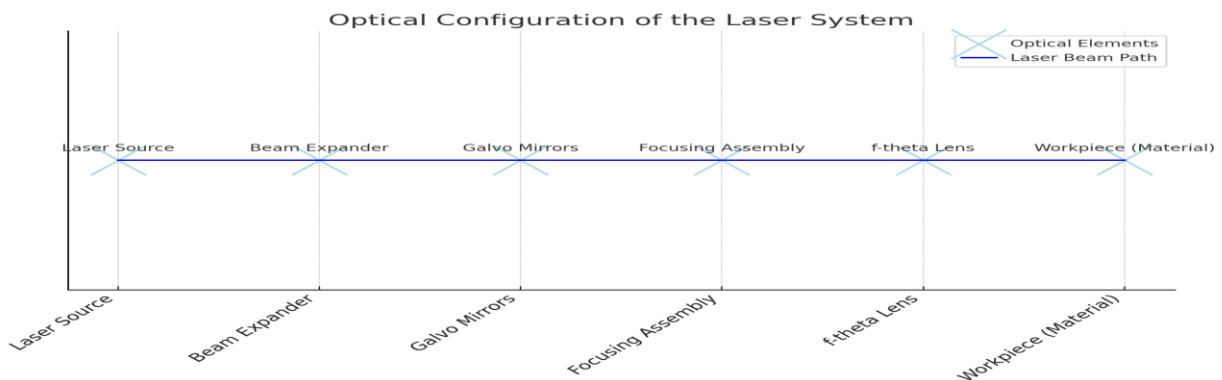


Figure 4.8. Optical Configuration of the LASER System.

Analysis of Tensile Test Results

The tensile test results performed on laser-perforated materials reveal significant performance differences between samples classified as NOK (Not OK) and those classified as OK, as illustrated in Figures 4.9 through 4.11. These variations indicate a substantial impact of electromagnetic noise on the mechanical behavior of the perforated material, emphasizing the importance of rigorous control and optimization of experimental parameters to ensure the quality of the laser microperforation process.

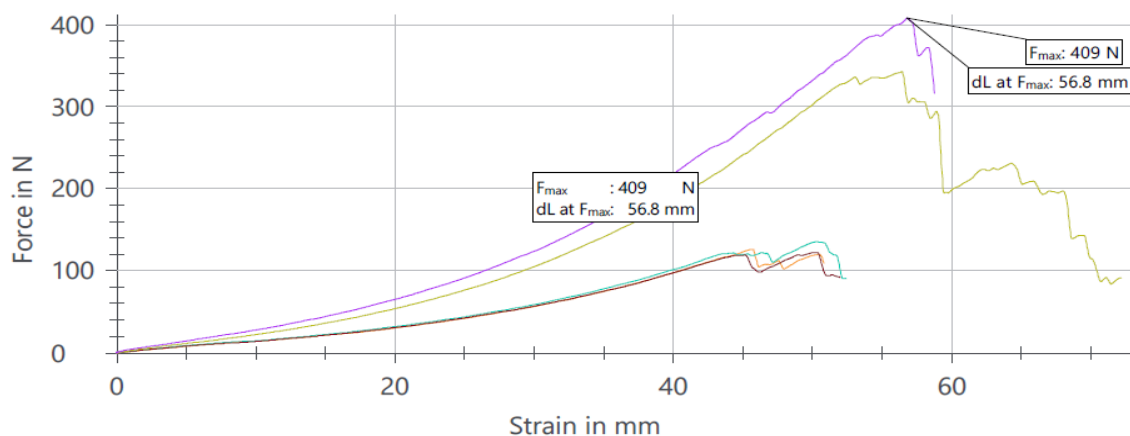


Figure 4.9. Analysis results after tensile testing with NOK values and noise level set at 0.8 V.

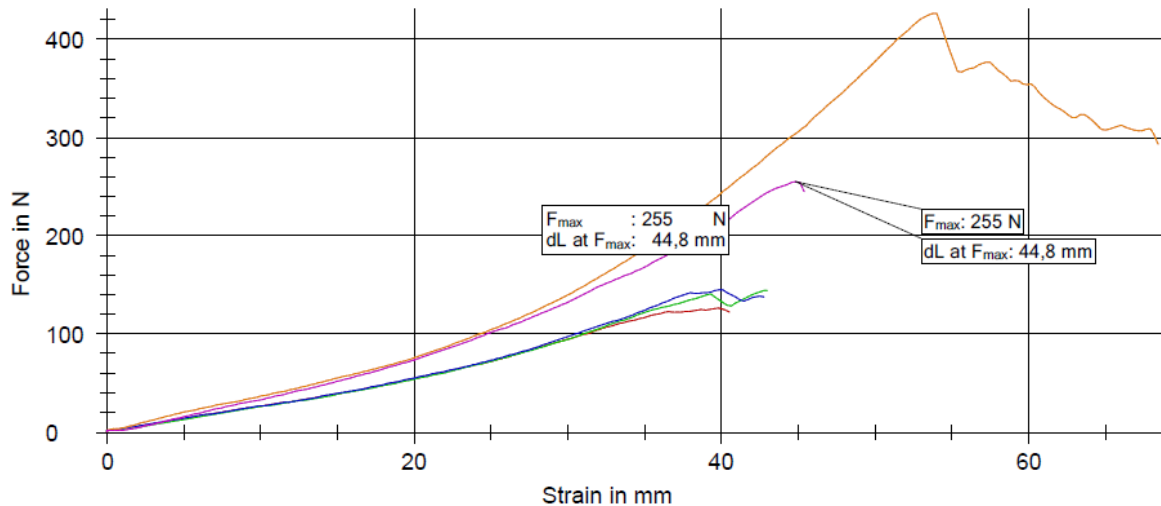


Figure 4.10. Analysis results after tensile testing with NOK values and noise level set at 1 V.

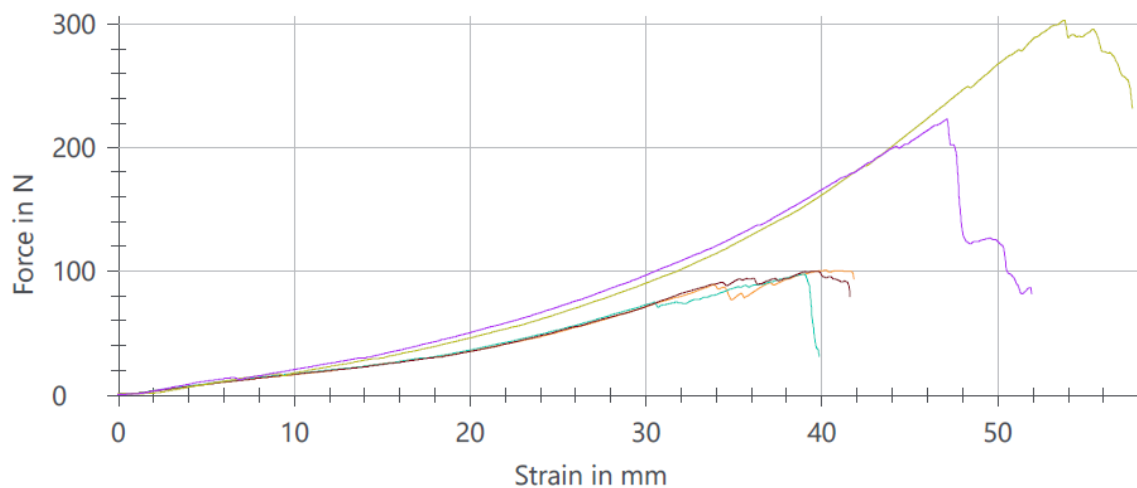


Figure 4.11. Analysis results after tensile testing with OK values and noise level set at 1.2 V.

Impact of Electromagnetic Noise Level on Tensile Strength

The analysis of the results highlights a direct correlation between the level of electromagnetic noise and the mechanical behavior of the perforated material:

- At 0.8 V, the perforations tend to be more rigid with rougher edges, suggesting excessive heat accumulation during the laser process, which alters the internal structure of the material. This overheating may lead to increased brittleness, affecting the material's ability to absorb mechanical shocks without damage.
- At 1 V, a reduction in tensile strength was observed, indicating a higher degree of instability in the perforations. This result suggests that the laser beam lacked optimal control over the microperforation, resulting in incomplete, uneven, or irregularly

edged perforations, thereby reducing the material's capacity to evenly distribute mechanical forces.

- At 1.2 V, the results are much more consistent and closer to the optimal values mandated by automotive safety standards. This indicates that within this EMI range, the laser beam operates in a more stable manner, and the perforations are executed with a high degree of precision and uniformity.
- These findings emphasize the necessity for precise control of electromagnetic noise levels, as uncontrolled EMI variations can significantly affect the mechanical strength of the perforated material.

4.3. Study on Laser Microperforation for the Integration of Sandwich Materials in Airbag Zones Using Special Regimes

Section 4.3 investigates the applicability of the laser microperforation process on sandwich materials used in airbag construction, through the adoption of special operating regimes. Sandwich materials consist of multiple functional layers, each serving different roles, such as the outer protective layer, the intermediate energy-absorbing layer, and the inner mechanical support layer.

An important aspect analyzed is the differentiated thermal behavior of each layer, which leads to non-uniform absorption of the laser energy. For example, the top layer may exhibit increased absorption and melt easily, while the inner, more thermally insulating layers may reflect or scatter the energy, affecting the uniformity of the perforation.

A major benefit highlighted by this study is the possibility of integrating sandwich materials into critical airbag zones where different mechanical strength, flexibility, and permeability characteristics are required. By finely adjusting the laser parameters according to the stratified architecture, local adaptation of the perforations is achievable based on the functional role of each zone within the material.

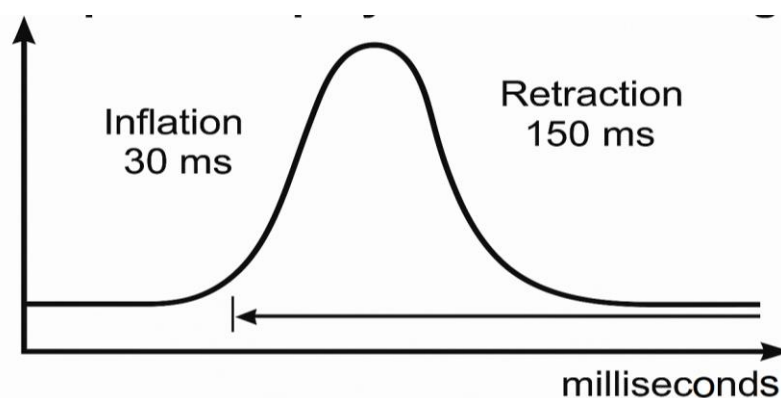
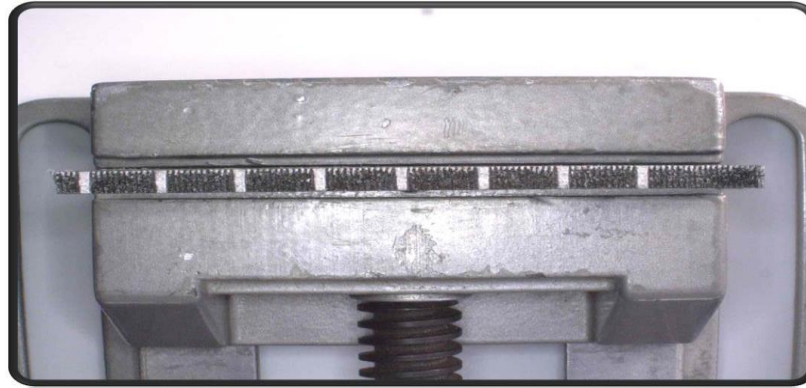


Figure 4.12. Optimal Deployment of an Airbag.

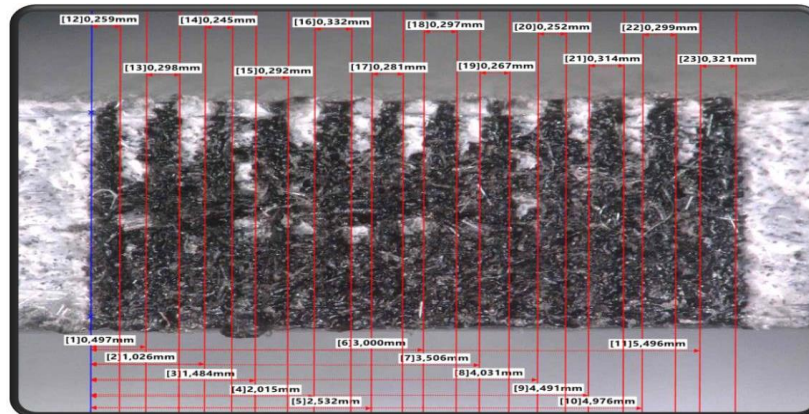
Tensile Strength Testing

The analysis of the results focuses on the tensile strength, microscopic compliance evaluation, and process efficiency.

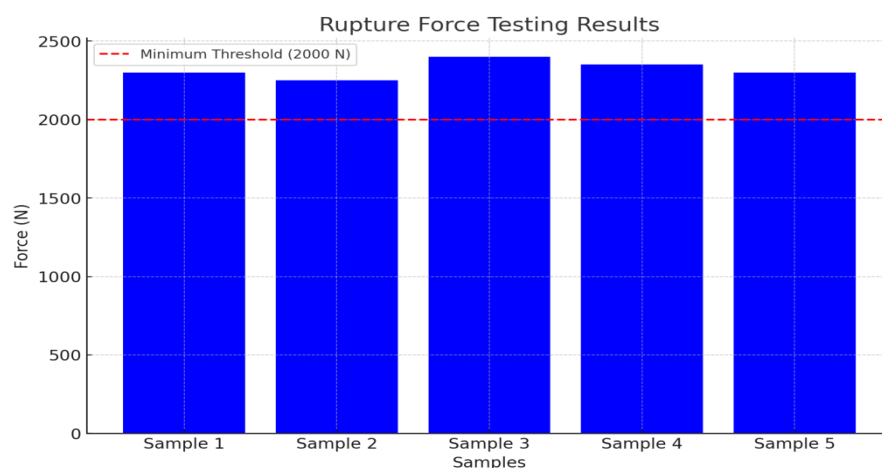
Tensile strength: The samples exceeded the established minimum threshold, recording an average tensile strength of 2300 N, thus confirming the material's robustness (Figure 4.13).



a)



b)



c)

Figure 4.13. a) Mechanical testing results: material fracture; b) Analysis of microperforation geometry; c) Tensile strength testing results.

The analysis of the results highlighted the performance of the tested materials regarding mechanical strength and compliance with automotive safety requirements. Tensile tests were conducted on a sample set of 50 pieces, selected from multiple injection batches to ensure a representative evaluation of the variability in materials used during the manufacturing process. This diversification of samples was essential for determining the consistency of mechanical properties and identifying any differences caused by variations in the production process.

During testing, all samples were subjected to progressively increasing tensile forces until the point of rupture was reached. The results showed that all samples exceeded the minimum threshold of 2000 N, demonstrating good mechanical performance of the material. The average recorded tensile strength was 2300 N, indicating that the material not only meets the minimum requirements but also provides an additional safety margin.

The perforations complied with positional and shape tolerances, exhibiting minimal thermal damage, which reflects the optimization of the process parameters (Figure 4.14).

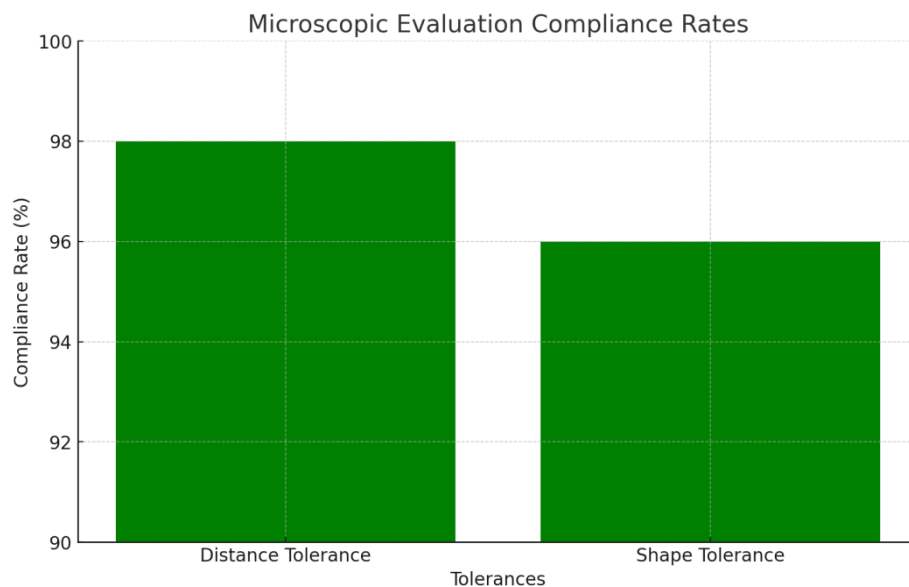


Figure 4.14. Results of the Microscopic Compliance Evaluation Analysis.

Microscopic Evaluations

In conclusion, high-resolution microscopy provided essential insights into the interaction between the laser and the material, enabling precise adjustments of processing parameters to improve material performance. These findings had a significant impact on the development of more reliable solutions for integrating sandwich materials into modern vehicle structures, contributing to increased safety and reliability of passive safety systems in the automotive industry.

Efficiency: Process cycle times were reduced by 15%, and the defect rate decreased below 2% due to improved stability and control (Figure 4.15).

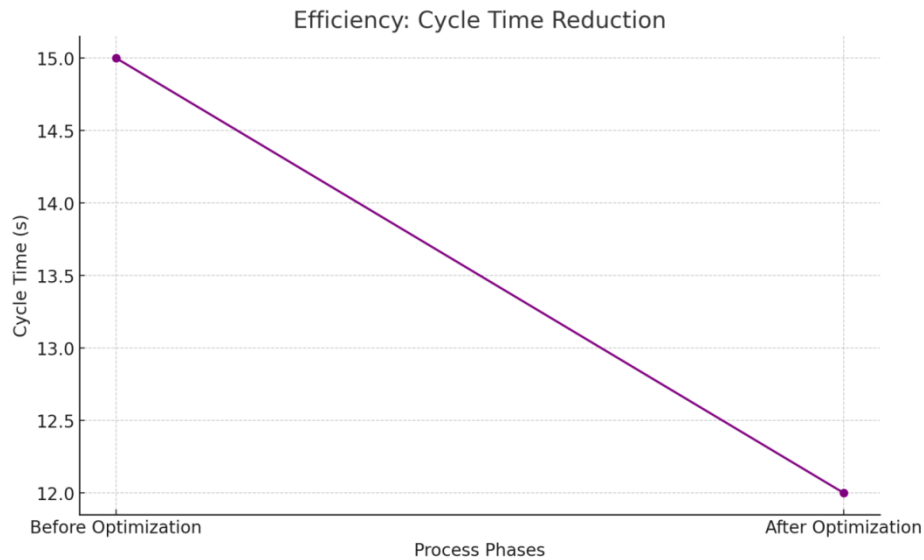


Figure 4.15. Results of the Process Cycle Time Reduction.

The analysis of process efficiency highlighted significant improvements in production cycle times and defect rates, demonstrating the optimization of technological parameters. The process optimization led to a 15% reduction in production cycle time, indicating a substantial increase in operational efficiency. This decrease in processing time was achieved through precise adjustments of laser parameters, enabling faster and more uniform perforation without compromising material quality. By stabilizing process parameters and enhancing operational control, the defect rate dropped below 2%, marking a significant improvement compared to previous values. This defect reduction was made possible through better calibration of the laser equipment, minimizing variability in perforation and eliminating issues such as thermal deformation and geometric irregularities.

4.4. Study on the Capability of the Laser Microperforation Machine in the Airbag Zone

Section 4.4 provides a detailed analysis of the capability of the laser microperforation machine used for processing automotive components in the airbag zone. This research is fundamental for validating the technological equipment in terms of precision, repeatability, reliability, and adaptability to the specific requirements of the automotive industry, where safety is a critical condition.

To quantify capability, statistical indicators such as C_p , C_{pk} , ANOVA analysis, and control charts were applied. These tools enabled a robust evaluation of process stability and capability over time, highlighting that the tested machine complies with the stringent standards of the automotive industry.

In conclusion, this section confirms the high capability of the analyzed laser microperforation machine, both from a quality and productivity perspective. The results support the integration of this technology into critical industrial processes such as airbag manufacturing, providing assurances regarding the safety, durability, and economic efficiency of the process. The study serves as a best practice model for equipment evaluation in advanced manufacturing contexts, contributing to the refinement of processes within the automotive industry.

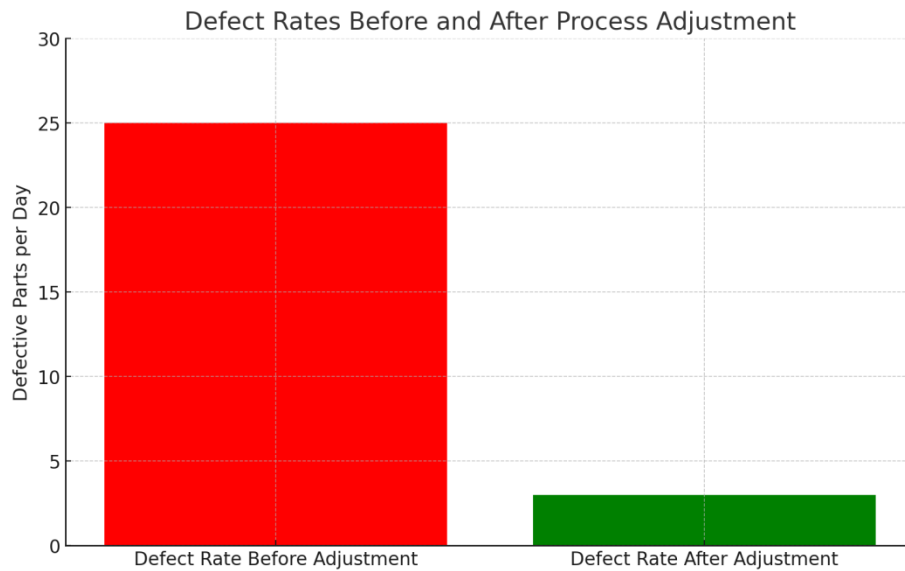


Figure 4.16. Defect rates before and after process adjustment.

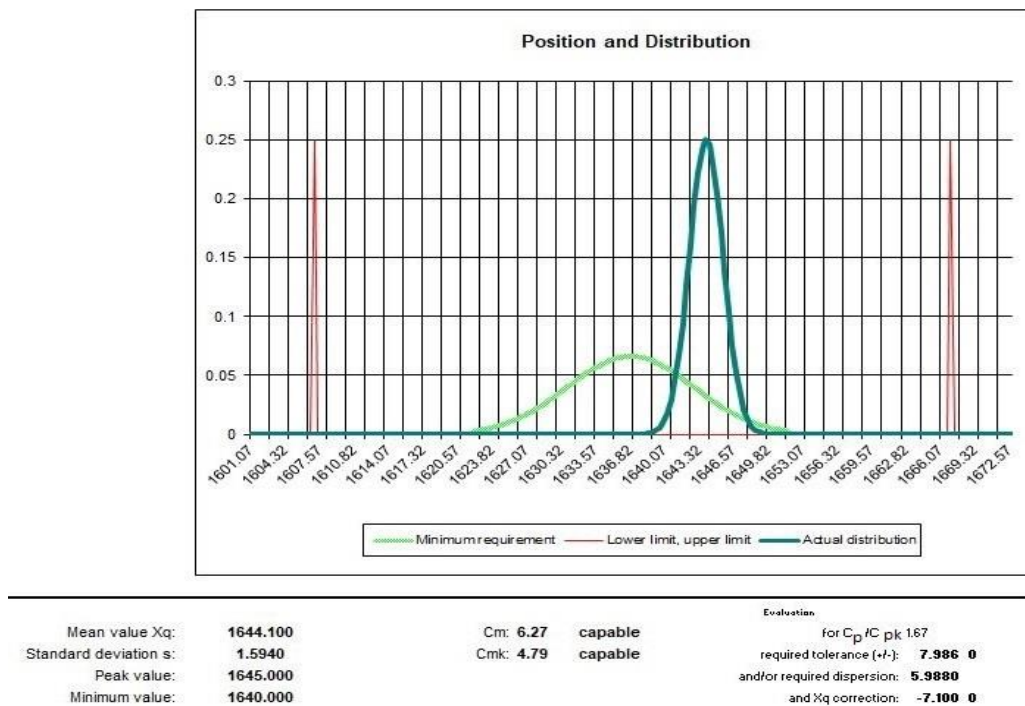


Figure 4.17. Machine capability analysis.

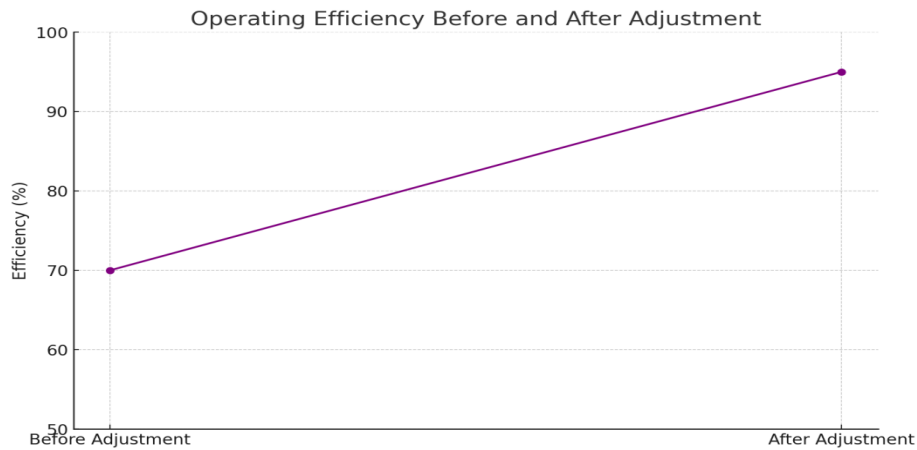


Figure 4.18. Operational efficiency before and after adjustment.

The results of this study demonstrate the significant impact that process optimization can have on the performance of a microperforation machine used in the production of automotive components. Adjustments made to process parameters led to a substantial reduction in defects, achieving an error rate as low as 0.2%, which reflects a considerable improvement compared to the initial stage. This defect reduction not only enhances the quality of the final product but also contributes to more efficient material utilization and waste reduction, thereby leading to a more sustainable and cost-effective process.

4.5. Efficiency and Precision of the Welding Process for Automotive Components in the Airbag Zone

Section 4.5 analyzes the efficiency and precision of the laser welding process applied to automotive components in the airbag zone, with a focus on the secure integration of materials and the maintenance of functional performance of the passive safety system. The welding process is essential for the durable joining of parts made from metallic or composite materials, ensuring high mechanical strength and effective sealing under critical operating conditions.

To validate weld quality, mechanical tests such as tensile, compression, and impact tests, as well as high-resolution visual inspections, were conducted. The results confirmed that welds performed under optimal conditions exhibit superior strength and do not compromise the functionality of the airbag system during rapid deployment.

An important contribution of the study is the development of multi-objective optimization algorithms that balance energy efficiency, processing speed, and weld quality. These algorithms were implemented in the welding machine control software, enabling real-time adaptation of parameters according to material variations and environmental conditions.

Heating

The heating phase plays a crucial role in the welding process of thermoplastic materials, being essential for achieving optimal material fusion without compromising its integrity. This stage involves

a series of critical steps to ensure efficient joining of plastic components used, for example, in airbag assembly.

Material properties and the design of the heating element are key factors determining the efficiency of the welding process. The melting points of thermoplastic materials vary, necessitating the setting of a uniform temperature of 600°C to ensure rapid and even heating. Typically, heating elements are made from materials with high thermal conductivity, such as aluminum or brass, chosen specifically to allow uniform heat distribution during the welding process (Figure 4.36).

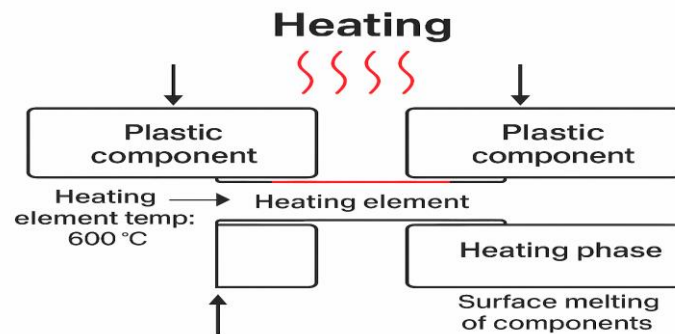


Figure 4.19. Operating Principle of the Welding Equipment.

Removal of the Heating Element

Careful and precise removal of the heating element is essential for maintaining the structural and functional integrity of the welded plastic components. This stage is critical, as it directly influences the final quality and reliability of the joint. The timing of the removal is particularly important, as the heating element must be withdrawn immediately after the molten surfaces reach an optimal level of viscosity.

Joining

The joining phase represents the culmination of the welding process, as it is the stage during which the actual fusion of the plastic components occurs. Achieving a strong and uniform weld critically depends on the precise alignment of the parts and the application of optimal pressure. Any deviation in this process can lead to the formation of weak points in the weld, compromising the durability and strength of the joint.

Prior to joining, meticulous alignment of the plastic surfaces is essential to ensure a perfect fit between them. This alignment contributes to the structural integrity of the joint, preventing the formation of gaps or areas with uneven distribution of molten material. Any misalignment can result in uneven pressure distribution during welding, affecting weld uniformity and potentially creating weak points.

In conclusion, the joining phase is crucial for the success of the entire welding process, as it influences the quality, uniformity, and durability of the joint. By applying advanced pressing technologies and cooling control, it is possible to ensure a strong and reliable weld capable of meeting the stringent requirements of modern industry.

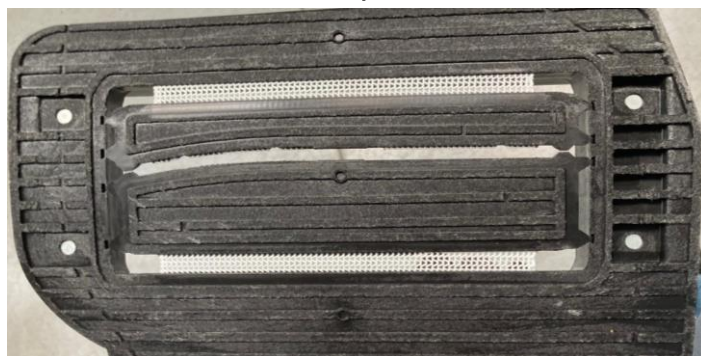
4.6. Evaluation of Experimental Results of the Laser Process in the Airbag Zone and Analysis of Its Influence on the Welding Process

Section 4.6 presents a detailed analysis of the experimental results obtained from the application of the laser process in the airbag zone, emphasizing the impact of these results on weld quality and the overall performance of automotive components. This evaluation is essential for validating the hypotheses formulated in earlier research stages and for developing optimization strategies within the manufacturing process.

This section confirms that an integrated evaluation of experimental results is critical for improving manufacturing processes based on laser technology. The interdependence between microperforation and welding is a crucial factor that must be considered in the design of production lines for components in the airbag zone. The results provide a solid scientific foundation for the implementation of advanced technological solutions, with direct benefits for the safety of automotive components.



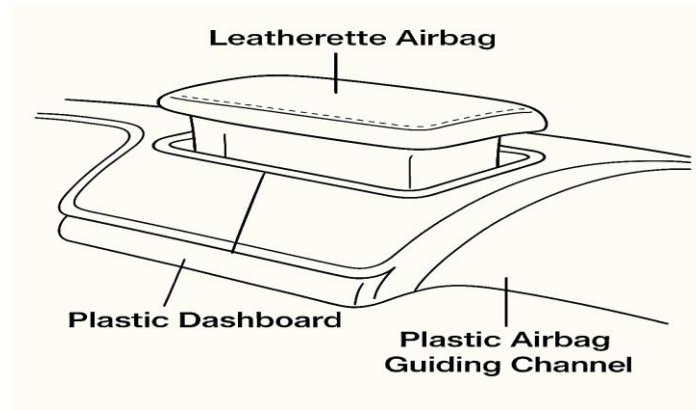
a)



b)



c)



d)

Figure 4.20. a) Welding equipment with heated element; b) Melting; c) Heated element welding; d) Airbag assembly consisting of synthetic leather, plastic dashboard, and plastic airbag guide channel.

In conclusion, laser processing in the airbag zone, careful treatment of synthetic leather, and precise welding of the guide channel are processes that collectively form an essential assembly for achieving a high-quality final product.

4.7. Conclusions

Section 4.7 provides a comprehensive synthesis of the conclusions drawn from the research and experiments conducted in Chapter 4, which focused on laser processing in the automotive airbag zone. The conclusions reflect both the validation of the initial hypotheses and the significant impact of laser technology on improving the quality, efficiency, and safety of industrial processes involved in manufacturing these critical components. This section emphasizes the interdependence between the microperforation and welding processes.

One of the main conclusions highlighted is the efficiency of laser technology in microperforating synthetic leather used in airbags. Precise monitoring and control of process parameters enabled the production of uniform perforations without compromising the mechanical integrity of the material. The application of special operating regimes and the integration of optical feedback demonstrated enhanced adaptability of laser systems to material variability.

Regarding the influence of electromagnetic noise, the study demonstrated that external disturbances can significantly affect the quality of microperforation and welding. The implemented electromagnetic protection measures, combined with robust monitoring systems, ensured stable operation of the equipment. Thus, the necessity of integrating an electromagnetic (EM) protection architecture into the design and operation of laser installations for the automotive industry was confirmed.

Concerning the integration of sandwich materials, the research showed the feasibility of perforating these using advanced strategies such as dynamic focusing and ultrashort pulses. Experimental results indicated that perforations can be precisely controlled on each constituent layer without affecting the composite material's functionality. This capability opens new directions for research and development involving complex materials in safety systems.

The capability evaluation of the microperforation machine confirmed the equipment's high performance in terms of precision, repeatability, and flexibility. Statistical tests showed that

variations are minimal and within the limits imposed by industrial standards. Moreover, the machine's adaptability to various material configurations and geometries enables the expansion of applications into other critical vehicle areas.

Finally, the overall analysis of the experimental results highlighted the close correlation between microperforation and welding in the airbag zone. The quality of the perforations directly influences welding success, and integrated optimization of both processes is essential to meet the stringent safety standards required in the automotive field. Implementing a unified strategy for monitoring, control, and optimization of both processes provides a solid framework for enhancing competitiveness and innovation in this sector.

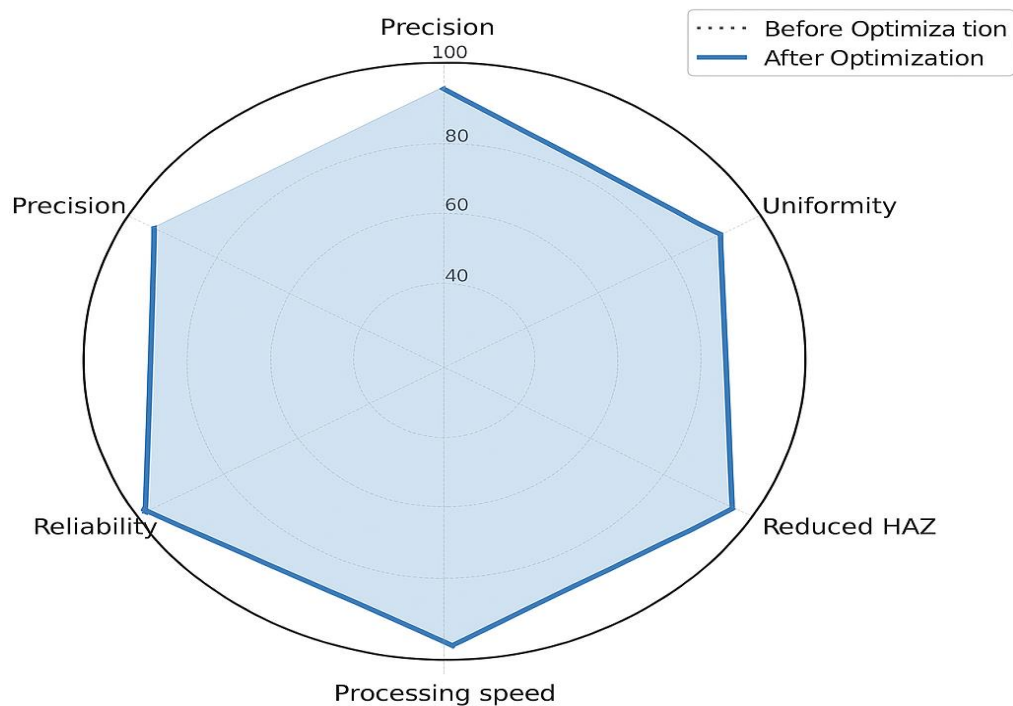


Figure 4.21. Technical Radar: Optimized Microperforation Process Performance

In conclusion, the results presented in this chapter demonstrate that the performance of the laser microperforation process depends on a complex set of technical and environmental factors. Its optimization requires an integrated, multidisciplinary approach that combines experimental analysis methods, numerical simulation, intelligent automation, and statistical process control.

CHAPTER 5. REAL-TIME INTEGRATION AND MONITORING OF THE PROCESS THROUGH SHOPFLOOR VISUALIZATION SYSTEMS (SFV)

5.1. Objectives and Scope of the SFV Guide

This shopfloor guide is intended to serve as a supplementary resource for all industries interested in utilizing the application, providing fundamental information for novice users. Additionally, it includes a summary of relevant specific submenus, comprehensive details about the interface structure and functionalities, as well as clear information regarding the responsibilities and contact persons within the Departments.

As a dynamic document, the guide should be consistently applied in practical activities, and its content should be regularly updated to reflect the latest changes and improvements. The guide's publication should always be carried out in the most recent version to ensure users have access to accurate and up-to-date information. This approach could ensure effective team alignment and optimal utilization of shopfloor resources.

5.2. Key User for Digitalization

Key users for digitalization are employees designated within an organization to support the implementation, utilization, and optimization of digital solutions. They act as intermediaries between end users and technical or IT teams, providing feedback and proposing improvements. Additionally, they are responsible for training colleagues in the use of new digital platforms and tools, thereby ensuring an efficient transition.

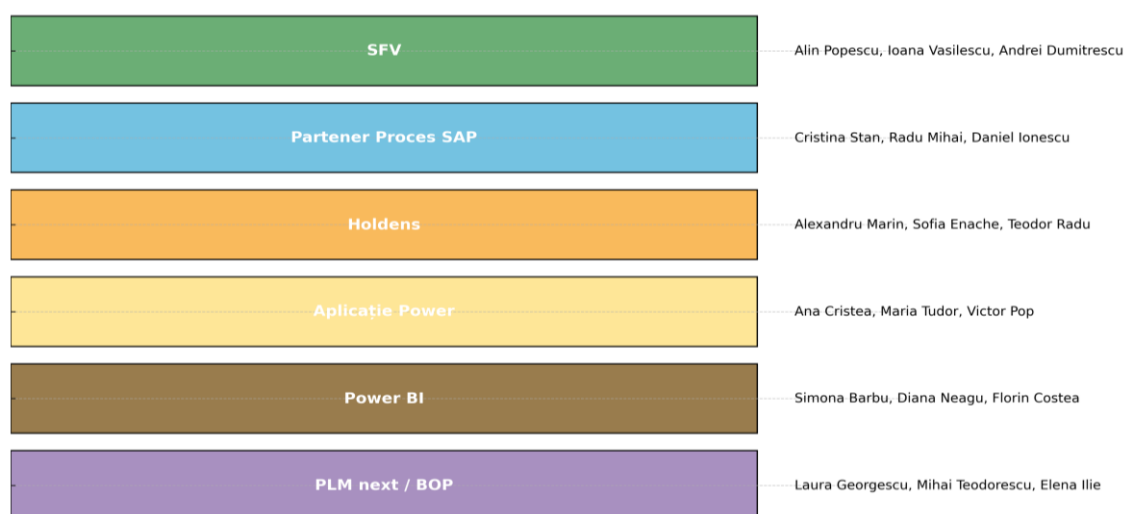


Figure 5.1 Key Users for Digitalization

5.3. Introduction of a Station in the Shopfloor

The diagram below details all three scenarios in which the implementation of OPC UA / SFV would be necessary, providing a clear overview of the possible situations and the steps that should be followed for each case.

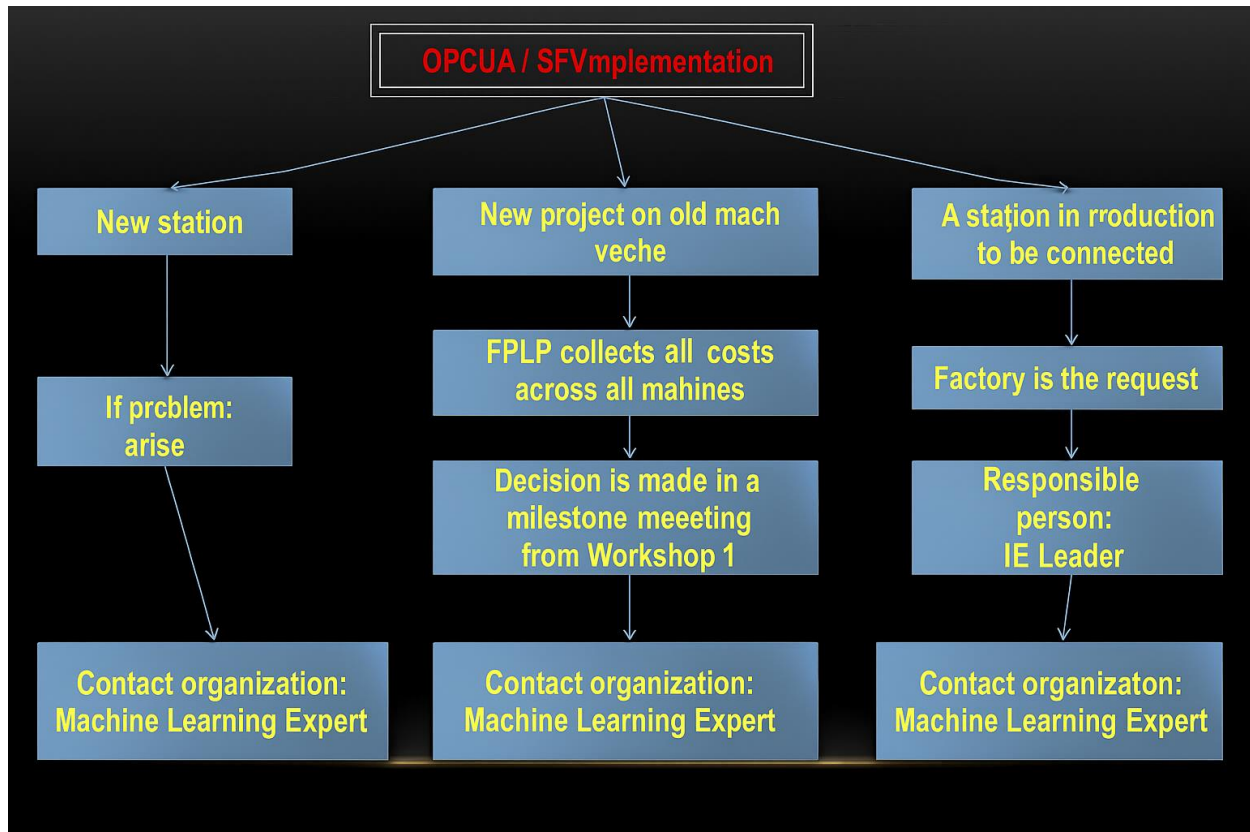


Figure 5.2. OPC UA/SFV Implementation

5.4. Access to Shopfloor Visualization

To gain access to the Shopfloor Visualization, a clear request process should be established, involving authentication on the platform, identification, and navigation to the “Service Requests” section, where users should have the ability to initiate a dedicated access request. Additionally, this process should include well-defined approval criteria and comply with internal procedures that are to be defined and implemented (Figure 5.3).

There should be a functionality allowing users to enter the term “Shopfloor” into a dedicated search bar, enabling them to quickly locate the desired option. This functionality should be intuitively integrated, facilitating access to relevant information and optimizing the user experience within the platform (Figure 5.4).

Users should be able to access the Shopfloor Visualization via a dedicated option within the platform. This should be designed in an accessible and intuitive manner, simplifying navigation and ensuring essential information is available quickly and efficiently (Figure 5.5).

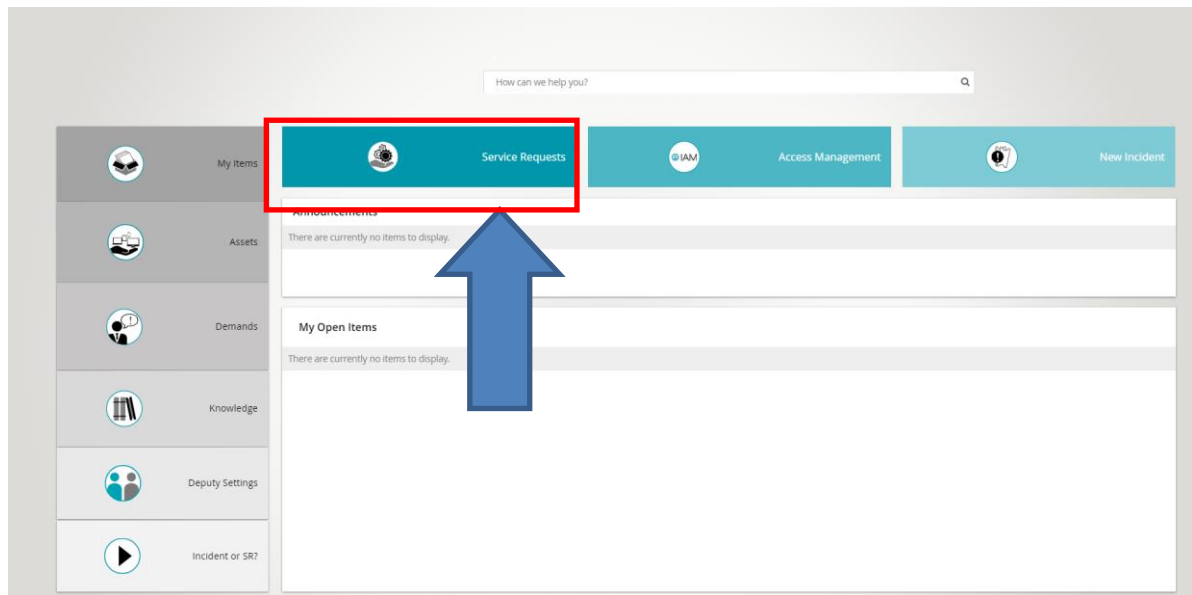


Figure 5.3. Service Requests

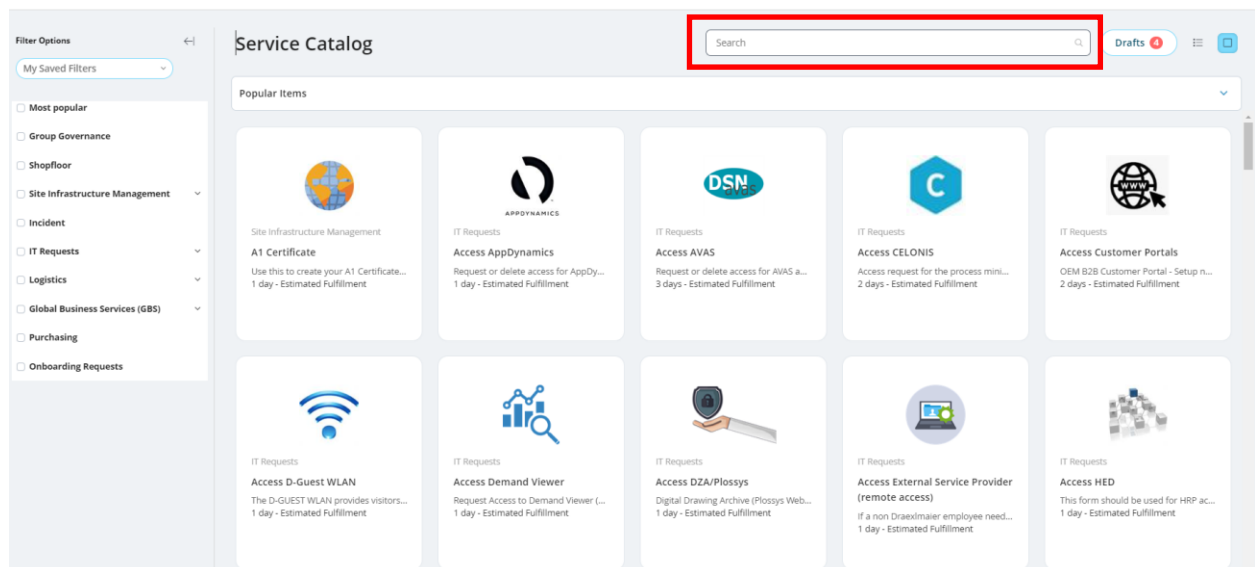


Figure 5.4. Dedicated Search

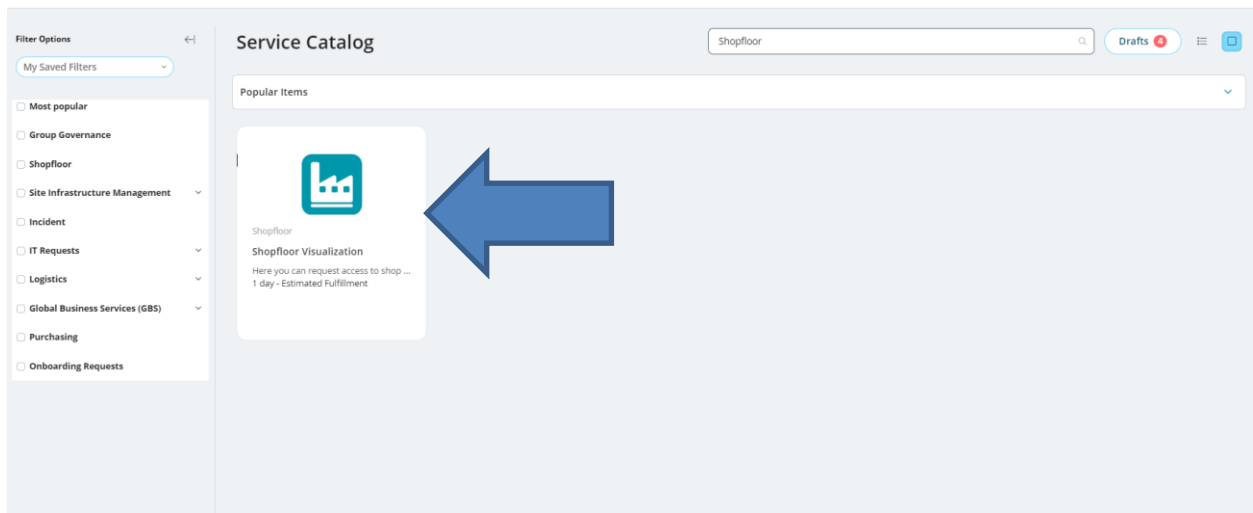


Figure 5.5. Service Catalog for SPV Access and Visualization

To continue the process, users should select the “User Access” option in the “Selection” field. If a user is to be designated as a “KEY User,” there should be a clear option to check the requirement for a “Technical Account Needed,” thereby ensuring appropriate access to system resources.

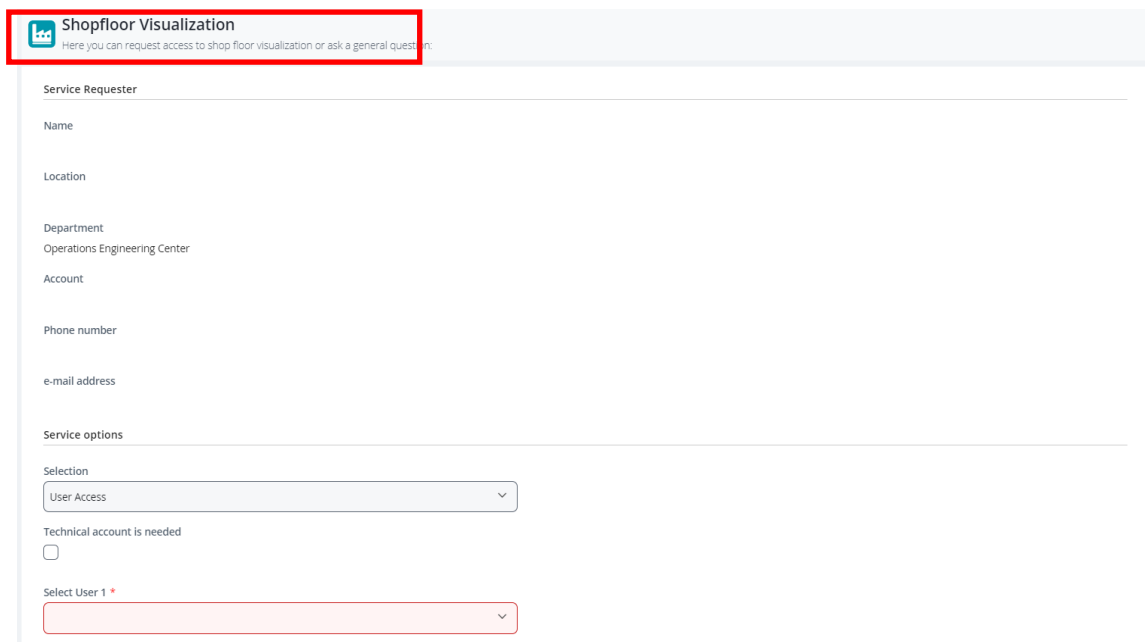


Figure 5.6. Service Request for User Access

Additionally, users should have the ability to select the name of the person for whom access is requested by using the “User Selection” field. Furthermore, in the dropdown menu, they should be able to choose the production unit for which access is required. The “GLOBAL” option should be available to allow access to all production units, thereby facilitating user management on a broader scale.

Service options

Selection

User Access

Technical account is needed

☐

Select User 1 *

Select to which location User 1 will have access? *

- ☐ Geisenhausen
- ☐ Geisenhausen 2
- ☐ Geisenhausen 3
- ☐ Giza
- ☐ Gliwice
- ☐ GLOBAL
- ☐ Grünheide
- ☐ Győr
- ☐ Heimsheim
- ☐ ...

Figure 5.7. Service Request Option for Global User Access

For more efficient administration, there should also be an option to select multiple individuals for whom access is requested simultaneously, thereby reducing the time required for managing individual requests and optimizing the permission assignment process.

Upon approval of access, users should receive a dedicated link that allows direct access to the home page of the Shopfloor Visualization, thus facilitating a rapid and efficient transition to platform usage:

EX: <https://visual.shopfloor-internal.com/securehome/selection>

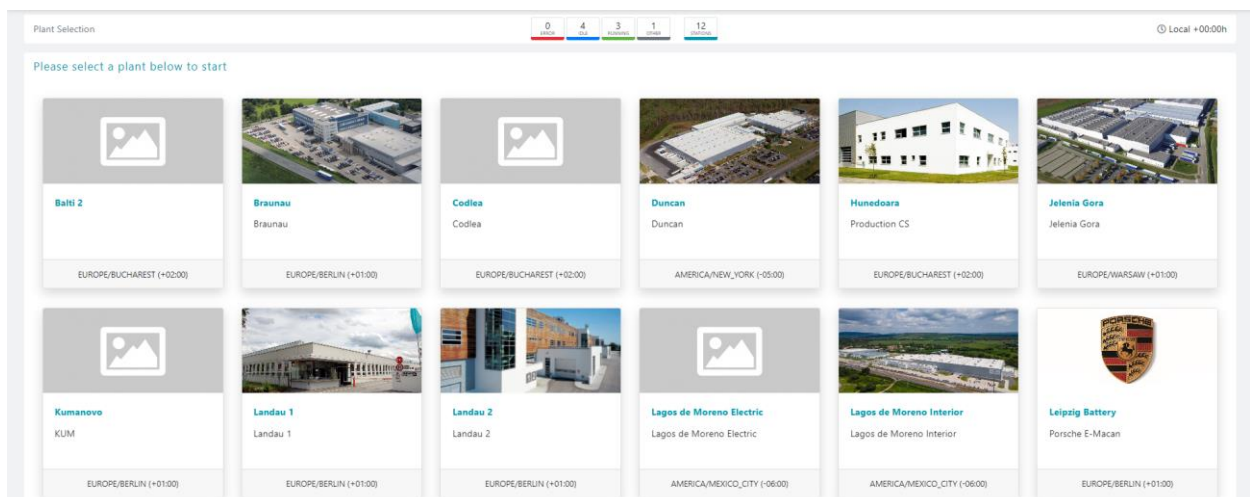


Figure 5.8. Workstation Visualization in SPV

Additionally, there should be the possibility to access the Shopfloor Visualization directly from SharePoint, providing users with a flexible and convenient alternative to quickly reach the desired interface, regardless of the platform being used.

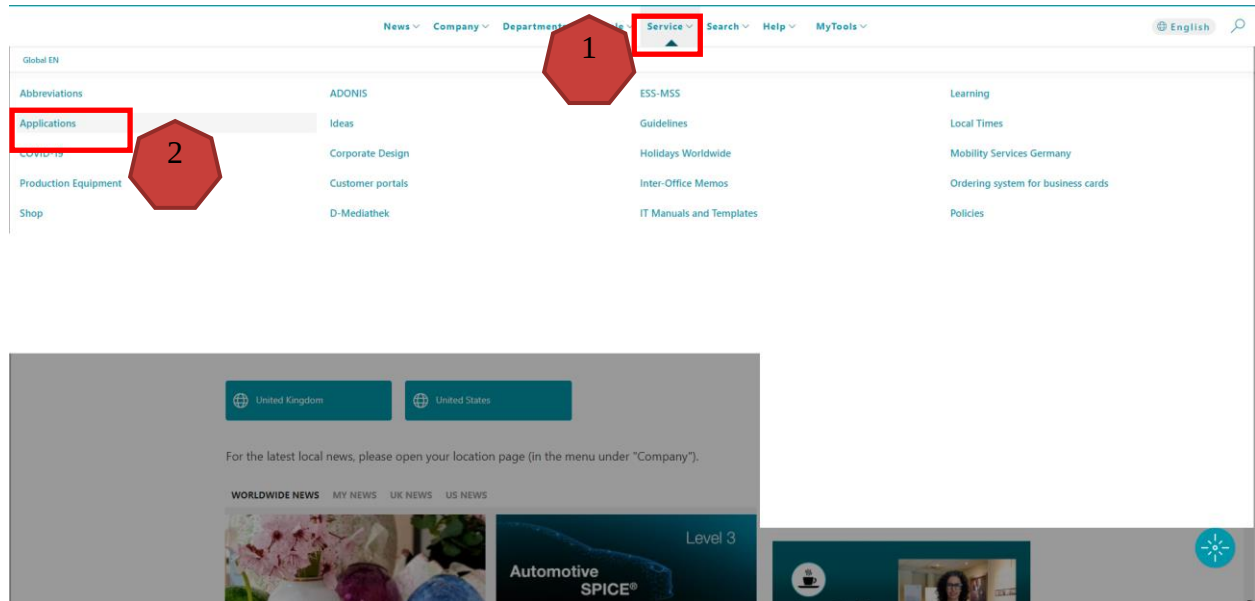


Figure 5.9. Shopfloor Visualization Directly from SharePoint

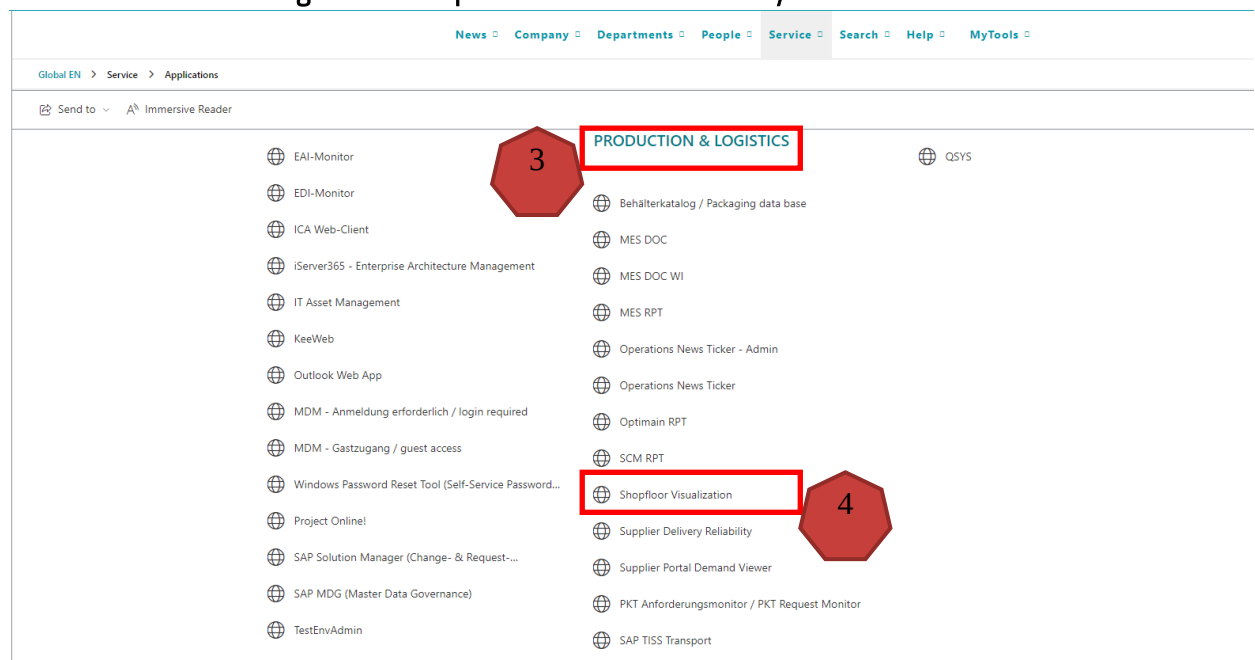


Figure 5.10. Shopfloor Visualization

5.5. Standard Naming for Shopfloor Visualization

There should be a means for users to access the presentation in Team Center using a dedicated link that allows quick navigation to the required resource. This functionality should be integrated in an intuitive manner, ensuring accessibility and ease of use.

Within a dedicated presentation titled "Standard Naming in Shopfloor Visualization," detailed instructions should be included regarding the process of creating production units, buildings, project areas, and workstations. This presentation should provide a clear and structured guide to support users in the correct implementation of these elements within the system.



Figure 5.11. Standard Naming in Shopfloor Visualization

5.6. New Machines in SFV

As a key user or person responsible for SFV, there should be a clear process requiring the completion of certain essential data and its submission to the responsible personnel in the IT department whenever a new workstation is to be introduced. This process should be well-structured and include defined steps for collecting and validating the necessary information, thereby ensuring the efficient and compliant integration of the new workstation into the system.

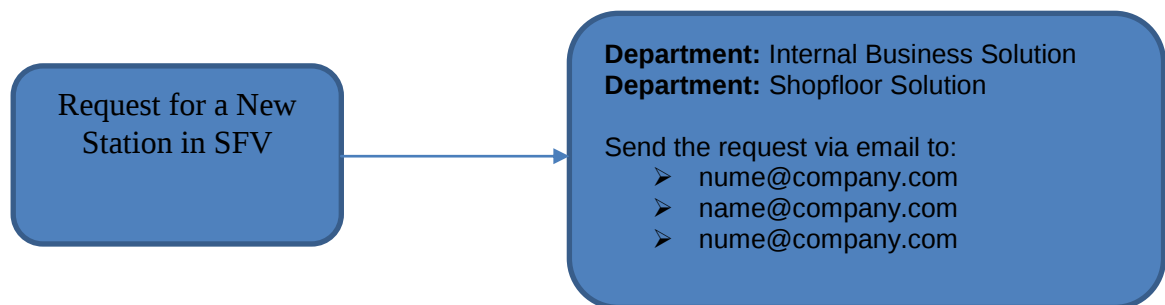


Figure 5.12. Implementation Request in Shopfloor Visualization

There should be a process through which a request is automatically generated in the portal for adding a new station in SFV. In cases where multiple stations need to be integrated simultaneously, it is recommended that users send an email listing all required stations, thereby avoiding the creation of a large number of individual requests in unTe. This mechanism should optimize the request process and reduce administrative workload, ensuring more efficient management of new stations.

Service Catalog

Shopfloor Visualization
Here you can request access to shop floor visualization or ask a general question:

Service Requester

Name

Location

Department
Operations Engineering Center

Account

Phone number

e-mail address

Question

User Access

Add Station to Shopfloor Visualization

Figure 5.13. Automatically Generated Portal Request for Adding a New Station in SFV

A table should be defined containing all necessary data for completing a request. This table should include clearly structured fields so that users can provide essential information in an organized and easily manageable manner. Implementing such a format could contribute to standardizing the request process and reducing errors associated with data entry.

OPC UA Connection String	
Frontend PC Name CAA	
Station Description	
Factory	
Location/Zone in SFV	
Planned Cycle Time	

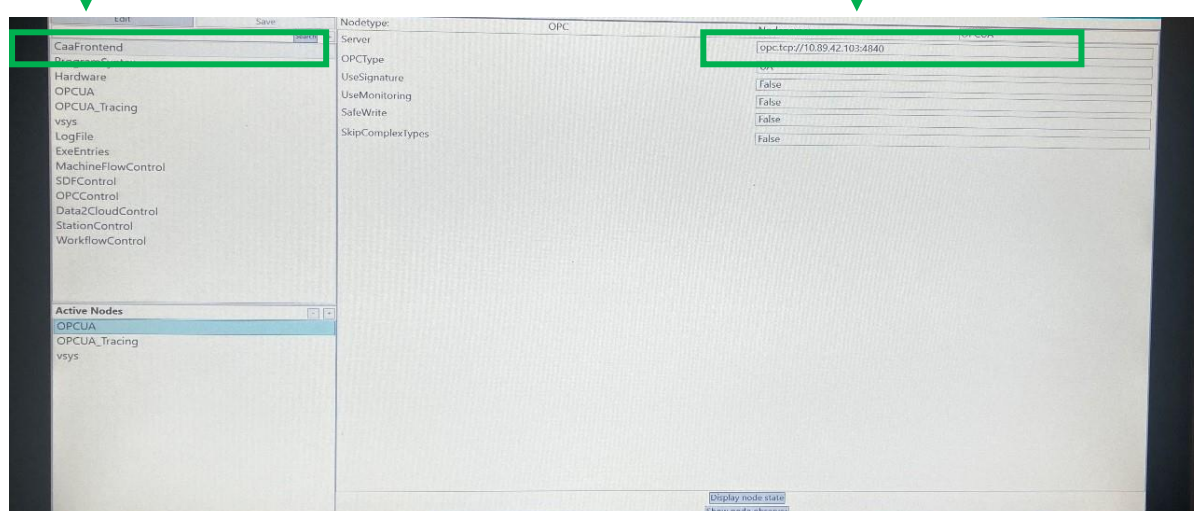


Figure 5.14. Sample Table with Correct Data

The OPC UA connection string should be directly identifiable on the workstation computer by accessing the relevant settings. It would be beneficial to have a standardized method through which this information is easily accessible to users, thereby reducing the time required to gather the necessary data for configuration.

The Frontend PC name (CAA) should be visible on a label placed on the workstation screen. To facilitate quick identification, a clear procedure could be implemented to specify the exact location of this label and how the displayed information should be used in the configuration process.

5.7. Vizualizarea Shopfloor

There should be a cloud-based web service, internally developed by the company, to enable the management and monitoring of industrial equipment. This service could facilitate the integration of various systems and optimize the flow of operational data.

A dedicated system could allow the display of machine data in a structured and accessible manner, providing users with relevant information about their performance and status at any given time.

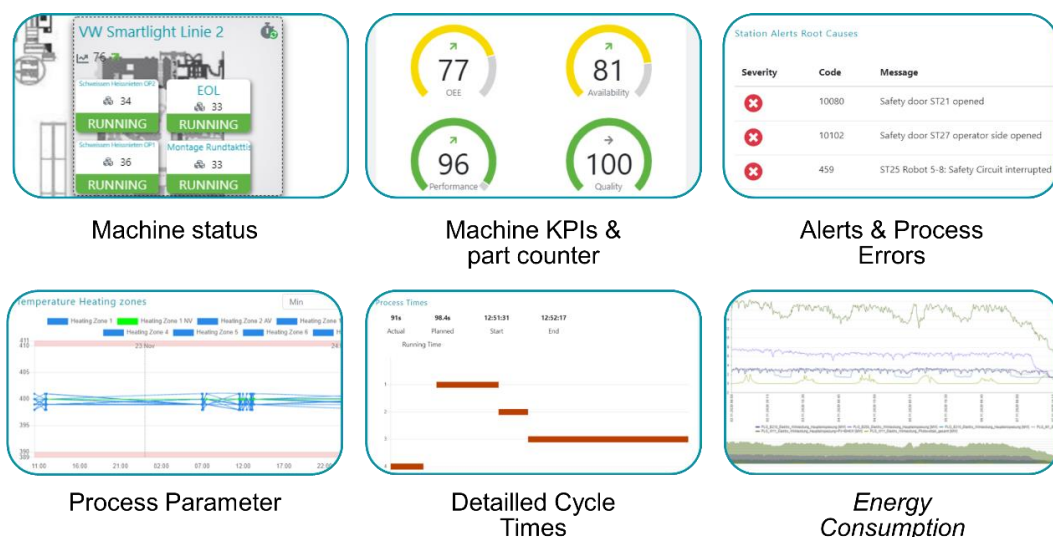


Figure 5.15. Machine Data Display

5.8. The Necessity of Shopfloor Visualization

Troubleshooting should be enabled through a system that provides detailed error messages and relevant statistical analyses. This mechanism could facilitate rapid identification of faults and optimization of technical interventions.

Process quality could be improved by using well-defined performance indicators that allow monitoring and optimizing operations based on concrete data and measurable objectives.

To reduce cycle times, there should be a system enabling precise identification of problematic stages in the process, offering solutions for their optimization and increasing overall production efficiency.

Such a system could represent the first step towards implementing a "Digital Factory," where all operational data is collected, analyzed, and utilized to automate and optimize industrial processes.

Real-time access to data should be possible regardless of location, providing users with up-to-date information on equipment status and processes without requiring physical presence on-site.

5.9. Architecture of the SFV System

In the following diagram, all systems involved should be allocated across the functional levels according to the VDI 5600 standard. The diagram could clearly illustrate the data flow from the production unit (production level) via the PLC to all other relevant systems, including the Shopfloor Visualization.

This representation should provide a detailed view of how information circulates between the various operational levels and highlight the critical connections between factory equipment and higher-level systems. Additionally, the diagram could emphasize the importance of coherent integration to ensure efficient and transparent data exchange among all system components.

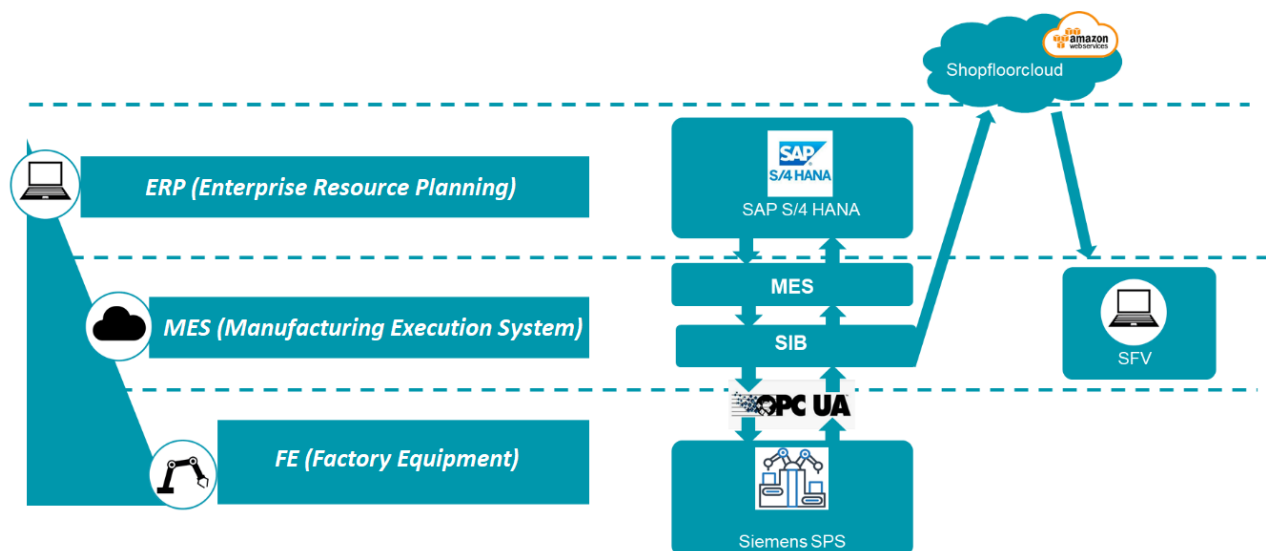


Figure 5.16. SFV System Architecture

5.10. Navigation and Functions of the Shopfloor Visualization

The navigation and functions of the Shopfloor Visualization should be designed in a clear and intuitive manner, enabling users to easily access relevant information and interact efficiently with the platform. The system could include various well-defined functionalities, such as quick access to operational data, real-time process visualization, and the generation of detailed reports.

Additionally, navigation options should facilitate seamless transitions between different sections of the platform, providing users with a consistent and simplified experience. These functionalities could support the monitoring and optimization of production operations, contributing to increased efficiency and transparency.

5.10.1. General Navigation

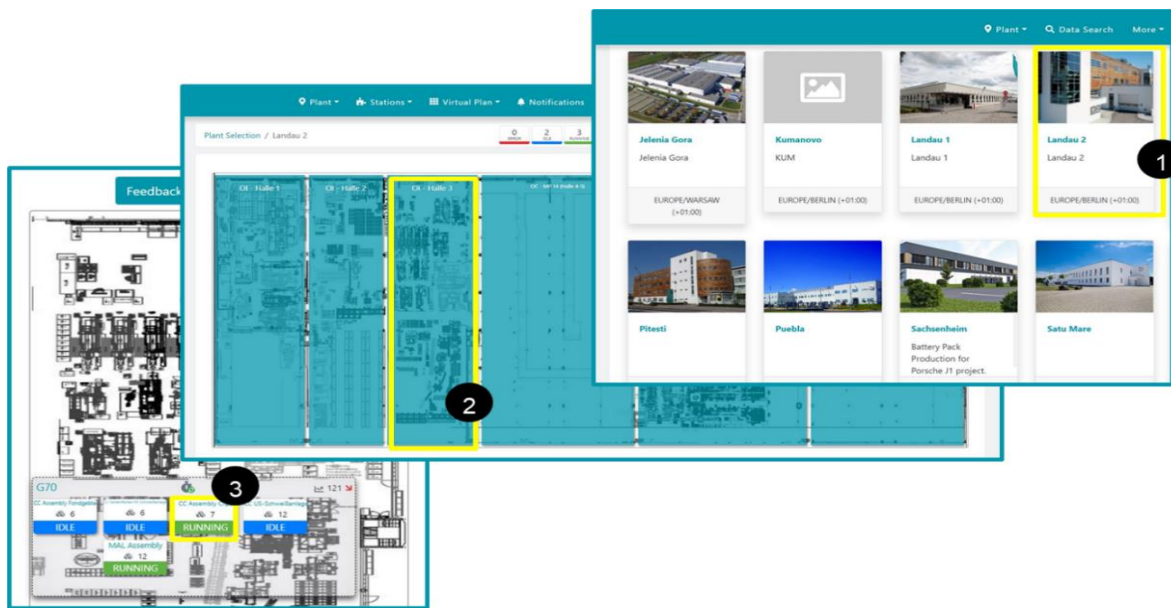


Figure 5.17. Navigation – SFV System

- **Factory Selection**

A clear option should be implemented to allow users to select the desired factory from a predefined list. This functionality could include filtering criteria to facilitate the rapid identification of the appropriate factory, thereby contributing to more efficient system navigation.

- **Building Selection**

There should be a method for users to select the specific building within the factory. This functionality could be integrated with an interactive map or a detailed list, providing users with a clear view of the organizational structure and facilitating access to relevant information.

- **Station Selection**

The system should include a feature that enables the selection of the desired workstation. This could be implemented via a list of options or a visual interface displaying the location of stations intuitively, thereby supporting detailed monitoring and management of processes.

5.10.2. Machine-Specific Submenu: Current Shift

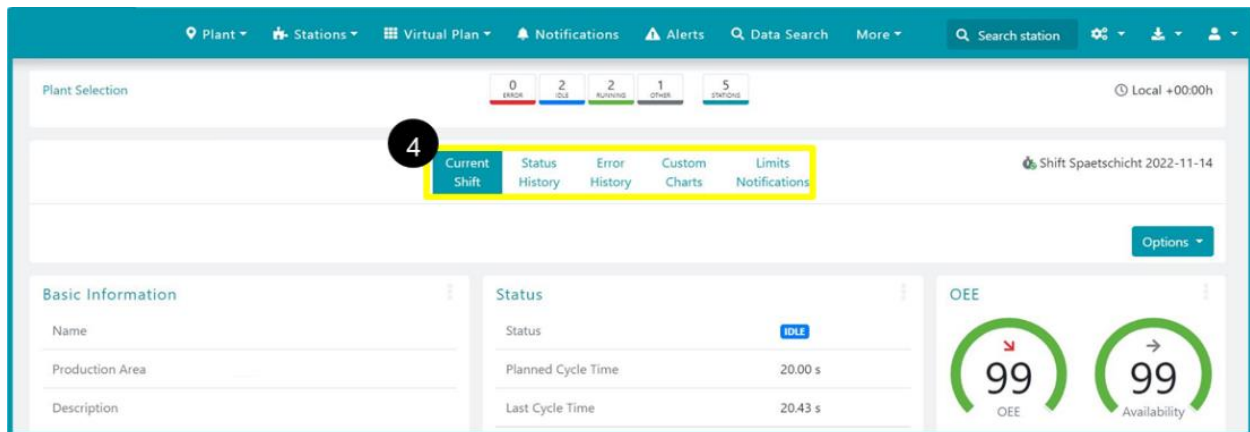


Figure 5.18. SFV System – Current Shift Submenu

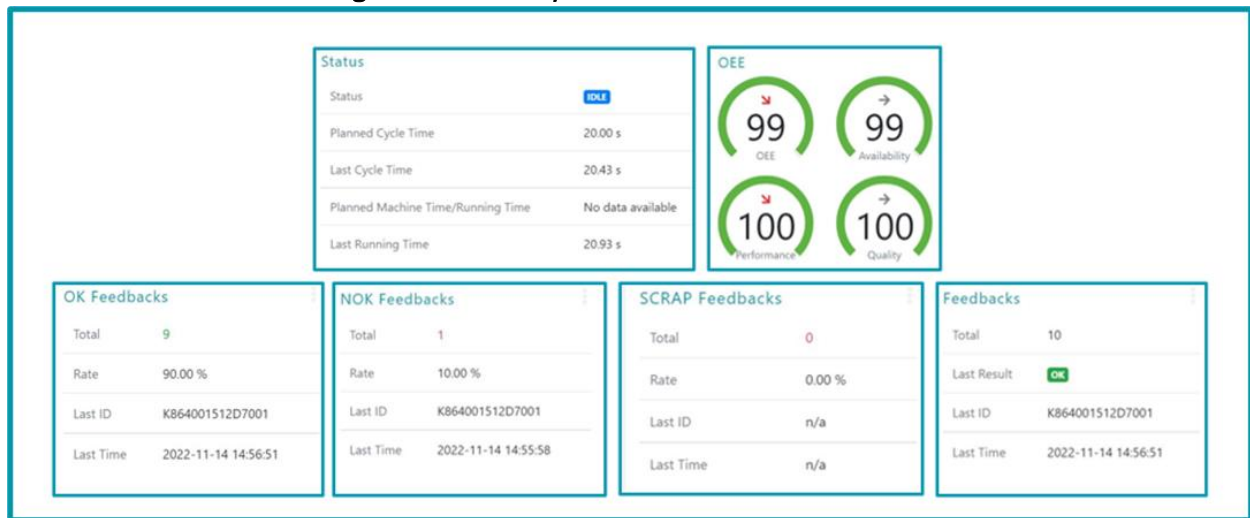


Figure 5.19. SFV System – Equipment Status Submenu

5.10.3. Machine-Specific Submenu: Status History

The analysis period should be selectable individually, providing users with the flexibility to choose the relevant time interval for evaluating equipment performance. This functionality could enable more detailed process monitoring and more precise adjustment of optimization strategies.

Cycle times and feedback for all components during the selected period should be presented in an intuitive graphical format. This system could allow users to analyze equipment performance evolution in detail and identify any deviations from planned values.

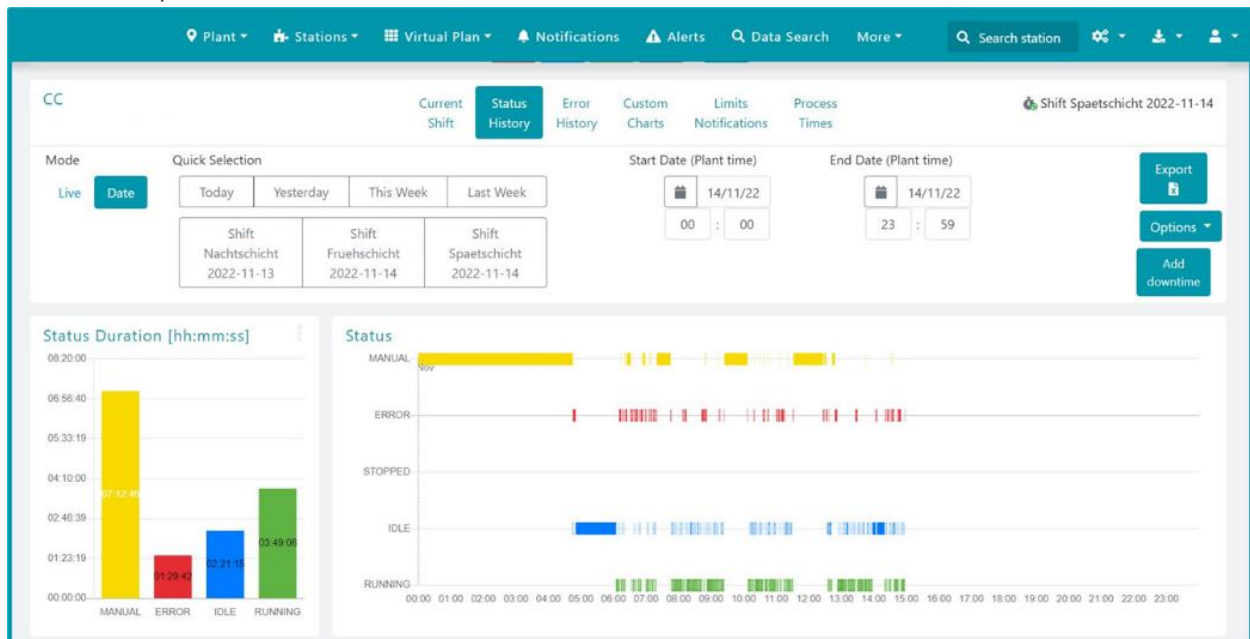


Figure 5.20. SFV System – Equipment History

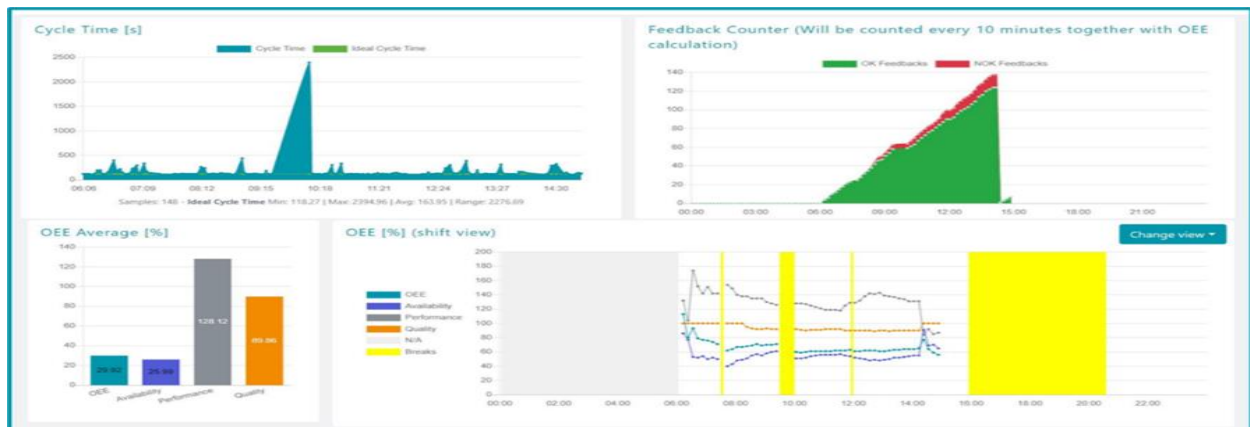


Figure 5.21. SFV System – Error Visualization

5.10.4. Machine-Specific Submenu: Custom Charts

The analysis period should be individually configurable, allowing users to select the relevant time interval for evaluating machine performance. This functionality could facilitate more precise monitoring tailored to the specific needs of each production process.

The creation and modification of charts should be possible through a dedicated function, accessible via an options menu, where users can add new graphical representations according to specific requirements. This system could enable advanced customization of how collected data are analyzed and interpreted.

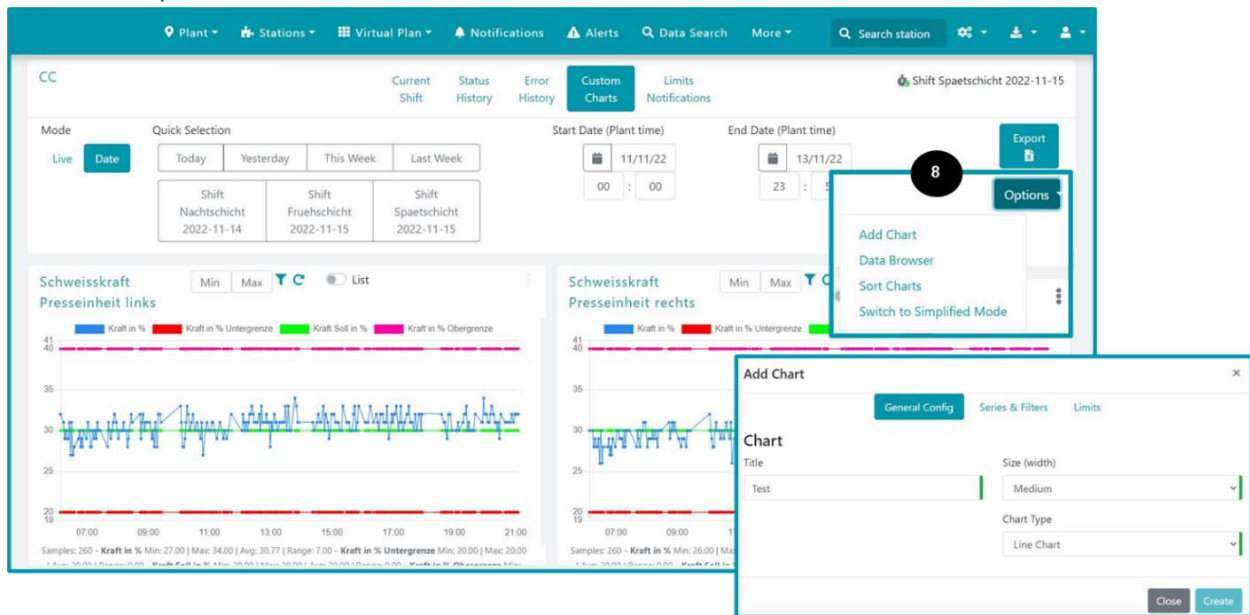


Figure 5.22. SFV System – Custom Charts

5.10.5. Machine-Specific Submenu: Process Time

The analysis period should be individually selectable, providing users with the flexibility to define the relevant time interval for evaluating process performance. This functionality could enable more precise monitoring tailored to the specific requirements of each production flow.

For more accurate analysis, precise information regarding the duration of each process step should be available. These data could support operations optimization and planning improvements, contributing to better resource utilization and increased production efficiency.

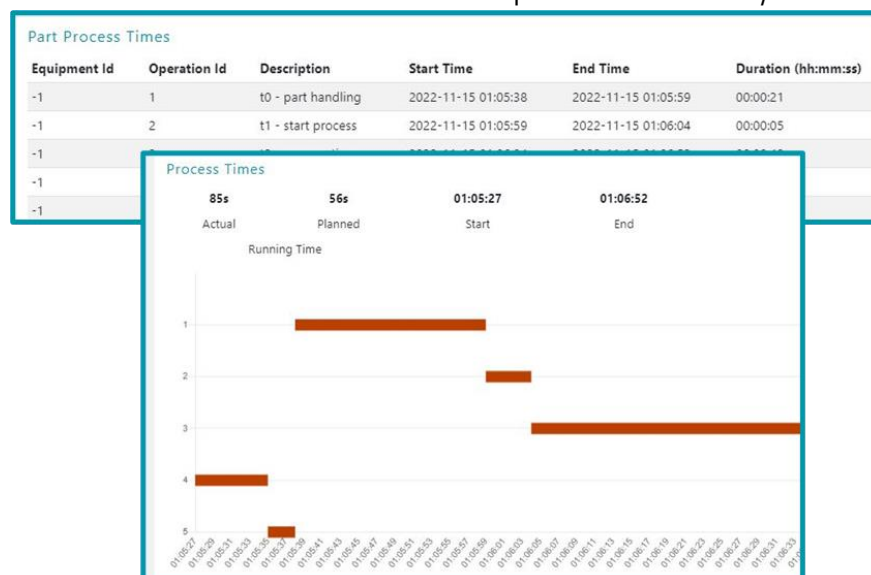


Figure 5.23. SFV System – Process Time

5.11. Interface Description

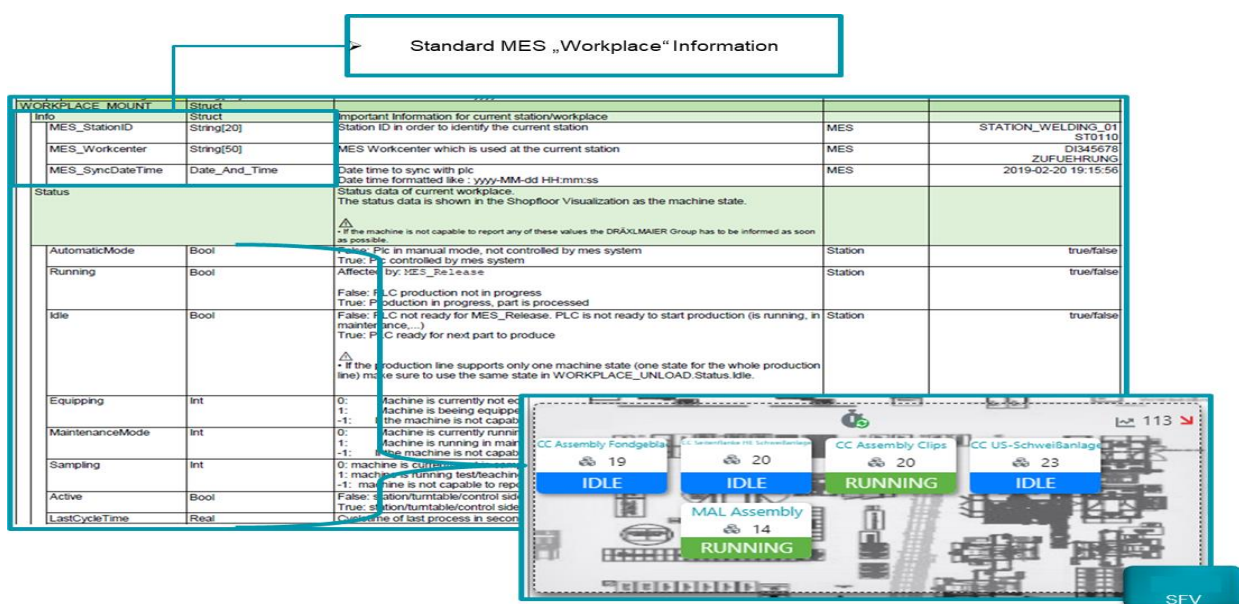
A technical document should clearly define all data and signals to be transmitted from the equipment to the Shopfloor Visualization system or to the MES. This document could establish the essential communication parameters between production systems and digital platforms, thereby ensuring coherent and efficient integration.

A general description of the interface should be available for each type of production unit, providing a standardized framework to facilitate implementation and compatibility among different systems. This approach could aid in standardizing processes and reducing the time required for integrating new equipment.

To ensure optimal functionality, the interface description should be individually tailored for each production unit. This customization process could allow for specific adjustments of communication parameters, transforming the document into a unique description dedicated to each piece of equipment according to its specific operational requirements.

5.11.1. Workstation: Information and Status

A detailed description of the various statuses should be available within the documentation titled "Navigation and Functions of the Shopfloor Visualization." This documentation could provide comprehensive and well-structured information about the meaning and use of each status, thereby supporting users in understanding and correctly applying them within operational processes. This section could serve as a central reference for clarifying any questions related to the functionalities and interpretation of the system statuses.



5.11.2. Process Results

The process description should be completed by the production unit upon the completion of each operational stage, ensuring clear and detailed documentation of how the activity was carried out. This could facilitate performance analysis and the identification of opportunities for improvement within the production flow.

Within this description, only process errors should be included, excluding any equipment malfunctions. This clear separation between operational issues and technical faults could contribute to more accurate diagnostics and the application of more effective corrective measures, thereby ensuring optimal production management.

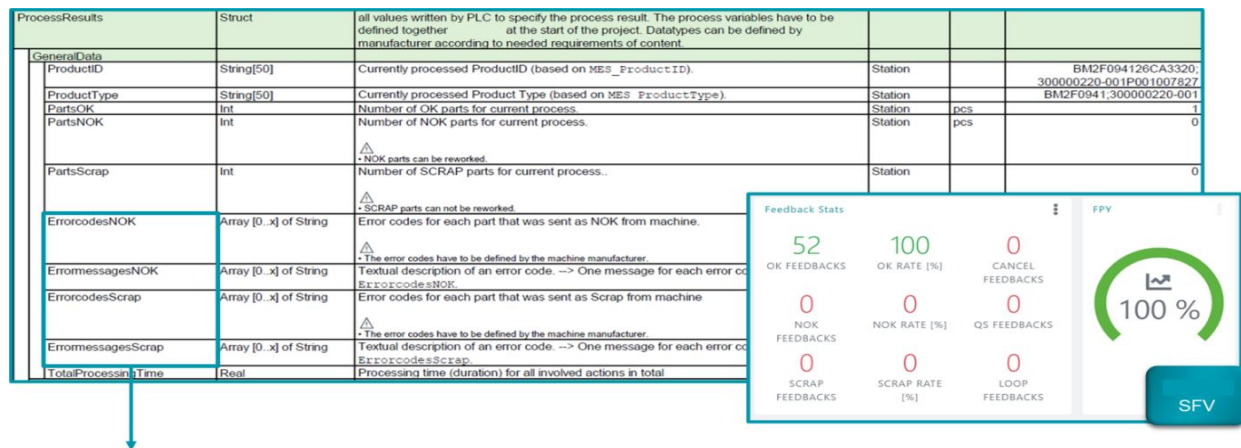


Figure 5.25. SFV System – Process Error

Process Error:

The definition and naming of process defects should be established directly by the supplier, thereby providing the flexibility to adapt the nomenclature to the specific requirements of their production system. This approach could facilitate better error management and clearer data interpretation by all parties involved in the process.

5.12. Conclusions

The full implementation and integration of the Shopfloor View (SFV) digital platform within the industrial infrastructure has led to a significant transformation in how production processes are managed, monitored, and optimized. The use of this system has enabled the digitization of critical operations on the production line and has generated real-time visibility over performance indicators, facilitating data-driven decision-making based on concrete and updated information.

In the medium and long term, the benefits of SFV platform implementation have materialized through a noticeable increase in operational efficiency, reduction of losses caused by defects and non-conformities, enhancement of process standardization, and optimization of resource utilization. Additionally, the detailed visualization of energy consumption and material usage has enabled the identification of inefficiency areas and the adoption of corrective measures with a positive impact on production sustainability.

In conclusion, the integration of the Shopfloor View system represents a major step towards consolidating a modern digital industrial infrastructure. This implementation has led to increased transparency, decision-making agility, reduction of operational costs, and alignment of the factory with Industry 4.0 principles. The observed post-implementation benefits confirm that the SFV platform is not only a monitoring tool but also a strategic element for operational excellence and long-term competitiveness of the organization.

Impact of SFV system implementation on production indicators

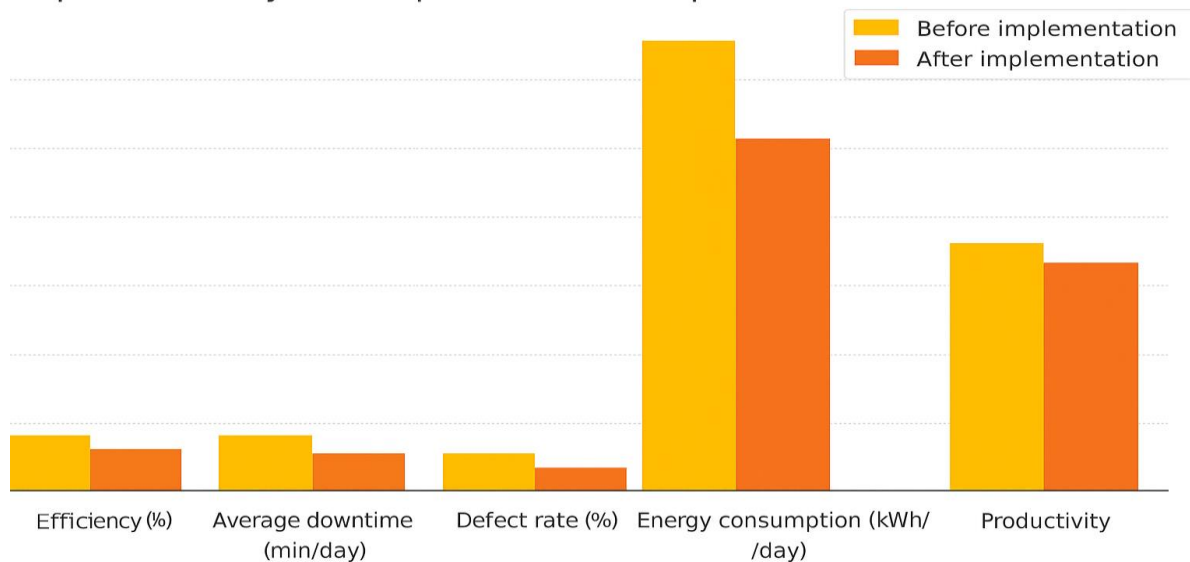


Figure 5.26. Impact of the Shopfloor View (SFV) System Implementation

Table 5.1. Comparative Analysis of Key Performance Indicators

Indicator	Before Implementation	After Implementation
OEE Efficiency (%)	65	82
Average Downtime (min/day)	120	45
Defect Rate (%)	5.5	1.8
Energy Consumption (kWh/day)	1800	1450
Productivity (units/day)	950	1200

The impact of the Shopfloor View (SFV) system implementation on key industrial performance indicators is as follows (Figure 5.26, Table 5.1):

- Significant increase in Overall Equipment Effectiveness (OEE) from 65% to 82%.
- Reduction in average daily downtime from 120 to 45 minutes.
- Decrease in defect rate from 5.5% to 1.8%, highlighting superior quality control.
- Optimization of energy consumption by approximately 350 kWh/day.
- Increase in productivity by over 250 units per day.

These improvements confirm the effectiveness of SFV platform integration and its strategic relevance in optimizing production processes.

CHAPTER 6. CONCLUSIONS, PERSONAL CONTRIBUTIONS, AND PERSPECTIVES FOR FUTURE RESEARCH

6.1. Conclusions

This doctoral thesis systematically and thoroughly addresses the laser microperforation process used in the automotive industry, emphasizing the optimization of the laser microperforation of textile materials employed in automotive applications, with a focus on improving the precision and uniformity of microperforations and highlighting their impact on process efficiency and sustainability. Furthermore, the evaluation of experimental results demonstrated the significant influence of electromagnetic interference on the quality of perforations and the mechanical performance of the perforated material.

Through a rigorous scientific approach that combines theoretical studies with experimental analyses and appropriate statistical modeling, the ultimate objective was to enhance the quality and reliability of microperforated automotive components, thus optimizing industrial production and contributing to the development of more efficient and sustainable technological solutions.

Another fundamental aspect of this research concerns the assessment of the economic and ecological implications of using laser technology in the automotive sector, considering the increasing demands for sustainability and energy efficiency. Integrating the results obtained within this thesis into industrial production processes can contribute to the development of advanced methodologies for increasing productivity and reducing material waste. Thus, by correlating experimental data with developed theoretical models, this work aims to provide a set of applicable solutions that enable the optimization of the laser microperforation process for the automotive industry.

The main conclusions drawn are as follows:

- Laser microperforation enables the creation of precise and uniform perforations, which are critical for the performance of materials used in airbags.
- Optimization of laser parameters such as power, frequency, and pulse duration contributes to reducing manufacturing defects and improving operational efficiency.
- Fluctuating levels of electromagnetic interference directly affect the quality of perforations and the mechanical behavior of the perforated material.
- Laser beam stability is influenced by the intensity of electromagnetic interference, which can lead to variations in perforation size and contour.
- At an optimal electromagnetic noise level (1.2 V), perforations are more uniform, and the distribution of mechanical stresses in the material is optimized.
- The laser processing in the airbag area is essential for passenger safety, ensuring controlled and rapid deployment upon activation.
- The precision of perforation influences the welding process of the airbag guiding channel, ensuring an optimal joint between components and reducing the risk of uncontrolled opening.

- The synthetic leather covering the dashboard must be carefully laser-treated to allow controlled and safe tearing in the event of impact, without compromising aesthetic appearance.

It can be noted that the undertaken research addresses a crucial niche within the field of laser material processing, specifically focusing on the analysis of the impact of electromagnetic interference (EMI) on the quality and consistency of perforations made on textile materials for airbags. The experimental analysis of laser microperforation results demonstrated that electromagnetic interference significantly affects the quality of perforations and the mechanical performance of the perforated material. Optimizing the electromagnetic noise level at 1.2 V provides an optimal balance between mechanical performance and perforation consistency, reducing process variability and improving the reliability of the final product.

Previous studies have predominantly concentrated on optimizing laser parameters without thoroughly exploring the influence of external factors such as electromagnetic interference on microperforation. This study fills this gap by highlighting how fluctuating noise levels can induce systematic errors in the perforation process and proposes solutions to eliminate these adverse effects.

By integrating advanced compensation mechanisms for electromagnetic fluctuations and employing signal filtering techniques for parasitic noise, this study proposes novel methods for stabilizing laser microperforation, resulting in:

- Improved precision of perforations and reduction of structural defects in perforated materials;
- Increased process repeatability and decreased deviations from nominal dimensions;
- Integration of intelligent electromagnetic noise control strategies that enable real-time adjustment of laser parameters.

Through efficient control of electromagnetic interference levels, this research contributes to enhancing the overall performance of the manufacturing process, reinforcing safety and reliability standards for components used in automotive airbags.

In conclusion, laser manufacturing technology applied in the airbag area, the careful treatment of synthetic leather, and the precise welding of the guiding channel collectively constitute an essential assembly for achieving a superior quality final product. This assembly not only ensures optimal functionality of the passive safety system but also contributes to maintaining a premium aesthetic appearance of the dashboard. By employing laser technology, flawless execution can be guaranteed, meeting both safety and design requirements. Thus, a perfect balance between functionality and aesthetics is achieved, providing a superior level of safety and comfort for all vehicle occupants.

6.2. Personal Contributions

This doctoral thesis presents original contributions in the field of optimizing the laser microperforation process, with a focus on reducing the impact of electromagnetic interference and improving the functionality of the airbag system.

The most significant contributions pertain to:

- Development of an optimization methodology for the laser microperforation process, ensuring uniformity of perforations and optimal distribution of mechanical stresses. This methodology includes precise adjustment of laser parameters, analysis of the effect of beam scanning speed on perforation uniformity, and the use of advanced control algorithms for process stabilization.
- Proposal of solutions for control and stabilization of the laser beam by employing advanced monitoring systems and automatic adjustment of laser parameters. These solutions were experimentally tested and resulted in increased stability of the perforation process, reducing variations in perforation size and shape.
- Detailed analysis of the influence of electromagnetic interference (EMI) on the quality of perforations and the mechanical performance of the perforated material. The study included an in-depth evaluation of how different levels of EMI affect the laser perforation process and identified methods to mitigate these effects through process parameter optimization.
- Experimental evaluation of the impact of electromagnetic fluctuations on the tensile strength of laser-perforated materials through a series of systematic experiments that demonstrated how variations in electromagnetic fields affect the microstructure and mechanical properties of the perforated material. This study established optimal exposure limits for the material to such factors.
- Investigation of the influence of laser processing on the quality of the weld in the airbag guiding channel and development of optimization strategies to ensure proper and secure fixation. The study highlighted the importance of laser parameters in maintaining the structural integrity of the material and identified effective strategies to improve the welding of airbag components.
- Identification of viable solutions for using filtering and control technologies of electromagnetic noise levels to improve perforation quality and the strength of perforated materials. Experimental analyses on rupture tests showed that active filtering of electromagnetic interference can contribute to enhancing the quality of the perforation process.
- Development of optimization strategies for treating synthetic leather to ensure a balance between safety, aesthetic appearance, and mechanical performance. These strategies included the use of thermal and chemical treatments that enhance material strength without compromising aesthetics or flexibility.
- Study of the influence of material thickness and laser power on perforation variability through a factorial analysis conducted on an extensive sample of 950 specimens. The results

demonstrated significant correlations between these parameters and perforation precision, contributing to improved process control.

- Implementation of an advanced real-time monitoring and control system for the microperforation process, enabling rapid detection of deviations and automatic adjustment of parameters to maintain consistency of perforations on the material surface. This system led to a significant reduction in perforation defects and an increase in process efficiency.
- Detailed study concerning the material used in the perforation process, including analysis of thickness, texture, and behavior at elevated temperatures. These characterizations allowed determination of optimal process parameters and adaptation of laser technologies to perforate the material without compromising its mechanical properties.
- Optimization of laser parameters to improve perforation quality, considering factors such as beam focusing, number of pulses, and scanning speed. It was demonstrated that precise configuration of these parameters reduces defects and ensures uniform perforations, contributing to enhanced performance of the perforated material.
- Implementation of a system with 200-femtosecond pulses and a 2 KHz repetition rate aimed at using a pulsed laser regime to minimize thermal damage to the material. This approach enabled the creation of precise perforations without negatively affecting the material structure.

6.3. Innovative Aspects of the Doctoral Thesis

This doctoral thesis is characterized by a series of relevant innovative aspects, both in terms of rigorous scientific foundation and direct industrial applicability, particularly within laser welding processes associated with airbags—critical safety components. The methodological and technological novelties include:

➤ *Dual Validation of the Process through Mechanical and Functional Testing*

The methodological innovation is reinforced by a two-level validation strategy: mechanical validation via standardized tensile tests and functional validation through testing of complete airbag assemblies. This dual verification, seldom encountered in conventional approaches, enables direct transfer of conclusions to functional safety requirements specific to regulated industries.

➤ *Analysis of Electromagnetic Interference (EMI) as a Process Disturbance Factor*

A significant innovative aspect lies in the incorporation of electromagnetic noise into the process behavior modeling. Based on specific mechanical testing results, an emerging perspective on the electromagnetic robustness of laser technology processes is developed—an area insufficiently addressed in existing literature. This approach holds potential for extension into the design of laser systems with stringent electromagnetic compatibility (EMC) requirements.

➤ *Integration of Processes and Results into a Correlative Process–Product Model*

By directly correlating process parameters with mechanical and functional performances of the finished product, an end-to-end perspective is developed. This model integrates process data, test results, and traceability, supporting the implementation of a proactive quality system based on prevention and integrated real-time control.

➤ ***Development and Implementation of a Shopfloor Process Visualization (SPV) System***

A practical novelty with significant impact on process operationalization is the implementation of an SPV solution that enables real-time display and tracking of critical process parameters and deviations. This system ensures integration of process data with the MES platform, facilitating rapid detection of nonconformities and substantiating operational decisions within a digitized production environment.

➤ ***Design of a Dedicated Station for Verification and Measurement of the Laser Line Position with Complete Traceability***

One of the most relevant innovative contributions is the development of an automated station for verifying the laser line position during the microperforation process. This station performs:

- unique association of each part with the captured image of the laser trajectory;
- recording in the traceability system of the correlation between the unique part identifier, the obtained image, and process parameters;
- dual validation of the process—both optical and functional—to guarantee conformity in critical applications.

The entire concept was developed to ensure redundancy and robustness in controlling a process directly impacting the end-user's safety, in accordance with critical system requirements. Given its high degree of originality, direct industrial applicability, and innovative integration of process-image-traceability, the solution is suitable for patent protection through an invention patent application.

6.4. Future Developments

The research outcomes presented in this doctoral thesis lay the foundation for new investigative directions aimed at enhancing the laser microperforation process, including but not limited to:

- Extending studies on the effects of electromagnetic interference (EMI) to other laser-based processes utilized within the automotive industry.
- Developing predictive models based on artificial intelligence for automatic adjustment of laser parameters in response to varying levels of electromagnetic noise..
- Optimizing the welding process of the airbag guiding channel using advanced laser technologies to ensure optimal safety system performance.
- Integrating optical feedback sensors enabling real-time adjustment of laser parameters, thus maintaining consistent perforation quality.
- Testing new types of textile materials for airbags that exhibit increased resistance to process variations and provide enhanced safety system performance.
- Developing advanced control systems for electromagnetic noise levels to ensure laser beam stability and perforation consistency.

The analysis of specific parameters influencing the microperforation process opens new research opportunities that can contribute to the advancement of knowledge and technologies applied in laser processing for the automotive sector.

Furthermore, the investigation of laser processing is not limited to defect detection but aims to contribute to the development of innovative solutions that significantly improve the laser cutting process for airbags. By implementing advanced techniques for analysis and optimization of process

parameters, the studies conducted within this thesis provide precise recommendations for necessary adjustments to achieve uniform and accurate perforations regardless of vehicle configuration.

Additionally, the extensive research presented represents a significant step toward enhancing the reliability and consistency of laser microperforation technologies applied to airbag components. The detailed studies and proposed measures emphasize the critical importance of quality assurance and process optimization within the automotive safety industry.

It is imperative for stakeholders to collaborate closely to ensure the effective implementation of these measures, thereby fostering a culture of continuous improvement and operational excellence in manufacturing practices.

6.5. Methods for Exploiting the Research Outcomes

The outcomes obtained throughout the scientific research program have been valorized through the following actions:

- Publication of scientific articles in internationally recognized journals indexed by Clarivate Analytics (ISI Web of Science), contributing to the advancement of knowledge in manufacturing technologies, particularly in laser microperforation: [RUS24a], [RUS24b], [DUM23].
- Presentation of results at international conferences, facilitating information exchange with researchers and industry specialists: [RUS23], [RUS24c], [DUM24a], [DUM24b], [DUM24c], [DUM24d], [RUS25a], [RUS25b].
- Collaboration with automotive industry partners for the implementation of proposed solutions in the manufacturing processes of airbags and other laser-processed textile components.
- Integration of study conclusions into development projects for new laser equipment tailored to the specific requirements of the automotive industry.
- Development of technological guidelines aimed at optimizing the laser perforation process, intended for industry professionals.
- Application of proposed optimization strategies in the production of critical safety components, enhancing product reliability and ensuring compliance with international standards.

6.6. Research Relevance

The relevance of this doctoral thesis is multifaceted, manifesting at technological, industrial, methodological, and academic levels. The research addresses a critical issue for passive safety in the automotive industry — the precise and controlled laser microperforation of materials used in airbag systems — employing a combination of advanced scientific tools, modern processing technologies, and intelligent manufacturing principles.

From a technological perspective, the relevance of this work stems from the direct applicability of the results to the manufacturing process of airbags. These components are vital for passenger protection

in the event of a collision and must operate with extreme precision and reliability. Microperforation is a crucial stage in their design, as it directly influences the deployment behavior of the airbag upon activation.

Furthermore, the research is relevant through its proposal of statistical validation methods and nondestructive inspection techniques that can be widely adopted across industries with strict quality and traceability requirements, such as aerospace, biomedical, and power electronics. The factorial analysis model combined with Shopfloor Process Visualization (SPV) evaluations provides a concrete example of how real-time quality control can be implemented, significantly reducing the costs and time associated with traditional evaluation methods.

In the context of sustainable development and energy efficiency demands, the thesis emphasizes resource optimization within the process. Through fine-tuning process parameters, the study demonstrates the potential to reduce material waste (from defective perforations), minimize energy consumption (by shortening processing time), and improve overall yield. These aspects respond directly to current automotive industry needs.

Methodologically, the thesis contributes a replicable and extensible model for analyzing and optimizing complex processes. Any manufacturing process involving multiple control parameters, complex interactions, and narrow tolerances can benefit from the proposed methodology. This cross-sector relevance enhances the value of the work as a reference for developing robust industrial processes.

One of the most significant contributions lies in the full integration of the digital Shopfloor concept. This becomes increasingly important within the Industry 4.0 revolution, which promotes the transformation of traditional factories into interconnected, intelligent, and fully automated environments. The Shopfloor system developed in this thesis is not merely a passive data collector but an active adaptive control element capable of real-time analysis of data from sensors and optical cameras.

The research relevance also extends to education and workforce training within the industry. The thesis provides a practical example of how to build an experimental, modeling, and validation framework for complex processes in academic or applied research settings. The developed models and algorithms can be adapted for pedagogical purposes, and the experimental platform can serve as a valuable resource for training engineers in advanced manufacturing technologies.

Scientifically, the work's relevance is supported by the opportunities it creates for future research. The conclusions outline emerging directions that can serve as themes for further investigations in both academia and industrial innovation centers.

Finally, the thesis holds strategic relevance amid globalization and the relocation of production chains to regions with increasingly stringent quality and traceability demands. By employing precise and controlled local methods, it helps establish conditions for manufacturing high-technology products

with a high degree of conformity, thus contributing to the competitiveness of the automotive industry at regional and European levels.

In conclusion, the relevance of this research is systemic: it offers solutions to a critical practical problem, consolidates a robust scientific methodology, introduces technological innovation through digital integration, and provides a replicable model applicable to other advanced manufacturing domains. Through these contributions, the work advances knowledge in industrial engineering and supports the transition to more efficient, safer, and smarter production systems.