ISSN 2523-6806

Volume 9, Issue 22 e2025922 — January — December — 2025

Journal of Technological Operations

ECORFAN®

Journal of Technological Operations, Volume 9, Issue 22: e2025922 January - December 2025, is a Continuous publication – ECORFAN-Taiwan. Taiwan,Taipei. YongHe district, ZhongXin, Street 69. Postcode: 23445. WEB: www.ecorfan.org/taiwan, revista@ecorfan.org. Editor in Chief: Barrero-Rosales, José Luis. PhD. ISSN: 2523-6806. Responsible for the last update of this issue of the ECORFAN Informatics Unit. Escamilla-Bouchán Imelda, Luna-Soto, Vladimir, updated December 30, 2025.

Journal of Technological Operations

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Knowledge Area

The works must be unpublished and refer to topics of production systems, mechanical properties, data transmission, process standardization, industrial engineering, composite materials, kinematic analysis, kinetic study, power generator, industrial and technological processes and other topics related to Engineering and Technology.

Content of Presentation

In the first article we present *Optimizing customer service processes using Lean Six Sigma in the manufacturing sector* by Espíndola-Álvarez, Jorge Antonio, León Ramírez, Valeria Carolia, López-Garza, Esmeralda and Castillo-Carrillo, María De Lourdes, with adscription at the Universidad Autónoma de Tamaulipas, as second article we present *Remote dry ice blaster cleaning as a maintenance technique turbine blades in wind farms* by Díaz-Herrera, Sebastián, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo-Pensado, Juan Luis, with adscription at the Benemérita Universidad Autónoma de Puebla, as third article we present *Uses of the Ultra-Trak 750 Sensor for ultrasonic flaw detection in machinery and Industrial facilities* by Duarte-Loera, Jorge, Nandayapa-Alfaro, Manuel de Jesús, Meraz-Méndez Manuel, and Reynoso-Jardón, Elva Lilia, with adscription at the Universidad Tecnológica de Chihuahua and Universidad Autónoma de Ciudad Juárez, as fourth article we present *Reducing setup times in the sandblasting process of an aerospace industry* by Cano-Carrasco, Adolfo, González-Mendivil, Manuel Antonio, Fornés-Rivera, René Daniel and Cañez-Barraza, Roberto, with adscription at the Instituto Tecnológico de Sonora.

Content

Journal of Technological Operations 9[22]1-9: e1922109
Article

Optimizing customer service processes using Lean Six Sigma in the manufacturing sector

Optimización de procesos de atención al cliente mediante Lean Six Sigma en el sector manufacturero

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SECIHTI classification:

Area: Engineering
Field: Technological Sciences
Discipline: Industrial Technology
Subdiscipline: Industrial processes

https://doi.org/10.35429/JTO.2025.9.22.1.1.9

History of the article:
Received: September 19, 2025
Accepted: December 30, 2025

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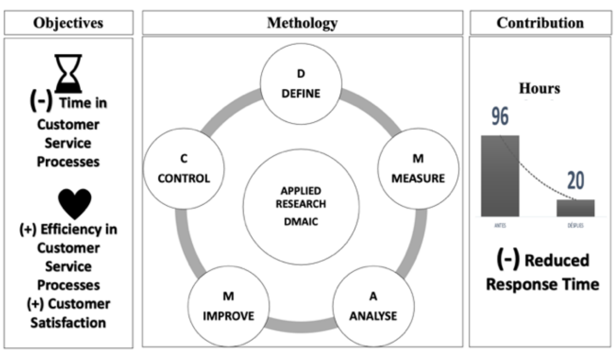
Abstract

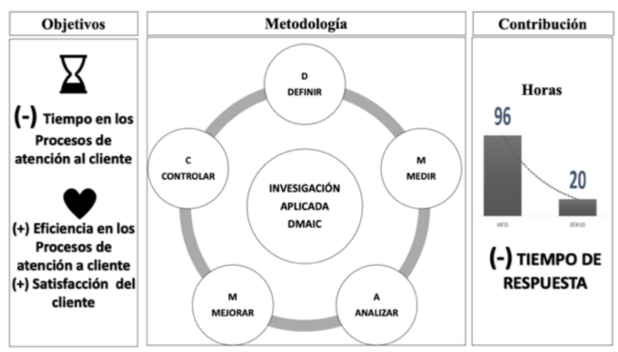
Technological advancements and the demand for faster service processes have raised quality and response standards in companies. This research presents a case study in a manufacturing firm aimed at improving customer service indicators through the implementation of Six Sigma methodology, specifically the DMAIC cycle. Results show significant improvements in response times, customer satisfaction, and operational efficiency, highlighting the importance of systematization and a structured approach to optimizing service processes in competitive and dynamic environments.



Customer Service, Process Optimization, Six Sigma

Resumen

Los avances tecnológicos y la demanda por procesos de servicio más rápidos han elevado los estándares de calidad y respuesta en las empresas. Esta investigación presenta un estudio de caso aplicado en una empresa manufacturera que busca mejorar sus indicadores de servicio al cliente mediante la implementación de la metodología Six Sigma, específicamente el ciclo DMAIC. Los resultados evidencian mejoras significativas en tiempos de respuesta, satisfacción y eficiencia operativa, subrayando la importancia de la sistematización y el enfoque estructurado para optimizar procesos de servicio en entornos competitivos y dinámicos.



Servicio al cliente, Optimización de Procesos, Six Sigma

Area: Development of strategic leading-edge technologies and open innovation for social transformation

Citation: Espíndola-Álvarez, Jorge Antonio, León Ramírez, Valeria Carolia, López-Garza, Esmeralda and Castillo-Carrillo, María De Lourdes. [2025]. Optimizing customer service processes using Lean Six Sigma in the manufacturing sector. Journal of Technological Operations. 9[22]1-9: e1922109.

Introduction

In a business environment marked by global competition, customer service has established itself as a key strategic factor that directly impacts consumer satisfaction, loyalty, and the reputation of organizations. Beyond interpersonal relationships, this function encompasses a complex network of internal processes that must respond effectively, accurately, and consistently to market expectations. Service quality has ceased to be an optional differentiator and has become an essential requirement for business sustainability [Groth, 2010].

Among the methodologies that have proven effective in continuous process improvement, Lean Six Sigma stands out. This strategy combines the waste-elimination principles of Lean with the statistical approach of Six Sigma, aimed at reducing variability and defects. Originally conceived in the manufacturing sector, this methodology has evolved and successfully spread to sectors such as financial services, hospitality, telecommunications, and customer service [Harry, 2000]; [George, 2002]. Its strength lies in the use of the DMAIC cycle (Define, Measure, Analyze, Improve, and Control), which allows for accurate diagnosis of process failures, proposals for data-based solutions, and the guarantee of sustainable improvements [Antony et. al., 2007].

This paper presents a case study of an industrial company located in Reynosa, Tamaulipas. This manufacturing organization with more than 500 employees faces critical issues that directly affect user experience and operational efficiency. The main challenges include excessive response times to inquiries, recurring errors in orders, lack of follow-up on requests, and fragmented administrative processes. These deficiencies have generated a negative perception among customers, affecting not only immediate satisfaction but also the company's image and the ability to maintain sustainable business relationships. The intervention through this study is justified by the need to introduce a formal process improvement methodology that will allow these negative indicators to be reversed. To date, attempts to resolve these problems have been reactive and poorly systematized, which has hindered the consolidation of a customer service system oriented toward operational excellence.

In this context, the application of Lean Six Sigma represents a concrete opportunity to establish diagnostic, intervention, and control mechanisms that raise service standards, align operations with customer expectations, and improve the company's competitiveness in the medium term.

The overall objective of this research is to evaluate the effectiveness of the Lean Six Sigma methodology in improving customer service quality within an industrial company by analyzing key indicators such as response times, first-contact resolution rates, process consistency, and perceived user satisfaction. Through the implementation of the DMAIC cycle, the company aims to identify key areas for improvement, propose efficiency-oriented solutions, and establish a monitoring system to ensure sustained improvements.

It is expected the structured application of Lean Six Sigma will reduce the average request-handling time by at least 20%, reduce the error rate in customer service processes by 15%, and increase customer satisfaction by 25% over a six-month period. These operational improvements not only aim to directly impact the customer experience, but also to reduce costs associated with complaint management and rework. This case study is not only valuable at the organizational level, but also at the academic level. From a theoretical perspective, it provides empirical evidence on the applicability of Lean Six Sigma in a customer service area, where its use is still limited and poorly documented. It also contributes to the understanding of how this methodology can be adapted to specific contexts, such as that of an industrial company in northern Mexico, facing real challenges related to its customer management. On a practical level, the results will generate a replicable model for other organizations that wish to professionalize their customer service processes through an approach driven by data, efficiency, and continuous improvement [Rahmatika, Bakhtiar, & Wicaksono, 2024].

Fundamentals of Six Sigma

In today's business environment, characterized by intense competition and increasingly demanding customers, quality customer service has become a decisive factor for the survival and success of organizations [Rust and Huang, 2014].

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Espíndola-Álvarez, Jorge Antonio, León Ramírez, Valeria Carolia, López-Garza, Esmeralda and Castillo-Carrillo, María De Lourdes. [2025]. Optimizing customer service processes using Lean Six Sigma in the manufacturing sector. Journal of Technological Operations. 9[22]1-9: e1922109.
https://doi.org/10.35429/JTO.2025.9.22.1.1.9

Offering a good product is not enough; the overall customer experience when interacting with the company is key to their satisfaction, loyalty, and recommendation. This experience depends on multiple variables, ranging from personal attention to operational efficiency, including expectation management and technological innovation.

Given this complexity, continuous improvement of service processes becomes imperative. Without a structured, data-driven approach, organizations may miss valuable opportunities to optimize resources, reduce costs, and increase customer satisfaction. In this context, Six Sigma emerges as a comprehensive methodology that, through variability reduction and rigorous analysis, improves service quality and consolidates an organizational culture oriented toward excellence. [Antony et al.,2007]; [George, 2002].

The term Six Sigma was born in the 1980s as a response to the need to improve quality in production and compete with increasingly demanding international standards [George, 2002]. Since then, its application has spread to various industries and sectors, including financial services, healthcare and customer service [Breyfogle III, 2000]. Six Sigma proposes a structured approach based on the rigorous collection and analysis of data to identify and eliminate sources of variability and errors [Kumar, Nowicki, Ramírez-Márquez and Verma (2008)].

Box 1

Table 1
Six Sigma Fundamentals

Aspect	Description
Main objective	Reduce variability and defects in processes to improve quality and efficiency.
Key principles	Customer focus, data-driven decision-making, variability reduction, leadership, and continuous improvement.
Main methodology	DMAIC Cycle: Define, Measure, Analyze, Improve, Control, which guides systematic process improvement.
Statistical tools	Histograms, control charts, regression analysis, root cause analysis, design of experiments (DOE).

Source: Prepared by the authors based on [Antony et. al., 2007]; [Rust and Huang, 2014].

Customer service

Customer service is a fundamental pillar for the sustainability and success of any organization. It not only influences customer satisfaction and loyalty, but also directly affects the company's reputation and financial results [Rust and Huang, 2014]. In an environment where products and services tend to be increasingly homogeneous, customer service becomes a key competitive differentiator [Grönroos, 2015] [Sulla, 2025] .

Service quality is not just the delivery of the product or service, but the total experience the customer receives, including customer service, problem-solving, and demonstrated empathy [Fitzsimmons and Fitzsimmons, 2011]. Therefore, understanding the theories that explain customer perception and evaluation is essential for designing effective improvement strategies.

Box 2

Table 2
Customer service theories

Theory	Description
SERVQUAL Model	It measures service quality from the customer's perspective through five dimensions: reliability, responsiveness, empathy, security, and tangibility.
Satisfaction Theory	He maintains that satisfaction is generated when the perceived performance of the service meets or exceeds customer expectations.
Moments of Truth	Concept that highlights the key points of customer-company interaction where the impression of service quality is formed.

Source: Prepared by the authors based on [Johnston, Clark and Shulver , 2010].

Customer service quality is based on aspects such as reliability, responsiveness, empathy, security, and tangibility [Fitzsimmons and Fitzsimmons, 2011]; [Grönroos, 2015]. Each of these elements contributes to the customer's perception of excellent service and the establishment of a relationship of trust with the organization.

ISSN: 2523-6806
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Continuous improvement

Continuous improvement, on the other hand, is a systematic approach that seeks to constantly optimize processes to eliminate waste and defects, ensuring that quality and efficiency evolve over time. The PDCA (Plan, Do, Check, Act) cycle is the basic tool that guides this process, fostering a culture of constant adaptation and learning [George, 2002] [Cuya and Osorio, 2025].

Box 3

Table 3
Principles of continuous improvement

Aspect	Definition / Application
Reliability	Consistent and accurate fulfillment of commitments made to the client.
Responsiveness	Speed and efficiency in addressing and solving customer needs.
Empathy	Personalized attention and understanding of the client's needs and emotions.
Security	Trust that the customer places in the company to protect their interests and data.
Tangibility	Visible physical aspects that influence the perception of service, such as facilities and staff appearance.
Customer Focus	Continuous improvement is aimed at meeting the real needs and expectations of the customer.
Employee Participation	Empowering employees to identify and solve problems improves processes and results.
Use of Data and Evidence	Decision-making based on objective analysis to identify opportunities for improvement.
PDCA Cycle	Structured methodology for planning, implementing, verifying and adjusting continuous improvements.

Source: Prepared by the authors based on [Fitzsimmons and Fitzsimmons, 2011]; [Grönroos, 2015]

Application of Six Sigma in Customer Service

Customer service presents particular challenges, such as the variability inherent in human interactions, managing expectations, integrating digital channels, and the difficulty of establishing objective metrics [Fitzsimmons and Fitzsimmons, 2011]; [Linderman et. al., 2003].

Six Sigma, with its structured, data-driven approach, can adapt to these challenges and become a strategic ally in improving service quality, its flexibility allows it to be adapted to customer service processes, as recent cases demonstrate. For example, [Lara-Hernández et al. ,2023] document the successful implementation of Six Sigma in a butcher shop, achieving significant improvements in service times, operational efficiency, and customer perception. Likewise, [Bolaños Muñoz & Valencia Caicedo, 2023] applied the Lean Six Sigma methodology to reduce waiting times in a Colombian engineering company, reducing dissatisfaction and strengthening the quality perceived by customers.

Box 4

Table 4
Principles and Benefits of Six Sigma

Principle	Description	Key benefits
Customer focus	All initiatives aim to meet real needs	Improving quality and customer experience
Data-driven	Decisions based on objective information	Variability reduction and process control
Leadership and culture of improvement	Involvement of management and teams	Sustainability of improvements and cultural change
Structured DMAIC cycle	Allows for systematic and continuous improvement	Concrete results: fewer defects and operating costs

Source: Prepared by the authors based on [Johnston, Clark and Shulver , 2010]; [Lara-Hernández et al. ,2023];[Linderman et. al., 2003].

Methodology

This study was developed using an applied research approach, focusing on solving a real-life problem related to customer service efficiency in a manufacturing organization. This approach was chosen in response to the need to generate practical and measurable improvements through the application of robust analytical tools such as Six Sigma, particularly its DMAIC methodology.

The implementation of the DMAIC cycle followed a structured process, encompassing everything from the initial diagnosis to the control phase, ensuring the sustainability of improvements.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

The implementation of each phase, its objectives, tools, and the key intermediate findings that led to the final results are detailed below [López et al., 2025].

Phase 1: Define and Measure: Understanding and Quantifying the Problem.

This initial stage focused on clearly identifying the customer service problem, defining its limits, and establishing a performance baseline with accurate data. The initial diagnosis revealed significant operational inefficiencies, primarily in manual purchase order management processes, resulting in prolonged response times (an average of three to four days) and low customer satisfaction. Customer surveys were administered and a comparative analysis with competitors was conducted to understand the magnitude of the gap.

Box 5

Table 5
Problem Definition and Measurement

Main Objective	Key Activities and Tools	Deliverables and Intermediate Findings	Indicators
Establish the problem, objectives and scope of the project.	- Interviews: With management and support staff. - SIPOC diagram: High-level mapping of the process. - Voice of the Customer (VOC): Surveys of 150 customers to validate critical needs (response time, accuracy). - Project Team formation.	- Operational inefficiency problem identified. - SMART goals established for KPIs. - Prioritization of "response time < 24 hours" and "100% accuracy."	Response time: 3-4 days (72 – 96 hrs.) Customer satisfaction: 1.72 (scale 0-5)
Quantify current process performance (baseline).	- Data Collection Plan: Collect data from 500 orders over a 3-month period. - Establish Baseline: Calculate averages, rates, and variability. - Measurement System Analysis: Verify data reliability.	- Detailed baseline of current performance. - Structured data for further analysis. - Confirmation of high variability over time.	Average response time: 72-96 hours Standard deviation of times: 24 hours CSAT (satisfied customers): 75% First contact resolution: 60% Internal errors: 30 errors/month Monthly operating cost: $30,000

Source: Elaboration Own

Phase 2: Analyze: Identify Root Causes.

With a clear problem definition and an established baseline, the Analyze phase focused on identifying the root causes of the inefficiencies. This analysis provided insight into why the current process was not meeting efficiency and customer satisfaction expectations.

Box 6

Table 6
Root Cause Analysis and Discovery

Main Objective	Key Activities and Tools	Discoveries and Validated Root Causes
Identify and validate the root causes of the problem.	- Value Stream Mapping (VSM): Detailing the purchase order process. - Root Cause Analysis: - Ishikawa diagram (People, Processes, Technology, etc.). - Pareto analysis (80/20 of problems/causes). - Quantitative data analysis (histograms, dispersion).	- Main bottlenecks: Manual validation and departmental authorization. - Root causes: Manual data entry, lack of standardized procedures, and absence of a centralized validation system. - Lack of standardization and manual dependency generate 80% of errors and delays.

Source: Elaboration Own

Phase 3: Improve and Control.

The Improve and Control phases focused on the design, implementation, and maintenance of solutions that directly addressed the identified root causes. Innovative solutions were sought, and robust mechanisms were established to ensure that improvements were sustainable over the long term and that the process remained under statistical control.

Table 7 details the implementation of these phases and the immediate results of the intervention. The key performance indicators (KPIs) monitored before and after the intervention, which validate the effectiveness of the solutions, are presented in the Results section.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Box 7

Table 6

Implementation and Control of Improvements

Main Objective	Key Activities and Tools	Implemented Solutions
Develop and implement solutions to eliminate root causes.	- Solution Generation: Digitalization (self-service portal), standardization, staff training, CRM optimization. - Pilot and Testing: Controlled implementation (1 month with a subset of orders/customers). - Cost-Benefit Analysis: Assessment of economic feasibility.	- Solution Generation: Digitalization (self-service portal), standardization, staff training, CRM optimization. - Pilot and Testing: Controlled implementation (1 month with a subset of orders/customers). - Cost-Benefit Analysis: Economic feasibility assessment.

Source: Elaboration Own

Results

The application of the Six Sigma methodology allowed us to identify structural inefficiencies in customer service processes, address root causes, and monitor changes through previously defined key performance indicators (KPIs). This intervention generated substantial improvements in five critical areas: response times, customer satisfaction, first-contact resolution, quality of internal processes, and operating costs.

Prior to implementation, the customer service system showed average response times of between three and four days, with a low first-contact resolution rate and a lower-than-expected satisfaction rate. Using the DMAIC approach, solutions were designed to standardize processes, automate repetitive tasks, train staff, and reduce errors resulting from manual information management.

As a result, the average response time was significantly reduced to 20 hours, representing a 72% improvement. This reduction directly impacted the perception of service quality, reflected in an increase in the customer satisfaction index (CSAT) from 75% to 86%. At the same time, the first contact resolution rate was improved from 60% to 70%, reducing customer effort and optimizing the team's operational load.

In terms of internal quality, the audits conducted showed a 40% reduction in errors in customer service processes, suggesting greater operational reliability. This improvement translated into a 31% reduction in operating costs, derived from fewer reprocessing, downtime, and duplicate tasks.

To ensure objective and traceable measurement, five key KPIs were defined to guide performance evaluation, both before and after the intervention. These indicators are presented in the following Table 8.

Box 7

Table 8

Key Performance Indicators (KPIs) implemented and results obtained

KPI	Formula	Goal	Before	After	Improvement
Average response time	∑ Response times / Total cases	≤ 24 hours	3–4 days	20 hours	-72%
Customer Satisfaction Index (CSAT)	% positive responses in post-service survey	≥ 85%	75%	86%	+15%
Resolution at first contact	Cases resolved at first contact / Total cases	≥ 70%	60%	70%	+10%
Internal error rate	Number of errors / Total orders processed	≤ 20 errors/month	30 errors/month	18 errors/month	-40%
Monthly operating cost	Costs before and after intervention	Reduction ≥ 10%	$30,000	$20,700	-31%

Source: Elaboration Own

The implementation of Six Sigma not only reduced the average response time but also significantly reduced the variability of these times, achieving more consistent and predictable service delivery, a key aspect for service reliability. The standard deviation in response times was reduced by 50%, consolidating a process under statistical control and minimizing the experience of atypical cases that prolonged wait times.

Regarding customer experience, in addition to the increase in the customer satisfaction index (CSAT), the Net Promoter Score (NPS) was evaluated, showing a 12% increase, indicating a higher level of service recommendation and greater loyalty. The support team showed an increase in productivity, with an 18% increase in cases handled per agent and a reduction in the time spent per case, reflecting more efficient management of human resources and better distribution of workloads.

Finally, the reprocessing or rework rate decreased by 35%, demonstrating that the improvements not only impacted superficial results, but also the robustness of the process, reducing redundant efforts and increasing the final quality of the service.

These results, summarized in Table 9, confirm that the intervention generated comprehensive benefits, from operations to customer experience, and support the viability of the Six Sigma methodology in service contexts.

Box 8

Table 8

Key Performance Indicators (KPIs) implemented and results obtained

KPI	Formula	Goal	Before	After	Improvement
Standard deviation times (hrs)	Variability in response times	≤ 12 hrs	24 hrs	12 hrs	-50%
Net Promoter Score (NPS)	% Promoters - % Detractors	≥ 50%	40%	52%	12%
Cases handled per agent/day	Total cases attended / Number of agents	Increase	25	30	18%
Time spent per case (min)	Total man-hours / Cases attended	Reduction	40	32	-20%
Reprocessing rate (%)	Cases requiring rework / Total cases	≤ 5%	7%	4.50%	-35%

Source: Elaboration Own

Conclusions

The implementation of the Six Sigma methodology in customer service has proven to be a transformative strategy that goes beyond simple process optimization. The results achieved reflect a substantial improvement in operational efficiency, service quality, and customer experience, fully validating the objectives and hypotheses proposed at the beginning of the study.

This intervention not only dramatically reduced response times and increased the first-contact resolution rate, but also significantly increased customer satisfaction, demonstrating the direct impact of Six Sigma on consolidating a more agile, reliable service focused on the real needs of the user.

Furthermore, the reduction in internal errors and the optimization of operating costs demonstrate that the methodology provides tangible and measurable benefits that strengthen the organization's competitiveness and sustainability. This study confirms that Six Sigma is not just a tool for manufacturing or production, but an applicable and valuable philosophy in the field of customer service, capable of generating cultural and operational changes that systematically drive continuous improvement.

The success of this implementation invites reflection on the importance of adopting structured, data-driven methodologies to address current challenges in service management, where agility and quality differentiate between leading and lagging companies. In this sense, the experience documented in this study provides concrete evidence and a replicable model for other organizations seeking to raise their service levels and strengthen their customer relationships in a competitive and dynamic environment.

Finally, this research reaffirms that the key to achieving excellence lies in the combination of technology, rigorous methodology, and a deep commitment to continuous improvement, where every action is geared toward creating tangible value for the customer and building more efficient, resilient, and sustainable organizations.

Declarations

Conflict of interest

The authors declare no conflicts of interest. They have no known competing financial interests or personal relationships that could have influenced the work presented in this article.

Author contribution

Sosa-Duran, José Guillermo: Led the conception of the study, including problem identification, design, and implementation of solution strategies. He was primarily responsible for developing the theoretical framework, analyzing the results, and formulating the conclusions.

Espíndola-Álvarez, Jorge Antonio: He contributed significantly to advising on the design and implementation of solution strategies. He actively participated in the development of the theoretical framework, the analysis of results, and the preparation of conclusions.

López-Garza, Esmeralda: Provided key advice in the design and implementation of solution strategies.

León-Ramírez, Valeria Carolina: Made final adjustments and revisions to the manuscript, ensuring the text's coherence and quality, and also handled the translation for publication.

Availability of data and materials

The data from this study are available to the interested public, while maintaining the privacy of the case study company.

Funding

This research did not receive any type of funding for its completion.

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Antecedents

Cuya Huaman, PE, & Osorio Menacho, JA (2025). Warehouse management model to increase logistics process efficiency using Lean Six Sigma in a ceramic tile retail company in Lima, Peru [Professional proficiency work, Peruvian University of Applied Sciences]. Peruvian University of Applied Sciences.

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Basics

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ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Journal of Technological Operations 9[22]1-17: e292217
Article

Remote dry ice blaster cleaning as a maintenance technique turbine blades in wind farms

Limpieza remota con blasteo de hielo seco como técnica de mantenimiento de álabes de turbinas en parques eólicos

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SECIHTI classification:

Area: Engineering
Field: Engineering
Discipline: Mechanical Engineering
Subdiscipline: Mechanical design

https://doi.org/10.35429/JTO.2025.9.22.2.1.16

History of the article:
Received: September 19, 2025
Accepted: December 10, 2025

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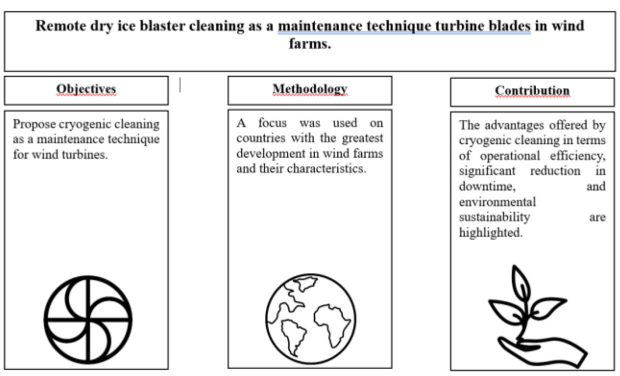
Abstract

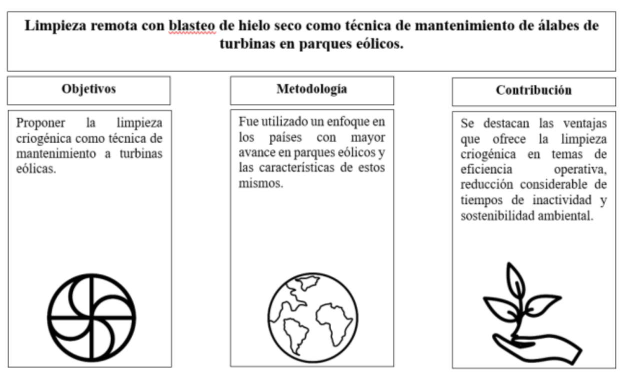
Wind energy, a zero-emission renewable energy source, has implemented increasingly larger turbine blades for greater production on land and offshore. The objective of this research was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. On the other hand, wind turbine blades with excellent aerodynamics increase their performance up to 6% annually. However, those without this technology will experience greater downtime, impacting their efficiency and profitability. A mixed analysis was performed to evaluate cleaning and maintenance methods for wind farm blades, identifying advantages and disadvantages through quantitative and qualitative methods. An analysis of existing blade cleaning methods was the trigger to propose an alternative remote cleaning method that meets the objectives of sustainable development and the circular economy. The optimization of this technology will be the subject of future work.



Cryogenic cleaning, wind farms, operational efficiency

Resumen

La energía eólica fuente de energía renovables cero emisiones han implementado alabes de turbinas cada vez más grandes para mayor producción en tierra como mar adentro. El objetivo de esta investigación fue proponer un método criogénico de limpieza y mantenimiento remoto para alabes de aerogeneradores Por otro lado, Los alabes de aerogeneradores con excelente aerodinámica aumentan su rendimiento hasta 6% anualmente, Sin embargo, los que no cuenten con esta, experimentaran mayores tiempos muertos impactando su eficiencia y rentabilidad. Un análisis mixto fue realizado en la evaluación de los métodos de limpieza y mantenimiento en alabes de parques eólicos, identificando ventajas y desventajas por métodos cuantitativos y cualitativos. Un análisis de los métodos existentes de limpieza de palas fue el detonante para proponer un método alternativo de limpieza remota que cumpla con los objetivos del desarrollo sustentable y la economía circular. La optimización de esta tecnología será motivo de trabajos futuros.



Limpieza criogénica, parques eólicos, eficiencia operativa

Area: Promotion of frontier research and basic science in all fields of knowledge

Citation: Díaz-Herrera, Sebastián, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo-Pensado, Juan Luis. [2025]. Remote dry ice blaster cleaning as a maintenance technique turbine blades in wind farms. Journal of Technological Operations. 9[22]1-16: e2922116.

Introduction

A fundamental analysis of the design phase of a wind farm is that of reliability evaluated from a quantitative and qualitative point of view. Fixed offshore wind turbines require a higher economic budget than those located on land, with the increase in water depth due to the complex marine conditions.

Wind turbines installed on floating structures represent a viable solution offering; more flexible construction and installation procedures, insensitive to water depth, higher wind speed, more difficult maintenance procedures, less noise pollution, lower demolition cost. Aafif et al. (2022), Albatayneh et al. (2025), Chan and Mo (2017), Jamshidi et al. (2019), Kang et al. (2018), Gonzalo et al. (2022) and Saleh et al. (2023).

The adverse operating conditions of semi-submersible and fixed floating offshore wind turbines determined that failures have a greater incidence in the support structures, hydraulic system, gearbox, generator, and other systems. These are due to factors such as salt spray, waves, high wind speed, among others. Early fault detection allowed for the implementation of predictive maintenance strategies that can plan actions based on repair times, average repair costs, and average number of personnel required for repairs.

The most critical maintenance systems are corrective maintenance in gearboxes, generators, turbine blades, and hydraulic systems, which require longer downtimes. Maintenance strategies were implemented with cause-and-effect analysis of faults, in a plan to improve the design and optimize maintenance programs.

In semi-submersible and fixed floating offshore wind turbines, it was identified that the mooring system - support structures (mooring line breakage, abnormal tension of turnbuckles, failure of anchor, buoys and fairleads) were the most prone component to failure with a rate of 17%, failures to hydraulic and pitch systems have a failure frequency around 13%, the generator with a frequency 12%, the gearbox and speed train with 8% representing the failures with the highest downtime due to repair that influence the performance of the wind turbine with impacts on the production of the wind farm.

On the other hand, lower incidence failures are electronic components and automatic control systems. Aafif et al. (2022), Adedeji et al. (2022), Albatayneh et al. (2025), Begun and Schlickewei (2024), Chen et al. (2021), Ding et al. (2025) and Kang et al. (2018).

The factors influencing the failure generation of semi-submersible and fixed floating offshore wind turbines are impact by brought or fallen objects, lightning strike, wind, aircraft accident, biological collision, strong waves, storm, typhoon, human error, poor operating environment, insufficient emergency measures.

As a result, collision protection measures, sophisticated weather forecasts, emergency response plans to reduce losses, and periodic detection to ensure the condition of the pillars are required. Jamshidi et al. (2019) and Kang et al. (2018).

Wind energy, a renewable energy source, has implemented increasingly longer and larger composite blades that allow for greater production of viable wind energy for electric power generation.

Monitoring the condition and maintenance of blades prevents damage, detects structural defects, and prolongs the turbine's lifespan in both offshore and onshore environments. Lopez and Kolios (2022), Danesh et al. (2025), Global Wind Energy Council, (2024), Katsaprakakis et al. (2021) and Saleh et al. (2023).

Wind turbine blades can suffer damage such as delamination, spalling, cracks, erosion, fouling, and coating by layers of contaminants, which cause changes in the roughness of the blade surface, negatively impacting aerodynamic performance.

Because of this, it is necessary to evaluate the degradation, performance, and condition to determine reliability and sustainability through technologies such as digital twins (virtual representation of comparison with real-time model update). The evaluation of blade conditions uses techniques and tests under international standards adaptable to each type of inspection and decision-making.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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https://doi.org/10.35429/JTO.2025.9.22.2.1.16

These can be maintenance techniques, tests (ultrasonic, thermography, radiographic, electromagnetic, acoustic emission, shearography), comparison and complementarity between analysis methods for decision-making, and real-time monitoring through technologies with artificial intelligence. Aafif et al. (2022), Bošnjaković et al. (2025b), Chan and Mo (2017), Danesh et al. (2025), Leon-Medina et al. (2025) and Sheehan et al. (2025).

The objective of this research was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. An analysis of existing blade cleaning methods was the trigger to propose an alternative remote cleaning method that meets the objectives of sustainable development and the circular economy. Lopez and Kolios (2022), Cold Jet Dry Ice Production, n.d., (2025) and Saleh et al. (2023).

Turbine blades are manufactured with a load-bearing spar that serves as a structure that provides strength and stiffness to the casing, with thin, pre-twisted walls to counteract compression, tension, and torsion-induced deformations during bending and buckling operation. The wind turbine blade has suction and pressure sides to optimize aerodynamic performance, and these sides are formed at the leading and trailing edges and flaps. Turbine blades must also withstand environmental conditions that include; humidity, fatigue, wind gusts, salinity environments, sand, lightning strikes, rain, hail, dust, ice, and insect contamination, which cause them to gradually develop defects. Zhang and Tee (2019).

How can efficient maintenance programs be achieved that meet the objectives of sustainable development and the circular economy, focusing on wind turbine blade cleaning and improving aerodynamics, directly linked to increased electricity generation and profitability?

For wind turbine blade cleaning monitoring, it is essential to use and develop advanced techniques to meet the need to reduce repair costs through early detection and removal of contaminants, thereby increasing the lifespan of wind turbines.

Therefore, remote-controlled non-destructive methods (visual, optical, ultrasonic, electromagnetic, thermal, and radiographic) have been developed to inspect blades using real-time monitoring databases with machine learning and comparison of classified characterization models for interpretation and decision-making. Bošnjaković et al. (2025b), (Cold Jet, 2025b), Lopez and Kolios (2022), Danesh et al. (2025) and Sheehan et al. (2025).

There are several methods used for the removal of industrial contamination. These methods are divided into physical, chemical, and physicochemical. In this research, dry ice cleaning is an abrasive physical method for the removal of industrial dirt. The cleaning mechanism is based on three main steps: surface subcooling, contamination fracturing due to the decrease in temperature, and dry ice sublimation, with rapid volume expansion that causes the propagation of contaminant cracks and the subsequent removal of dirt.

Finally, residual particles are carried out of the cleaning zone by the gas flow. The safety of dry ice cleaning technology is a decontamination method with minimal controlled surface erosion, no secondary residue, no phase change of contaminants, and no massive damage to the morphology of the part. This method is safe, and the material removal rate can be considered almost zero under optimized method conditions, considering that it influences a controlled surface roughness pattern and depends on factors such as: mixture percentages, dry ice particle size, mixing fluid velocity at the nozzle, angle of attack, and application distance, but does not affect the microstructure of the materials and controls the roughness pattern uniformly. The dry ice cryogenic cleaning method meets all specifications for cleaning wind turbine blades in accordance with international regulations, sustainable development goals, and the circular economy. Admin (2025), (Global Wind Energy Council, 2024) and Todorović (2025b). The optimization of this technology will be the subject of future work.

Research methodology

This research adopted a mixed approach, applying both quantitative and qualitative technologies, utilizing systematic processes, as well as records and estimated data.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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The objective of this research was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. To this end, the application of the quantitative method was relevant in identifying control variables involved in previous studies evaluating cleaning and maintenance methods for wind farm blades, identifying advantages and disadvantages. An analysis of existing blade cleaning methods was the trigger for proposing an alternative remote cleaning method that meets the objectives of sustainable development and the circular economy. Quantitative indices of wind power generation reports based on mixed records determine that contaminated wind turbine blades decrease their productivity by 2% to 6%. On the other hand, the experiences of wind farm personnel qualitatively identify that damage to wind turbine blades due to contaminants, lightning damage, and wear are the main cause of loss of efficiency in the wind turbine system. This coincides with scientific reports, contrasting the experience and statistics that were considered as the application of the mixed method that allowed the possibility of obtaining results from the estimation of variables, which played an important role in decision-making.

A mixed analysis was performed in the evaluation of cleaning and maintenance methods on wind farm blades, identifying advantages and disadvantages by quantitative and qualitative methods. The operational data resulting from this research determined that, for monitoring wind turbine blade cleaning, it is essential to use and develop advanced techniques to meet the need to reduce repair costs through early detection of contaminants and their removal that allow increasing the useful life of wind turbines.

Therefore, remote-controlled non-destructive methods (visual, optical, ultrasonic, electromagnetic, thermal, and radiographic) have been developed to inspect blades using real-time monitoring databases with machine learning and comparison of classified characterization models for interpretation and decision-making. Finally, using a mixed method, an analysis of the control variables was performed, allowing for an understanding of how to achieve efficient maintenance programs that meet the objectives of sustainable development and the circular economy, focusing on cleaning wind turbine blades that improve aerodynamics directly linked to increased electricity generation and profitability.

This research proposes the cryogenic dry ice cleaning technique after being evaluated based on its technical process variables in a quantitative manner as a physical abrasive method for the removal of industrial dirt. The safety of dry ice cleaning technology was qualitatively evaluated as a decontamination method with controlled surface erosion, without secondary residues, without phase change of the contaminants and it is proposed to evaluate in a mixed way, which does not generate damage to the morphology of the part through digital twins. (Akgül, 2024, Admin (2025b), Albatayneh et al. (2025), Bošnjaković et al. (2025b), Leon-Medina et al. (2025), Li et al. (2022) and Liu et al. (2023).

Classification of faults in wind turbines

The global wind energy market has experienced rapid growth as countries strive to reduce carbon emissions and transition to renewable energy sources. These environments expose turbines to various stressors, such as extreme weather conditions, UV radiation, saltwater corrosion, and abrasive particles, which affect their durability and efficiency. The wind industry is facing increasing pressure to improve turbine longevity and reliability while minimizing maintenance costs. This is essential to ensure the long-term sustainability and profitability of wind energy operations (Aafif et al. (2022), Chan and Mo (2017), (Global Wind Energy Council, 2024) and Saleh et al. (2023).

The ten countries with the largest wind power generation capacity are: China with 460 GW, the United States with 150 GW, India with 60 GW, Germany with 45 GW, the United Kingdom with 39 GW, France with 25 GW, Spain with 20 GW, Brazil with 19 GW, Poland with 15 GW, and South Africa with 12 GW. Albatayneh et al. (2025) and Global Wind Energy Council, (2024). Blades are one of the most important components of a wind turbine. Failures related to the blade system include: structural failure, rotor system, tip damage, edge damage, casing damage, hub damage, bearing wear, split tip, lightning strike, edge cracks, erosion, leading and trailing edge delamination, spalling, casing delamination, beam-to-casing joint crack, root clearance, uncontrolled surface roughness, unbalance, pitch mismatch, pin corrosion, element deformation, and fatigue of fibrous composite materials. Lopez and Kolios (2022), Katsaprakakis et al. (2021b) and Zhang and Tee (2019).

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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The yaw system keeps the wind turbine aligned with the main wind direction as it changes under normal operating conditions. Wind speed generates load fluctuations on the blade surfaces depending on the angle of attack. Optimization of the wind turbine rotor torque is based on changes in yaw angle. If the yaw system is not synchronized between blades or has a suboptimal angle of attack, it will generate vibrations in the blades, tower, and nacelle. An imbalance in the blade system can even endanger the safety of the wind turbine, even to the point of destruction. Damage to composite wind turbine blades can be classified as: debonding of the skin/adhesive or main spar/adhesive layer, failure of the adhesive bond between the skins on the upwind and downwind leading or trailing edges, debonding of the sandwich panel face/core, delamination caused by tensile loading or buckling, and fiber failure in tension. Compression laminate failure, buckling-induced coating/adhesive peeling, gel coat cracking, and gel coat/coat peeling. Lopez and Kolios (2022) and Katsaprakakis et al. (2021b).

To identify critical failure events, methods are used to obtain sets of cuts. This is an algorithm to verify the reliability of the system or component through resolution of fault trees such as; the yaw system, logic gates, codes, yaw motor, drive alarm, meteorological unit, limit switch, among others. Chan and Mo (2017) and Ding et al. (2025).

The failure rate of wind turbines varies depending on the subsystem and varies between onshore and offshore systems, where severe environmental conditions such as storms, corrosion, leaks, salt spray, sandstorms, and high wind speeds significantly impact turbine reliability and availability. A previous assessment estimated that failure rates for electrical and electronic components and blade systems are seven times higher than for onshore turbines. However, for gearboxes and drivetrain systems, the approximate annual failure rate was estimated to be around four times higher than for onshore turbines. Therefore, planned maintenance periods should be less than 50 days. Aafif et al. (2022), Chan and Mo (2017), Chen et al. (2021), Dagdag and Kim (2024b), and Schouten et al. (2021).

Wind turbine blade inspection methods are divided into contact methods (magnetic, electromagnetic, eddy current, traditional ultrasonic, and liquid penetrant testing) and non-contact methods (visual inspection, ultrasonic, acoustic, mechanical vibration, electromagnetic, thermographic, radiographic, and shearographic techniques).

The failure frequencies in gearbox systems are shown in Figure 1. These are; control failure 0.25, sensor failure 0.19, hub failure 0.14, yaw system failure 0.12, converter failure 0.11, structural failure of the blades 0.07, brake failure 0.04, transformer failure 0.035, drive train failure 0.03 and bearing failure 0.028 Chen et al. (2021) and Gong and Chen (2024).

Box 1

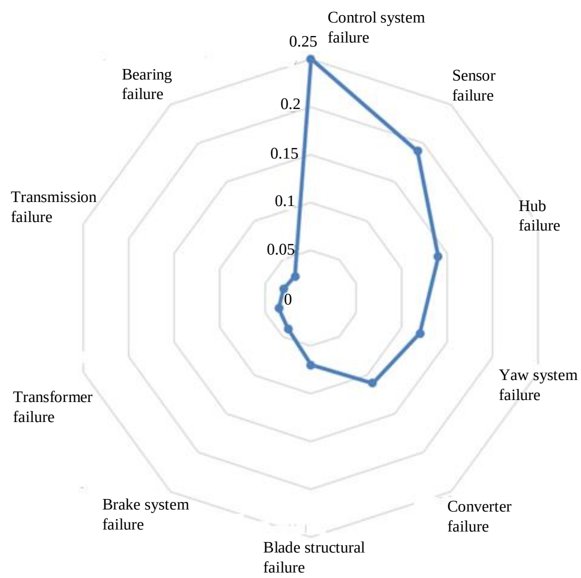

Figure 1

Failure frequency per year in gearbox systems.

Source: Own Elaboration

The fault frequencies in generator systems are shown in Figure 2. These are; media leakage 0.78, parameter deviation 0.15, asymmetry 0.05, abnormal vibration 0.03, structural deficiency 0.02, cable failure 0.01, instrument misreading 0.008, synchronization failure 0.006, failure to start on demand 0.004, broken bar 0.003, temperature over limit 0.002 and sensor failure 0.001 Chen et al. (2021) and Gong and Chen (2024).

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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Box 2

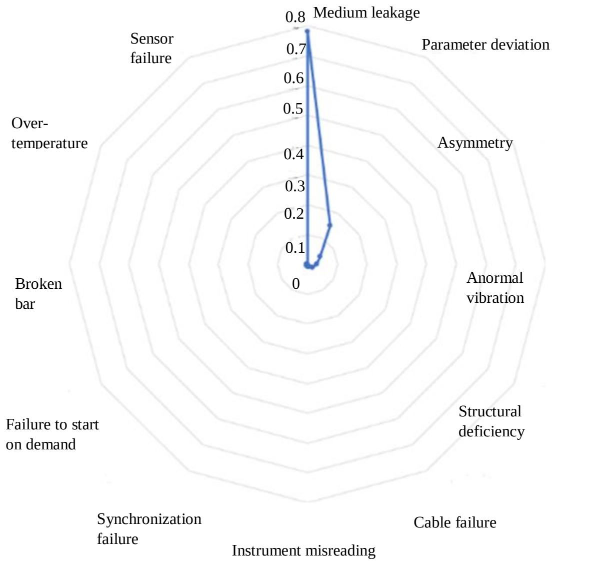

Figure 2
Frequency of failures per year in generator systems
Source: Own Elaboration

The frequency of failures in other wind turbine systems. You can see in Figure 3. These are; pin corrosion 0.28, abrasive wear 0.24, abnormal vibration 0.13, gear fatigue 0.06, bearing pitting 0.06, poor lubricating oil quality 0.04, abnormal filter 0.04, dirt 0.04, gear pitting 0.04, poor gear tooth design 0.04, excessive pressure 0.04, gear tooth deterioration 0.02, tooth surface defects 0.02, sticking 0.019, and overheating 0.018. Ding et al. (2025) and Schouten et al. (2021).

Box 3

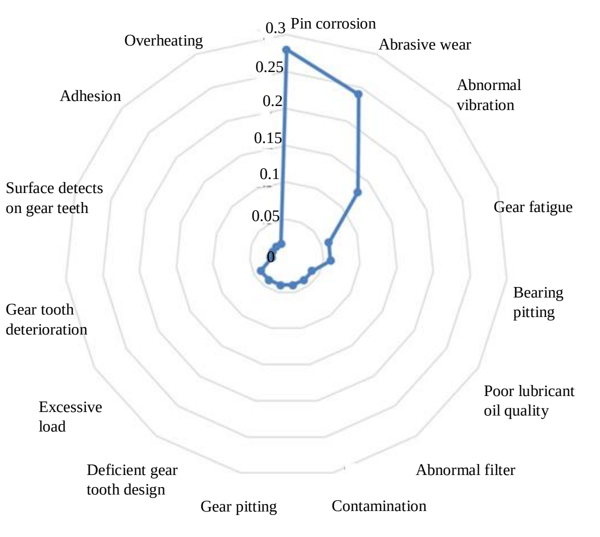

Figure 3
Failure frequency per year of other wind turbine systems.
Source: Own Elaboration

Materials and manufacturing of wind turbine blades

The materials and manufacturing processes used in wind turbine blades must meet low density, high strength, stability, elasticity, and rigidity requirements to ensure optimal aerodynamic performance in the face of lightning strikes, humidity, temperature, and salt and sand storms. Therefore, they are manufactured with glass or carbon fiber reinforcement in a polymer matrix (epoxy or polyester); Covestro and Arkema Elium infusible polyurethane thermoplastic resins for longer blades; sandwich core materials (polyvinyl chloride, polyethylene terephthalate, styrene-acrylonitrile, or balsa wood); bonded joints, cladding (polyurethane), and lightning rods. Material combinations are chosen considering the cost of the vacuum-assisted resin transfer molding manufacturing process and resin infusion technologies.

The geometric nonlinearity of an infusion-manufactured wind turbine blade can cause crack damage that increases with local buckling, the Brazier effect, and large deformations under complex loads in service. The fibers used in blades can be: carbon fibers have greater stiffness and lower density than glass fibers; E-glass fibers; alkali-free, made from calcium alumina borosilicate; S-glass fibers; made from magnesium aluminosilicates; R-glass fibers; made from calcium aluminosilicates. On the other hand, aramid fibers (aromatic polyamide) but with serious disadvantages low compressive strength, low adhesion to polymeric resins; they absorb moisture; they degrade due to ultraviolet radiation. Basalt fibers; 30% stronger, 15-20% stiffer and 8-10% lighter than E-glass; and lastly, and with greater disadvantages, natural fibers; sisal, flax, hemp etc., which are hydrophilic and have poor adhesion to both thermoplastic and thermosetting polymers. Lopez and Kolios (2022).

Wind turbine blade maintenance

Wind turbine blade maintenance ensures their efficiency, safety, and longevity. Regular inspections detect cracks, erosion, lightning damage, and structural integrity. Maintaining aerodynamic performance requires high-tech access and logistics methods with real-time monitoring, such as drones and database transfer via artificial intelligence.

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On the other hand, traditional methods such as ropes (ideal for rapid mobilization for small repairs) and gondolas (carrying more tools and materials for multi-hour jobs), with the associated insecurity, and jack-up or service vessels (onboard workshops for blade changes or heavy repairs offshore). However, traditional maintenance techniques continue to thrive due to maneuvering limitations, maintenance methods that high technologies cannot currently cover. Aafif et al. (2022), Adedeji et al. (2022), Bošnjaković et al. (2025b), Danesh et al. (2025), Kong et al. (2022) and Yan et al. (2023).

Wind turbine maintenance programs begin at the beginning of their useful life in an initial phase of 0-5 years; manufacturing defects are identified, a performance baseline is established, adhesion checks of the leading and trailing edge protection and verification of surface quality are carried out. In the intermediate phase of their useful life, corresponding to 5-20 years, uptime is maximized and wear is addressed.

Finally, in the final stage of their useful life of 20-25 years, conservation maintenance is carried out to allow safe and profitable operation with a view to a decommissioning program aligned with circular economy objectives. Aafif et al. (2022), Adedeji et al. (2022), Begun and Schlickewei (2024), El-Naggar et al. (2023) and Zavvar et al. (2025).

Proactive maintenance in wind turbine blades is an advanced asset management strategy focused on preventing failures before they occur based on identifying and eliminating root causes using historical data and predicts acting when data indicates it, which reduces downtime, improves safety, optimizes costs and prolongs the turbine lifespan. Visual and thermographic drone scans to detect surface erosion, delamination or underground voids, practical checks for leading edge notches, tip rounding, blade balancing, cleaning and recoating to restore the airfoil, patching or composite infusion for surface cracks/delamination, reapplication of erosion resistant coatings are proactive maintenance activities in wind turbine blades. Lopez and Kolios (2022), El-Naggar et al. (2023), Kaewbumrung et al. (2024), Schouten et al. (2021) and Zavvar et al. (2025).

SCADA-integrated wind turbine blade monitoring detects vibration, acoustic/leak sensors, detachments, and cracks early on. Complete routine inspections are performed every 6 to 12 months using drones, depending on the requirements of the database indicators. Maximizing aerodynamic performance directly impacts energy efficiency, as small areas of erosion on the leading and trailing edges reduce production by 1% to 3%. Failure prevention will prevent unplanned shutdowns or catastrophic blade losses.

Drone imaging has revolutionized wind turbine blade inspections. High-resolution visual cameras capture ultra-sharp images (up to 40 MP) of blade surfaces to detect cracks, erosion, lightning, and delamination. Drones also feature infrared (thermal) imaging technologies, which can remotely detect defects in blade coatings and substrates, as well as moisture penetration and bond failures, in the absence of light. LiDAR (Light Detection and Ranging): 3D models of blade geometry to identify deformations. Multispectral imaging: Useful for detecting material degradation or coating wear that is imperceptible to the naked eye. Lopez and Kolios (2022) and LiDAR Technology, n.d.-b, (2025).

Cleaning methods for wind turbine blades

Manual cleaning-washing and repair method; technicians rappel from a suspended rope or an elevated gondola platform, taking advantage of favorable weather conditions. Cleaning is carried out using low-pressure water spray, soft brushes, and mild biodegradable detergents to remove sand, salt, and biological debris adhering to the blade. Techniques include sanding, painting, finish marking, repairing or replacing the erosion shield, filling composite cracks and curing resin, dynamic balancing, efficient water management at remote sites, and completing repair logs. Visually and manually inspecting blades may overlook details or make errors due to fatigue and spatial identification of the fault. Zhang and Tee (2019) and Zhang W. et al. (2025).

Robotic scrubber and drone cleaning method: Self-propelled robots or multi-rotor drones equipped with rotating brushes or ultrasonic transducers can inspect and clean blades autonomously.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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https://doi.org/10.35429/JTO.2025.9.22.2.1.16

By integrating cameras and humidity sensors, they record coverage maps in real time, ensuring thorough blade treatment with minimal human supervision. However, this technique has limitations in cleaning performance due to the variables that influence adhesion removal and the final finish obtained, making it dependent on the manual method. Gong and Chen (2024). Laser ablation cleaning method; is an emerging, non-contact, innovative, and environmentally friendly technique that uses optimized pulsed lasers to vaporize contaminants (bird droppings, oxidation layers) generating a plasma column that emits light, which can be analyzed by breakdown spectroscopy to identify the chemical composition of the dirt without damaging the composite substrate. Laser systems can simultaneously analyze the material composition, providing operators with immediate information on cuticle depth and cleaning effectiveness. This method integrates robotics and drones for remote and automated cleaning, but is still under development, however, it promises to reduce downtime and improve turbine efficiency by up to 40% with faster, safer, and more sustainable maintenance. Adedeji et al. (2022), Begun and Schlickewei (2024), Kaewbumrung et al. (2024) and Zavvar et al. (2025).

Cleaning method: hydrophobic coatings; the application of non-stick films instead of routine low-surface-energy washes facilitates water film cleaning and reduces fouling adhesion by more than 50%. When combined with occasional light cleaning, these coatings extend cleaning intervals while maintaining the blade's aerodynamic efficiency.

Mixed cleaning methods: By combining traditional rope-access washing with robotics, coatings, and even lasers, modern wind farms can keep blades operating at peak aerodynamic performance with less risk, less water consumption, and fewer man hours.

Recommendations: Always follow a documented cleaning-inspection cycle to detect damage early; collect cleaning efficiency data in a maintenance management system to optimize cleaning programs and reduce costs. Use environmentally certified detergents and closed-loop water systems to minimize ecological impact, especially in sensitive landscapes. Abderrahmane et al. (2022) and Dagdag and Kim (2024b).

Remote trajectory capture is Artificial Intelligence.

Drone flight patterns and data capture follow preprogrammed flight paths around each blade (non-destructive, non-contact testing), using GPS and obstacle avoidance sensors to maintain a constant distance and angle. This coverage achieves a 360° sweep by orbiting the turbine and capturing images from multiple elevations and angles. They use AI-based flight control to automatically focus on areas of interest, such as leading edges or known stress zones. Image processing and data analysis are uploaded to cloud platforms where AI algorithms detect anomalies and classify damage types by wear pattern. Results are often visualized in interactive 3D models or digital twins, allowing engineers to analyze defects in greater detail and plan repairs. Standardized flight paths of 30 minutes or less allow blade inspections to be performed while the turbines are still in operation. This ensures a full sweep of consistent data for digital twin analysis. Leon-Medina et al. (2025), Li et al. (2022), Liu et al. (2023), Shah et al. (2024), Yan et al. (2023) and Zeitler et al. (2023).

Optimizing drone route recording using Artificial Intelligence.

Automated route planning is performed using a genetic algorithm that optimizes the shortest and most efficient route to maximize coverage and minimize battery life using dynamic reinforcement learning. Real-time route adaptation and the use of sensors (LiDAR, cameras, GPS) feed AI models with continuous data, enabling instant obstacle detection and avoidance. Drones adjust their trajectories on the fly in response to weather changes, moving objects, or unexpected no-fly zones. Optimal flight sequences reduce inspection times and labor costs. Energy-monitoring algorithms plan energy-efficient trajectories by optimizing swarm coordination to synchronize multiple drones, sharing position data to maintain formations and avoid collisions. Past data and route management optimize machine learning. Vision-based simultaneous localization and mapping in GPS-deprived environments represents one of the maintenance trends for wind turbine blades. El-Naggar et al. (2023), Gong and Chen (2024), Kaewbumrung et al. (2024), Kong et al. (2022) and LiDAR Technology, s. f.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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Artificial intelligence algorithms are programmed to recognize, categorize by type and severity the patterns in thermal images, detecting anomalies such as delamination, moisture ingress and tribological faults, eliminating the need to manually review thousands of images reducing human error and fatigue prioritizing repairs based on risk and urgency under trend analysis and repeatable digital twin integration across turbine batches making it ideal for wind farms with global repeatability. Artificial Intelligence and Machine Learning faces obstacles and challenges such as false positives, data capture assurance, standardization, compatibility between models, "long tail" cases lack of credibility based on the explainable, data privacy, continuous updating and budget injection top state of the art at all times. Albatayneh et al. (2025), Bošnjaković et al. (2025), Ding et al. (2025), Kong et al. (2022), Li et al. (2022), Shah et al. (2024), Sheehan et al. (2025) and Zhang W. et al. (2025).

Remote cleaning analysis and comparison with digital twins

Wind turbine blades accumulate dust, pollen, salt, sand, insects, bird droppings, and soot, especially near deserts, farms, or offshore areas. This buildup hardens the leading and trailing edges, altering the blade's aerodynamic profile. This increases drag, reduces lift, and reduces annual energy production by 2% to 6%, resulting in thousands of dollars in lost revenue per turbine per year.

Uncontrolled surface roughness causes turbulent flow and unstable aerodynamic loads, accelerating blade and powertrain fatigue. The debris becomes a source of corrosion from ice or salt, eroding the composite surface and shortening blade life. Non-destructive testing methods (ultrasound, thermography) require clean surfaces to detect cracks or adhesion defects. A clean blade guarantees accurate condition monitoring. Meanwhile, smart coatings integrate de-icing technologies or hydrophobic surfaces that repel water and prevent ice from adhering. Especially those reinforced with nanoparticles such as graphene, these coatings resist this erosion, preserving lift and reducing drag. The coatings are designed to last longer and self-heal from minor damage, improving aerodynamic performance by maintaining a smooth and clean surface. Zhang and Tee (2019) and Zhang W. et al. (2025).

AI algorithms process real-time data from sensors embedded in or near the blades, measuring vibration, stress, temperature, and acoustic signals. These patterns indirectly help detect anomalies such as cracks, delamination, or ice buildup before they become critical due to changing sensor signal patterns. AI models are run directly on-site using edge computing devices, Artificial Neural Networks (pattern recognition and anomaly detection), Convolutional Neural Networks (for analyzing images and acoustic spectrograms), Fuzzy Logic Systems (uncertainty removal), Genetic Algorithms (natural selection that optimizes inspection programs), and statistical methods, such as Decision Trees (reference modeling and trend analysis), reducing the need to send large amounts of data to the cloud.

This enables faster diagnostics and lower latency in remote wind farms. By learning from historical performance and failure data, AI can monitor, learn, protect, and predict when a blade is likely to need cleaning, repair, or replacement, minimizing downtime and maximizing energy consumption. Liu et al. (2023), Zavvar et al. (2025), and Zeitler et al. (2023).

Proposal for cryogenic cleaning of blades using the dry ice blasting method

Dry ice cryogenic blasting is a cleaning equipment method that offers a powerful and environmentally friendly alternative to laser, sand, soda, and various traditional abrasive methods. Dry ice blasting uses solid CO_2 pellets at -70°C. Upon impact with the surface to be cleaned and pressure changes, they sublimate, removing contaminants without damaging underlying surfaces or leaving secondary residue. Admin (2025b) and Dagdag and Kim (2024).

The pellet size (0.3–3.0 mm) ensures application-specific cleaning performance. Sure, Flow Feed: Vibration agitation and ramrod flow ensure continuous pellet feeding. The insulated hopper or tank maintains pellets at maximum cleaning temperature. Smart Interface: Programmable and monitor real-time performance metrics for consistent results. Non-abrasive and non-conductive: Safe for delicate parts, electrical equipment, and finished surfaces. - Zero secondary waste: CO_2 pellets are vaporized, eliminating media disposal costs.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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Clean-in-place: No disassembly or drying required, less downtime and fewer man-hours. Environmentally friendly: Recycled CO_2 helps companies meet their sustainability goals and promotes a circular economy. Factory air supply or compressor (110V/220V). Hose and nozzle: Variety of diameters and shapes to tailor ice and air flow. Dry ice supply: On-site pelletizer or external supply It is a production system that goes beyond cleaning on-site dry ice production machines that convert recycled CO_2 into pellets, ensuring consistent ice quality and reducing logistics costs. This comprehensive approach integrates shot peening and manufacturing to maximize uptime and sustainability. Admin (2025b).

Custom nozzle designs optimize reach and pattern for complex geometries. Industry-specific applications include mold cleaning for plastics, rubber, and foams, automotive, electrical equipment maintenance, food, energy, nuclear decontamination, aerospace production, surface pretreatment, lead paint removal, restoration, and countless other applications where cleaning must not leave behind additional residue or change the state of matter. Aafif et al. (2022), (International Organization for Standardization, 2017) and Manikowski et al. (2025).

ISO 21072-1:2019, in its general requirements for cryogenic cleaning equipment, covers performance, safety interlocks and materials compatibility cryogenic equipment Doc. EIGA 170/21 design, operation, maintenance. Abderrahmane et al. (2022), Albatayneh et al. (2025), (Cold Jet, 2025), (International Organization for Standardization, 2004) and Cold Jet Dry Ice Production, n.d., (2025).

Dry ice cryogenic cleaning has a higher initial cost than traditional methods but is much lower than laser ablation cleaning. However, it often pays for itself in the long run thanks to reduced labor, downtime, and cleaning costs.

The initial cost of cryogenic cleaning equipment in the global market ranges between $15,000 and $50,000 USD. The operating costs of cryogenic cleaning using CO_2 pellets depend on several factors specific to the industrial process and the resulting product.

Both laser and cryogenic cleaning techniques share the costs of autonomous drones and digital twin technologies. Maintenance and surface wear: Cryogenic cleaning is gentler, reduces long-term maintenance costs, and is environmentally friendly with no chemicals, water runoff, or any type of abrasive to dispose of. Cryogenic cleaning meets all the specifications in industries where uptime and precision are crucial. Abderrahmane et al. (2022), McMorland et al. (2022), and Gonzalo et al. (2022).

A numerical analysis of supersonic flow through dry ice blasting nozzles is based on comparative studies of nozzle designs, particle transport efficiency, and cryogenic cleaning (an effective method for industrial soil removal that treats contaminated surfaces). The dry ice blasting method operates through three main phenomena: thermal effects (cooling), kinetic energy abrasion, and sublimation.

The final force impacting the surface to be cleaned is the sum of three components: the force of the compressed air, the force exerted by the solid CO_2 particles due to their velocity, and the sublimation force resulting from a sudden phase change accompanied by rapid volume expansion. Critical factors in this cleaning mechanism are the system components that influence these parameters: nozzle design and angle of attack adaptable to the geometries of the surface to be cleaned, the effect of dry ice particle size on surface finish behavior, and cleaning mixture parameters.

A simulation of dry ice particle flow in two-phase supersonic flow with particle collisions and mass consumption in the environment, and its behavior in a supersonic nozzle. The observed pressure and velocity profiles (Mach number 1 being supersonic) are typical of a two-phase convergent-divergent nozzle. Particle transport efficiency depends on the nozzle geometry, inlet pressure, and particle size. Nozzle efficiencies exceed 85%, with a maximum efficiency of 91.1% at an inlet pressure of 4 bar. The lowest efficiencies (highest losses) were observed for particles with a diameter of 250 µm. The cleaning zone was defined as a region 15–30 cm from the nozzle exit. Particle velocities range from 50 to 150 m/s, depending on the distance, particle diameter, and nozzle geometry. Admin (2025b) and Todorović (2025b).

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

There are several methods used for the removal of industrial contamination. These methods are divided into physical, chemical, and physicochemical. In this study, dry ice cleaning is an abrasive physical method for removing industrial dirt. A dry ice cleaning system consists of an air compressor, a gas dryer, a dry ice pellet feeder, and a blasting nozzle.

Procedure: Air is compressed and dried, then mixed with dry ice pellets in a mixer. The pellets are fragmented into smaller particles, and the mixture flows through the nozzle, where a pressure change accelerates the solid-gas mixture to high speed and directs it toward the contaminated surface. The cleaning mechanism is based on three main steps: surface subcooling, contamination fracturing due to a decrease in temperature, and dry ice sublimation, with rapid volume expansion, which causes crack propagation of the contaminant and subsequent removal of dirt.

Finally, residual particles are carried out of the cleaning zone by the gas flow. The maximum air pressure does not exceed 16 bar, while the dry ice mass flow rate remains below 200 kg/h. Supersonic two-phase flow nozzles. A dedicated cryogenic cleaning nozzle length optimization in the context of noise generation is presented in Noise Reduction Optimization Admin (2025b), Manikowski et al. (2025) and Todorović (2025b) the properties of dry ice pellets depend on their manufacturing process and their lifetime (interaction with air). See Figure 4.

Box 4

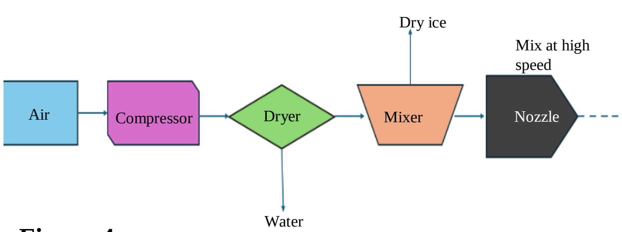

Figure 4

Flow diagram of cryogenic cleaning with dry ice blasting.

Source: Own Elaboration

The safety of dry ice cleaning technology for wind turbine blades using autonomous technologies can be observed in Figure 5. This is a decontamination method with controlled surface erosion, without secondary residues, without phase change of contaminants, and without massive damage to the part morphology.

This method is safe, and the material removal rate can be considered almost zero under method optimization conditions, considering that it influences a controlled surface roughness pattern and that it depends on factors such as; mixture percentages, dry ice particle size, mixing fluid velocity in the nozzle, angle of attack, and application distance, but it does not affect the microstructure of the materials and controls the roughness pattern uniformly. Manikowski et al. (2025).

Box 5

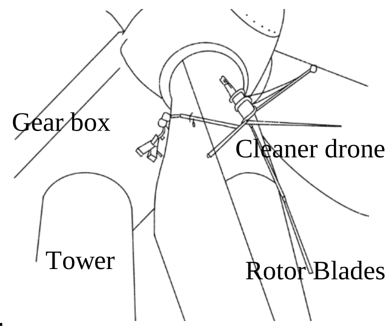

Figure 5

Cryogenic dry ice cleaning of wind turbine blades with autonomous technologies.

Source: Own Elaboration

Previous studies have shown that there are two basic types of contamination: loose contaminants, which usually attach to the surface by weak Van der Waals forces, and fixed contaminants, in the layer of surfaces with adhesion by encrustation to the material. Traditional cleaning methods, shot blasting, cleaning with chemical solvents generate secondary contaminated waste that requires additional decontamination. Radioactive decontamination at the Fukushima nuclear power plant, unmanned vehicles use cryogenic cleaning to remove hazardous chemicals.

The international standards that standardize cryogenic cleaning with dry ice in the aerospace and nuclear industries, where this cleaning method is most developed, are: ASTM D5608; standard practices for decontamination of field equipment used at low level radioactive waste sites (ASTM International, 2019), ASTM E2721; evaluation of effectiveness of decontamination procedures for surfaces (ASTM International, 2016), ISO 17873, nuclear facilities criteria for the design and operation of ventilation systems, ISO 16647; Radiation protection monitoring and clearance of materials from nuclear facilities,

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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China Energy (NB/T20142-2012) Guide for Chemical Decontamination of Primary Loop System and Components of PWR Nuclear Power Plants Admin (2025b) and (International Organization for Standardization, 2017).

Cryogenic cleaning has shown that dry ice decontamination parameters such as pressure, angle and blast time can have a significant impact on the decontamination effect without damage to the substrate, but changing the above parameters can lead to its use as a cleaning medium for maintenance, as it can even cause damage to the material by using it as a removal medium in preparation of new deposition films on composite materials such as graphene, carbon and glass fibres inherent to the substrate in wind turbine blades. Dagdag and Kim (2024b).

The cryogenic dry ice cleaning method is an excellent cleaning method with controlled regulation of material removal that can be used as a means of surface cleaning of contaminants in the form of surface conservation with manufacturer specifications or roughness regulation for surfaces including those with a mirror finish, whose roughness oscillates around 2 μRa, up to being used as a means of removing very high rates of material for repair systems, where it can replace manufacturing processes such as shot blasting, grinding, sanding, etc. that depending on the particle size of the dry ice, the angle of attack of the nozzle, the impact speed of the mixture on the surface to be treated, the distance from the nozzle to the surface and the exposure time of the process, it can be used for the required industrial purposes. Dagdag and Kim (2024b) and (International Organization for Standardization, 2004). You can observe Figure 6.

Box 6

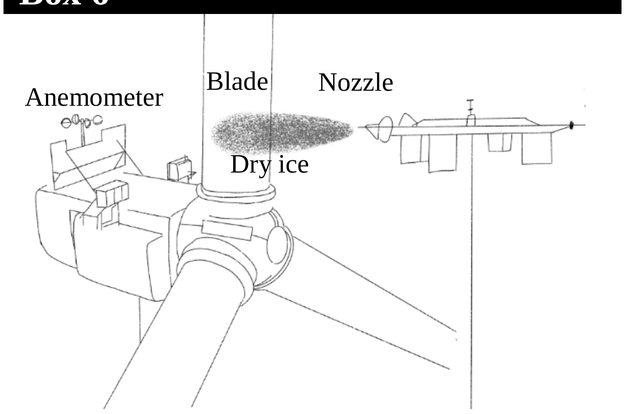

Figure 6
Cryogenic cleaning of blades with parameter control through digital twins.
Source: Own Elaboration

During maintenance tasks, the maximum level of decontamination is sought and damage to components must be minimized to allow their reuse. Previous studies of the cryogenic dry ice cleaning method identified that in cleaning processes without substrate attack on metals and non-metals, the material removal rate was determined to be in the range of [0.5 to 24] g/m². However, very little research has been conducted on polymeric materials and composite materials. Abderrahmane et al. (2022), Admin (2025b), McMorland et al. (2022) and Gonzalo et al. (2022).

To evaluate the erosion damage caused by dry ice blasting on surfaces, a commercial dry ice blasting machine assisted by an air compressor (flow pressure of 0.1–0.9 MPa and volume of 100 L) and a rectangular nozzle (exit dimensions of 25 mm × 5 mm) connected to it by a flexible hose were used as an experimental platform. The dry ice blasting machine receives compressed air from the compressor, which propels the dry ice pellets at high speed through the hose and out of the nozzle, impacting the sample surface. The wear marks, as a function of area and depth, are dependent on process variables such as angle of attack, pressure, dry ice flow, distance, and positioning time in the same area (feed). You can see them in Figure 7.

Box 7

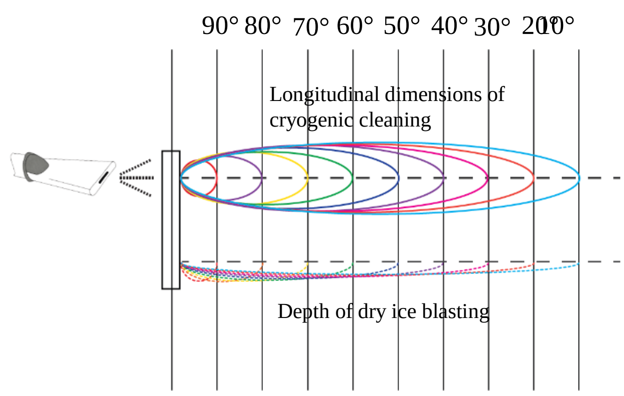

Figure 7
Cryogenic cleaning wear marks.
Source: Own Elaboration

Materials with high coefficients of thermal expansion, such as brass, can experience greater thermal stress during rapid cooling, causing microcracks or surface corrosion. Conversely, materials with lower coefficients of thermal expansion tend to exhibit greater stability and less damage under the same conditions.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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At cryogenic temperatures (below −150°C), carbon fiber is known to have a low or even negative coefficient of thermal expansion in that range, making it ideal for aerospace structures, cryostats, and space telescope components.

On the other hand, composite materials like epoxies can withstand cryogenic shocks of 5–10 min without cracking, carbon-epoxy residual stresses up to 30–50 MPa making them feasible for dry ice cryogenic blasting, maximum CO_2 rate and short shot peening time are recommended with 5 bar pressure and 80 kg/h CO_2 rate, similar residual stresses as low as 0.9 MPa are obtained. Admin (2025b), (Cold Jet, 2025b), Cold Jet Dry Ice Production, n.d., (2025) and Rama et al. (2023).

Exposing a fully cured epoxy to cryogenic temperatures does not cause chemical degradation; -150°C to absolute zero. Common data sheets indicate -55°C remains unchanged at -273°C. What does change is the stiffness: upon cooling, the elastic modulus increases and the material becomes more brittle, which reduces stress on the bonded parts during cooling.

Commercially available cryogenic-grade epoxies EPO-TEK series: 301-2/301-2FL, T7110, EJ2189 are particularly characterized by high shear strength and low thermal stress under cryogenic conditions. Certified adhesives in tensile and shear tests at ~77 K, CTD Cryobond 621, Masterbond EP29LPSP and 3M Scotchweld 2216 showed no failures. (Cold Jet, 2025b), Ding et al. (2025) and Rama et al. (2023).

Wind turbine blades are designed to withstand frigid winds. Typical blade composites (polymers reinforced with glass or carbon fiber) are perfectly resistant down to approximately -30°C to -50°C. Beyond that, in truly "cryogenic" territory (below -150°C), most standard epoxies and polyesters become glassy and very brittle.

In practice, wind farms in Arctic or high-altitude environments mitigate icing and extreme cold with: blade heating systems (electric or hot air), surface coatings that resist ice buildup, and material adjustments that reduce the ductile-to-brittle transition.

High toughness and thermal shock resistance: they maintain their bond without cracking even under rapid temperature drops, application methods: vacuum impregnation techniques and microwave curing, case studies: cryogenic bonds in liquid hydrogen tanks and satellite sensors, nano-reinforcements (graphene, nanodiamond) to improve conductivity and resistance to thermal shock. Admin (2025b) and (Cold Jet, 2025b), Gong and Chen (2024).

Methodology

Develop give the meaning of the variables in linear writing and important is the comparison of the used criteria.

Results

The results shall be by section of the article.

Conclusions

Cryogenic dry ice cleaning represents an advanced technology that meets all the requirements for decontamination and preparation of substrates for new film deposition on wind turbine blades, increasing the efficiency of wind energy utilization. This technique fulfills the objective set forth in this research, which was to propose a cryogenic method for remote cleaning and maintenance of wind turbine blades. Cryogenic cleaning, supported by technologies such as digital twins and autonomous systems, makes it the most promising methodology on the market for cleaning wind turbine blades with minimal invasiveness.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Díaz-Herrera, Sebastián: Participated in developing the research concept, collecting information, and drafting several sections of the article, drawing on his professional expertise.

Cruz-Gómez, Marco Antonio: Assisted in reviewing the manuscript and offered overall improvement recommendations, supported by his professional background.

Mejía-Pérez, José Alfredo: Took part in revising and drafting multiple sections of the article, contributing with his professional knowledge.

Castillo-Pensado, Juan Luis: Collaborated in the review and preparation of several sections, informed by his professional experience.

Availability of data and materials

This work is a review of existing literature, relying solely on previously published sources. No original datasets were produced as part of this study.

Funding

This work was self-funded by the authors.

Acknowledgements

To the Benemérita Universidad Autónoma de Puebla; Engineering Faculty for the support in the use of its infrastructure., To the Tribology and Transport Group, BUAP, for their support in the analysis and development of the work, and 189 Disaster Prevention, Sustainable Development and Tribology Academic body, BUAP.

Abbreviations

3D	Three-dimensional
AI	Artificial Intelligence
ASTM	American Society for Testing and Materials
cm	centimeters
CO_2	Carbon dioxide
EIGA	European Industrial Gases Association
GPS	Global Positioning System
GW	Gigawatts
ISO	International Organization for Standarization
K	Kelvin
Kg/h	Kilograms per hour
L	Liter
LiDAR	Light Detection and Ranging
MP	Megapixels
MPa	Megapascal
SCADA	Supervisory Control And Data Acquisition
USD	United States dollar
UV radiation	Ultraviolet radiation
V	Volts
g/m^2	Grams per square meter
m/s	Meters per second
mm	Millimeters
µm	Micrometers
µRa	Average roughness value (Ra) measured in micrometers (µm)
°	Degrees
°C	Degrees Celsius

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ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Journal of Technological Operations 9[22]1-8: e3922108
Article

Uses of the Ultra-Trak 750 Sensor for ultrasonic flaw detection in machinery and Industrial facilities

Usos del Sensor Ultra Trak 750 para la detección ultrasónica de fallas en maquinarias e instalaciones Industriales

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SECIHTI classification:

Area: Engineering
Field: Engineering
Discipline: Electronic Engineering
Subdiscipline: Electronics device

https://doi.org/10.35429/JTO.2025.9.22.3.1.8

History of the article:
Received: September 30, 2025
Accepted: December 10, 2025

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Abstract

The objective of this paper is to describe the use of the Ultra-Trak 750 sensor for ultrasonic fault detection in industrial machinery and facilities. It presents the sensor's operating characteristics, applications, and limitations. Additionally, the methodology for manufacturing an ultrasonic detector using the Ultra-Trak 750 sensor is also presented, useful for predictive and corrective maintenance. The detector measures the intensity of captured ultrasonic signals in decibels (dB) and converts these signals into audible flow noise that can be heard through headphones. The paper explains how faults in industrial components are detected and identified by measuring the ultrasonic intensity generated during operation. The highest dB readings occur at the fault location, allowing for precise fault identification

Ultrasonic Detector, Ultrasonic Sensor, Ultrasound

Resumen

El objetivo del trabajo es describir cómo se utiliza el sensor Ultra Trak 750 para la detección ultrasónica de fallas en maquinarias e instalaciones industriales. Se presentan las características de operación del sensor, así como sus alcances y limitaciones. Además, se muestra la metodología para fabricar un detector ultrasónico a partir del sensor Ultra-Trak 750, útil para el mantenimiento predictivo y correctivo. El detector ofrece en sus mediciones los decibeles (dB) de intensidad de las señales ultrasónicas captadas y convierte las señales ultrasónicas en un ruido de caudal que es posible escuchar en unos audífonos. Se explica cómo se encuentran e identifican distintas fallas en los elementos industriales, midiendo con el detector ultrasónico, los dB de intensidad ultrasónica que las fallas generan al estar en operación, pues en la posición de la falla, los dB medidos son máximos.

Detector ultrasónico, Sensor ultrasónico, Ultrasonido

Area: Development of strategic leading-edge technologies and open innovation for social transformation

Citation: Duarte-Loera, Jorge, Nandayapa-Alfaro, Manuel de Jesús, Meraz-Méndez Manuel, and Reynoso-Jardón, Elva Lilia. [2025]. Uses of the Ultra-Trak 750 Sensor for ultrasonic flaw detection in machinery and Industrial facilities. Journal of Technological Operations. 9[22]1-8: e3922108.

Introduction

Ultrasound is a type of acoustic sound wave with frequencies above 20 kHz, making it inaudible to the human ear. Its wide range of applications stems from several key characteristics: it can be focused into a beam, follows the laws of reflection and refraction, and can be reflected by small objects. Additionally, ultrasound can propagate through any medium—solid, liquid, or gas and the amount of reflected acoustic energy depends on the acoustic impedance differences within the medium. Ultrasonic waves are transmitted or reflected through materials, a physical principle that enables the detection of faults in mechanical components (Martínez, Vitola, & Sandoval, 2007). In medicine, ultrasound is primarily used to generate two- or three-dimensional images of internal organs in a non-invasive manner (Qiaoliang, et al., 2013) (Yi, et al., 2020) (YONGFENG, et al., 2020).

In engineering, a key application of ultrasound is in non-destructive testing (NDT). NDT encompasses any testing method that evaluates a material without altering its physical or chemical properties, enabling the assessment of product quality (Pulido, 2021). Ultrasound is commonly employed in NDT to inspect and assess the integrity of welds, as well as to detect defects within materials (López, Trujillo, & Parra, 2011). Another significant application of ultrasound is in predictive maintenance, where it is used to monitor equipment conditions and identify potential failures before they occur.

Predictive maintenance is a branch of industrial maintenance that employs specialized techniques and equipment to detect faults in machinery, equipment, and industrial facilities at an early stage. This approach enables maintenance activities to be scheduled within time frames that minimize disruptions to productivity. Common techniques used in predictive maintenance include vibration analysis, infrared thermography, oil analysis, and ultrasonic inspection (Medrano, González, & Díaz de León, 2018).

Ultrasonic analysis is a technique used in predictive maintenance. Using ultrasound, it is possible to detect faults that would otherwise go unnoticed. Based on the principle that faults in machinery and equipment generate ultrasound, faults are detected using an ultrasonic detector.

Since the decibel (dB) reading of ultrasonic intensity displayed by the detector is at its highest at the location where the fault is located, this method is effective.

Ultrasonic fault detection is very efficient, as it locates the exact position of the fault and allows the problem to be pinpointed before it causes interruptions, which can lead to significant economic losses (IMG, 2020). The defects in machinery and equipment that generate ultrasound and that can be located with an ultrasonic detector are leaks of pressurized and vacuum gases in pressurized systems, bearings in poor condition or poorly lubricated, friction between mechanical elements, cavitation in hydraulic systems, and the presence of electric arcs in motors, transformers, and installations (Preditec, 2023).

In predictive maintenance, ultrasonic detectors are employed to measure the intensity of ultrasonic emissions in decibels (dB). Faults are identified at locations where the measured dB values peak, indicating the presence of abnormal conditions (Preditécnico, 2012; Medráno, González, & Díaz de León, 2018).

The ultrasonic detector displays the dB reading on a meter and converts the ultrasound into an audible frequency, which is heard through headphones as a flow noise. Figure 1 illustrates a technician measuring the ultrasonic intensity, in decibels (dB), emitted by an electric motor using a generic industrial ultrasonic detector.

The technician is also listening to the ultrasound as flow noise through headphones (IMG, 2020). An ultrasonic detector is a valuable predictive maintenance tool that every company should have. However, not every company can afford this equipment due to its high cost.

The purpose of this article is to describe how to build a more affordable ultrasonic detector for predictive maintenance, using the Ultra Trak 750 sensor.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Duarte-Loera, Jorge, Nandayapa-Alfaro, Manuel de Jesús, Meraz-Méndez Manuel, and Reynoso-Jardón, Elva Lilia. [2025]. Uses of the Ultra-Trak 750 Sensor for ultrasonic flaw detection in machinery and Industrial facilities. Journal of Technological Operations. 9[22]1-8: e3922108.
https://doi.org/10.35429/JTO.2025.9.22.3.1.8

Box 1

Figure 1
A technician using an ultrasonic detector on an electric motor

(IMG, 2020)

Methodology

A. Ultra Trak 750 ultrasonic sensor

The UE Ultra-Trak 750 is a contact ultrasonic sensor manufactured by UE Systems Inc. It is designed to detect structure-borne ultrasound and is configured for continuous monitoring of changes in ultrasonic intensity, measured in decibels (dB), captured by the sensor's probe. The device operates within a frequency range of 20 kHz to 40 kHz, detecting ultrasonic intensities from 0 dB to 60 dB, with an overall dynamic range of approximately 100 dB. It offers a maximum measurement tolerance of ±2%

The sensor is powered by a direct voltage supply ranging from 18 V to 30 V and consumes between 0 and 30 mA, depending on the detected dB level. Sensitivity can be set to maximum or adjusted manually, or via a TTL signal operating between 1 and 5 Hz. The Ultra-Trak 750 also features an audio output that converts ultrasonic signals into audible sound through heterodyning. This output has a bandwidth of approximately 2 kHz, delivers a low-level signal of around 100 mV, and has an output impedance of approximately 100 Ω (USER_UT750, 2023). Figure 2 shows the Ultra-Trak 750 ultrasonic sensor (IMG, 2020).

Box 2

Figure 2
Ultra Trak 750 ultrasonic sensor

(IMG, 2020)

The sensor is operated through seven distinct color-coded cables. Table 1 presents the corresponding cable connections and their functions (USER_UT750, 2023).

Box 3

Table 1
Ultra Trak 750 wires connections

Color	Función
Black	Ground
Red	Power supply, range between 18 and 30VDC
Yellow	Audio output
Blue	Maximum or adjustable sensitivity mode
Orange	Manual sensitivity adjustment
Green	TTL sensitivity adjustment, signal between 1 and 5 Hz
Brown	0 to 30mA output. Maximum ground connection for energized operation jump

(USER_UT750, 2023)

Figure 3 illustrates the recommended sensor connection configuration for converting the captured ultrasonic signal into a corresponding voltage signal (USER_UT750, 2023).

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Duarte-Loera, Jorge, Nandayapa-Alfaro, Manuel de Jesús, Meraz-Méndez Manuel, and Reynoso-Jardón, Elva Lilia. [2025]. Uses of the Ultra-Trak 750 Sensor for ultrasonic flaw detection in machinery and Industrial facilities. Journal of Technological Operations. 9[22]1-8: e3922108.
https://doi.org/10.35429/JTO.2025.9.22.3.1.8

Box 4

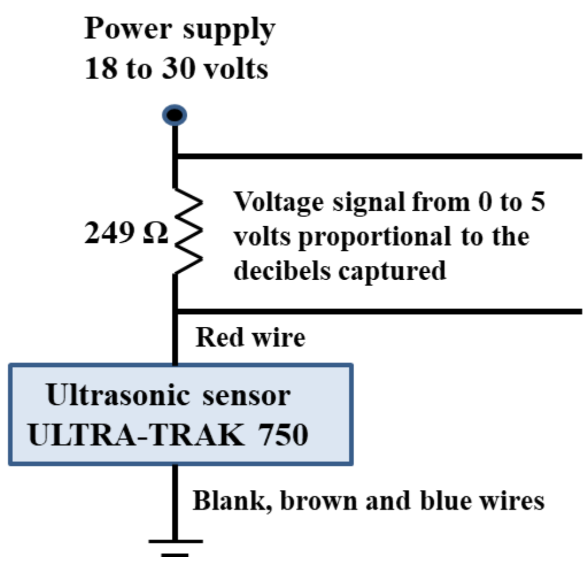

Figure 3
Conversion of the ultrasonic signal into a voltage signal
(USER_UT750, 2023)

The manufacturer provides the sensor transfer function, which is represented by equation 1. With this formula, the dB of ultrasonic intensity detected is calculated from the output current of the internal current source of the ULTRA-TRAK 750 sensor (USER_UT750, 2023).

$$dB = 2.4403\, I_s - 6.5144 \quad (1)$$

where:
dB = decibels of ultrasound detected
I_s= current consumed by the sensor in mA

The current I_s is converted to a voltage V_s by passing it through a 249 Ω resistor according to Ohm's law (Rela, 2010) and is described by equation 2.

$$V_s = 249\, I_s \quad (2)$$

B. Ultrasonic detector based on the Ultra-Trak 750 sensor

Figure 4 presents a block diagram of an ultrasonic detector design based on the Ultra-Trak 750 sensor. The probe, which is in direct contact with the surface of the element being measured, is threaded onto the Ultra-Trak 750 ultrasonic sensor. A regulated 24 VDC power supply is used, providing at least 100 mA. The positive terminal of the power supply energizes the sensor's blue wire to activate maximum sensitivity mode and powers the red wire through a 249 Ω current-limiting resistor.

The black and brown wires connect to the negative terminal of the power supply. The ultrasonic signal captured by the Ultra-Trak 750 is converted into a high-impedance audible signal, accessible via the yellow wire. This audio signal is then amplified and routed to headphones, enabling the operator to hear the ultrasonic emissions as a flow-like noise.

The voltage drop across the 249 Ω resistor produces an analog signal with a maximum amplitude of 5 V, proportional to variations in the intensity of the captured ultrasonic waves, measured in decibels (dB) (USER_UT750, 2023). This signal is fed into a differential analog input of the NI USB-6008 data acquisition (DAQ) card, where it is digitized at a sampling rate of 10,000 samples per second with 12-bit resolution (USER_USB-6008, 2021). The digitized data are transmitted via USB to a laptop for processing.

The laptop must have software installed that allows data acquisition and processing, and that presents, as results, a graph of the measured dB and the average dB value for each measurement taken. For example, it could be LabVIEW, Matlab, or another software. An algorithm written for this software is responsible for controlling the correct operation of the ultrasonic detector and is shown in Figure 5. As indicated in Figure 5, a 2-second measurement is taken at a point on the element. The algorithm configures the USB-6008 to acquire 20,000 data points at a rate of 10,000 samples/second. The acquired data are stored in the data vector *R(n)*, as indicated by equation 3 (Proakys & Manolakys, 2007).

$$R(n) = \{R(0), \dots, R(19{,}999)\} \quad (3)$$

Equation 4 is derived from Equations 1, 2, and 3, and is used to calculate the vector *dB(n)*, which contains the decibel (dB) values corresponding to each data point in *R(n)*. The variable *offset* represents the zero deviation of the ultrasonic detector, which in this case is 5 dB.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Box 5

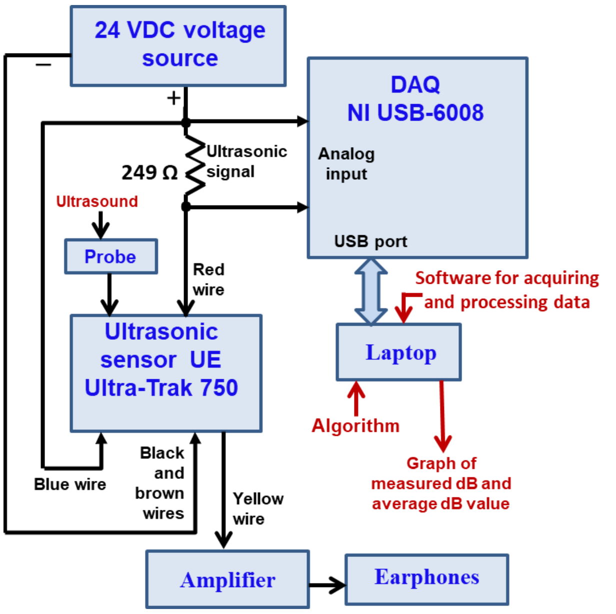

Figure 4
Ultrasonic detector with Ultra Trak 750 sensor

Box 6

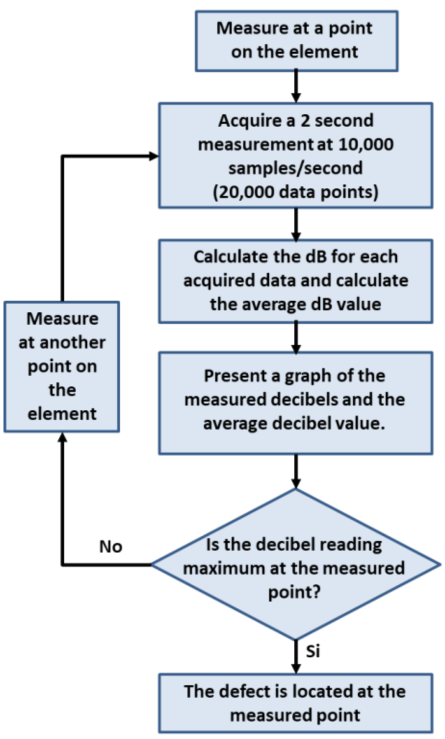

Figure 5
Ultrasonic detector algorithm

$$dB(n) = \frac{(2.4403)(1000)}{249}\,R(n) - 6.5144 - offset \qquad (4)$$

The variable dB_{prom} is the average dB value of the measurement and is calculated with equation 5 (Proakys & Manolakys, 2007).

$$dB_{prom} = \frac{1}{19{,}999} \sum_{n=0}^{19{,}999} dB(n) \qquad (5)$$

The algorithm displays the results as a graph of the vector *dB(n)* along with the value of the variable dB_{prom} . If the average dB reading reaches its maximum value, the defect is considered to be located at the measured point. Otherwise, a new measurement is taken at a different location, and the process is repeated until the condition is satisfied.

Results

Figure 6 illustrates an ultrasonic detector developed using the proposed methodology. The components shown include the Ultra-Trak 750 ultrasonic sensor with its probe mounted to the sensor, the USB-6008 module for data digitization, a regulated 24 VDC power supply, and an audio amplifier. The detector also features a headphone jack, which delivers an audio signal proportional to the captured ultrasonic emissions.

Box 7

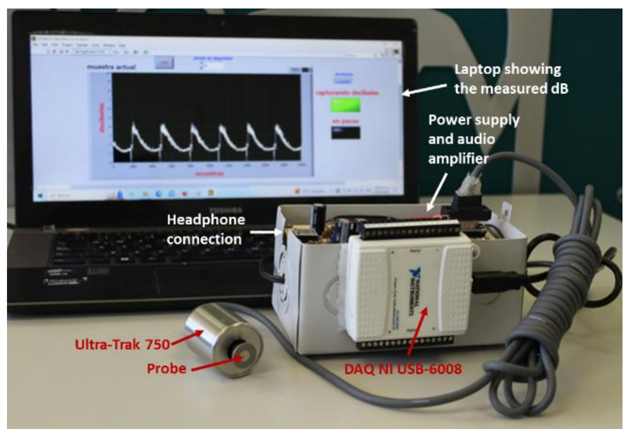

Figure 6
Ultrasonic detector with Ultra Trak 750 sensor

Figure 7 displays the results of a measurement performed by the ultrasonic detector during a bearing inspection. The graph presents the recorded dB values over a two-second interval, along with the calculated average value of 32.7149 dB. The figure also shows the ultrasonic sensor's probe in contact with the bearing surface during the measurement.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Box 8

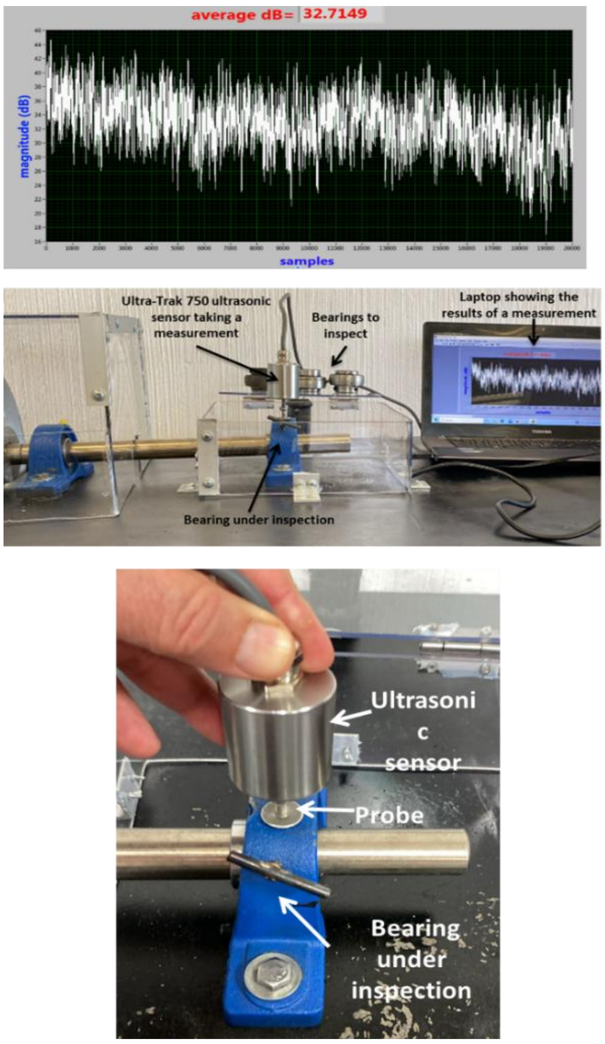

Figure 7
Ultrasonic detector developed by measuring a bearing

Table 2 presents measurements taken at different distances along a section of compressed air-pressurized pipe with a leak point. The average dB measured is highest at the leak point (40 dB) and gradually and considerably decreases before and after the leak point. The leak point has the highest reading, allowing for its detection.

Box 9

Table 2
Average decibels measured in a compressed air pipe that leaks

Position of the measurement taken	Average decibels measured
40 cm before the leak point	7 dB
20 cm before the leak point	9 dB
10 cm before the leak point	15 dB
5 cm before the leak point	32 dB
At the point of the leak	40 dB
5 cm after the leak point	29 dB
10 cm after the leak point	13 dB
20 cm after the leak point	7 dB

Conclusions

The introduction of the document outlines the fundamental characteristics and properties of ultrasound, emphasizing its relevance in engineering applications and its role in predictive maintenance. It indicates how various faults in machinery and industrial equipment can be located using an ultrasonic detector by scanning the dB of ultrasonic intensity at different points on the element under inspection. It also indicates how the fault position is located at the location where the average dB measured is highest.

The methodology outlines the technical specifications of the Ultra-Trak 750 ultrasonic sensor, including its detection range, maximum measurement tolerance, and transfer function. A block diagram is provided to illustrate the development of an ultrasonic detector for predictive maintenance using this sensor. Additionally, the methodology presents and explains the algorithm used to create the executable program that governs the operation of the ultrasonic detector.

The results show an ultrasonic detector manufactured using the proposed methodology, its parts, and the graph and average dB values shown as the results of the ultrasonic detector's measurements. A reading taken from a bearing under inspection is also illustrated, and an explanation is given of how a leak point is in a section of compressed air-pressurized pipe based on several measurements taken with the developed ultrasonic detector. The leak point is located where the measured dB values are highest.

The proposed ultrasonic detector is a valuable tool for predictive maintenance, allowing for early detection of defects. It is also more affordable than a generic ultrasonic detector.

Declarations

Conflict of interest

The authors declare no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

Author contribution

Jorge-Duarte, Loera. PhD: He contributed to the project idea, the research method, the development of electronic circuits, and the development of the algorithm.

Nandayapa-Alfaro, Manuel de Jesús. PhD: He contributed to the research method, the development of electronic circuits, and the development of the executable program.

Reynoso Jardón, Elva Lilia. PhD: She contributed to the literature review, the design and validation of the ultrasonic detector, and the translation of the document into English.

Meraz-Méndez, Manuel. PhD: He contributed to the literature review, the design and validation of the ultrasonic detector, and the translation of the document into English.

Availability of data and materials

Laptop, Ultrasonic Sensor, Ultra Trak 750, Electronic Material, and LabVIEW 2020 Software.

Acknowledgements

The authors express their gratitude for the support received in various areas from the Technological University of Chihuahua (Department of Industrial Maintenance Engineering) and the Autonomous University of Ciudad Juárez (Institute of Engineering and Technology).

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Journal of Technological Operations 9[22]1-11: e4922111
Article

Reducing setup times in the sandblasting process of an aerospace industry

Reducción de tiempos de preparación en el proceso de arenado de una industria aeroespacial

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SECIHTI classification:

Area: Engineering
Field: Engineering
Discipline: Industrial Engineer
Subdiscipline: Manufacture

https://doi.org/10.35429/JTO.2025.9.22.4.1.11

History of the article:
Received: September 19, 2025
Accepted: December 10, 2025

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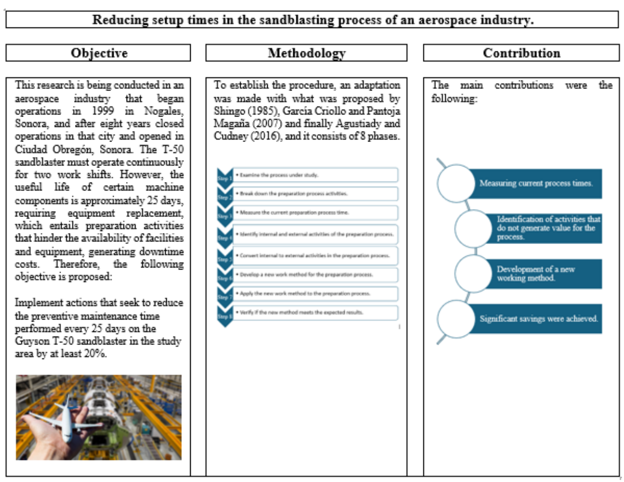
Abstract

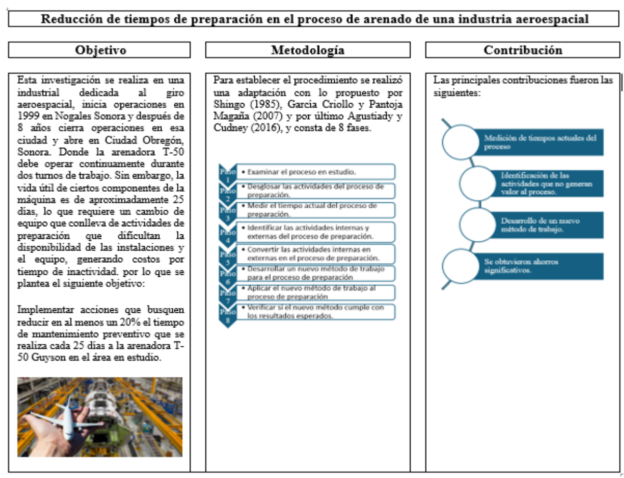
This research demonstrates the benefits of applying the SMED tool by reducing the time required for equipment setup. The process addressed is the sandblasting process of an aerospace component manufacturing company, which receives preventive maintenance every 25 days. The recorded times vary greatly depending on the worker performing the maintenance process, so the objective was to implement actions that seek to reduce preventive maintenance time by at least 20%. The results clearly show an improvement in time reduction from 8 to 4.5 hours, equivalent to 42 hours for a total of 12 annual maintenance operations, saving $2,216 USD.



SMED, setup, lean manufacturing

Resumen

Esta investigación muestra los beneficios de la aplicación de la herramienta SMED al reducir el tiempo necesario para la configuración de los equipos. El proceso abordado es el proceso de arenado de una empresa de fabricación de componentes para la industria aeroespacial la cual recibe mantenimiento preventivo cada 25 días. Los tiempos registrados varían en gran medida dependiendo del trabajador que realiza el proceso de mantenimiento por lo cual se estableció como objetivo Implementar acciones que busquen reducir al menos un 20 % el tiempo de mantenimiento preventivo. Los resultados hacen evidente la mejora en la reducción del tiempo de 8 a 4.5 hrs equivalentes a 42 hrs por una cantidad de 12 mantenimientos anuales con un ahorro de $2,216 USD.



SMED, tiempo de cambio, manufactura esbelta

Area: Development of strategic leading-edge technologies and open innovation for social transformation

Citation: Cano-Carrasco, Adolfo, González-Mendivil, Manuel Antonio, Fornés-Rivera, René Daniel and Cañez-Barraza, Roberto. [2024]. Reducing setup times in the sandblasting process of an aerospace industry. 9[22]1-11: e4922111.

Introduction

Sonora has the second largest aerospace cluster in the country, behind only Querétaro, however, it has a particularity that makes it more competitive: the Megaregion. Sonora and Arizona share economic, social, cultural, educational, and security relations, making them main trading partners. Sonora has 69 established companies in the aerospace sector, which are located in various municipalities. In Ciudad Obregón, there are two companies dedicated to aircraft maintenance and repair, Radiall, while the second is QET Tech Aerospace (Bahena, 2021). In the research carried out to characterize the aerospace industry in Mexico and determine the challenges of the Sonora region (Vázquez and Bocanegra, 2018), the following findings are presented: The vast majority of aerospace companies operate with flexible manufacturing and constant innovation, which is why more sophisticated machinery is acquired that allows multiple operations to be performed to save time and thus respond to the needs of high production levels. Another characteristic of the aerospace industry that becomes evident is the high number of part numbers that must be run in the processes while responding in high or low volume according to the needs of the client.

Another aspect on which the production strategy of this industry is based is the reduction of changeover or preparation time to the maximum through SMED techniques (single minute exchange of die), in which one of the companies achieved a reduction in preparation time from 45 min to 15 min. Another fact is that these companies invest in motivating their staff to seek innovation in production processes to avoid waste and be more competitive.

On the other hand, in a research carried out by Chávez (2021) on lean manufacturing practices and their level of implementation, it was observed in a sample of companies from different electronic, automotive, aerospace, medical and other sectors; in which the levels of implementation in the different lean manufacturing practices there are similarities in many of the applied techniques, mentioning them from highest to lowest level of implementation are 5s, visual management, standard work, continuous flow, cellular distribution, VSM (Value Stream Map), level production, TPM (Total Productive Maintenance), SMED;

The practices with differences in the degree of implementation in the group of companies studied were Quality at the source, milestone system and Jidoka.

This project is developed in a company that manufactures high-reliability interconnection components for numerous industries such as aerospace, defense, medical and telecommunications.

In 1999, the company began operations in Mexico in the city of Nogales, Sonora. After eight years, it closed its operations in Nogales to resume operations in Ciudad Obregón. In 2007, it continued its operations of part machining and cable and switch assembly. It wasn't until 2009 that the third plant, responsible for the platinum plating process, opened. Beginning in 2011, the company dramatically increased its workforce, thus obtaining NADCAP (National Aerospace and Defense Contractors Accreditation Program) certification in 2016.

It has several departments within 35,052 m2, with more than 900 employees distributed in diverse areas such as multipin, machining, SW-FO, HR, maintenance, plating, CA-CO-AN, quality, Lean and engineering and technology. Within the organization under study, there are three industrial warehouses: final assembly, machining, and plating, warehouses one, two, and three respectively. These areas have the capacity to produce a wide variety of products, including: multipin connectors, antennas, radio frequency assembly cables, radio frequency coaxial connectors, switches, and fiber optic cables. Multipin connectors must be processed by the plating area to comply with regulatory requirements.

All products produced in the plating area begin with the sandblasting process, where the parts are brought from machining, then after the plating process they go to final assembly and are then packaged. The purpose of the sandblasting process is to increase the roughness of the part so that the chemicals to which the part is subsequently subjected can adhere more easily. This process is carried out using the Guyson T-50 Sandblasting Machine (see figure 1). This machine fires high-pressure sand jets to wash plastic parts and is fed with 25 kg bags through a feed hopper.

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The sandblaster receives preventive maintenance every 25 days. Recorded times vary greatly depending on the worker performing the maintenance process, and each worker performs it using a personalized method, without following standardized instructions.

Box 1

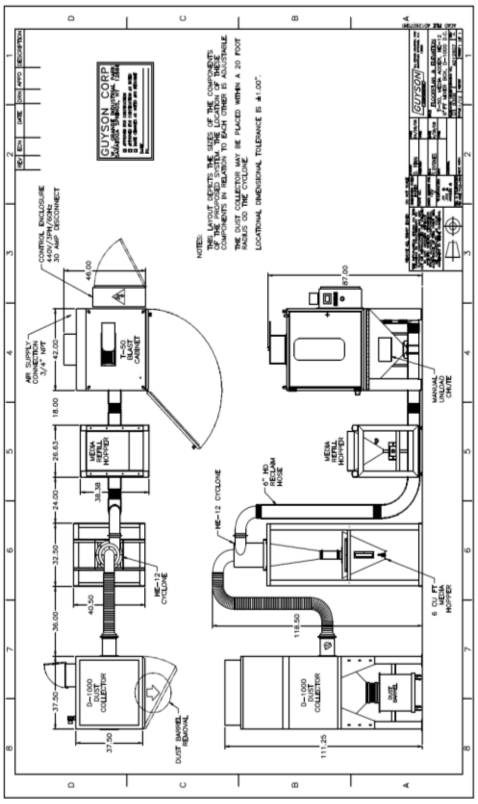

Figure 1
Technical diagram of the T-50 Guyson sandblaster.
Source: T-50 Guyson Sandblaster Operation Manual (2019).

In the case of the sandblasting process, the T-50 Sandblaster must operate continuously during two work shifts. However, the useful life of certain components of the machine is approximately 25 days, requiring a consequent changeover that entails preparation activities that impede the availability of the facility and equipment, generating downtime costs. This leads to the following question: What actions should be taken to reduce the setup time of preventive maintenance performed on the Guyson T-50 Sandblaster every 25 days by at least 20%?.

Objective

Implement actions that seek to reduce by at least 20% the preventive maintenance time performed every 25 days on the T-50 Guyson Sandblaster in the area under study.

Theoretical Framework

The need to reduce batch changeover times arises as customer purchasing habits change, with customers seeking greater product variety and smaller batch sizes. Therefore, time is seen as an aspect requiring special attention. With the priority of maintaining competitiveness in the face of new market characteristics, there are two options: either reducing changeover times to work with a greater variety of products and parts in small batches, or continuing to produce large batches, which leads to increased inventory levels and associated maintenance costs (Morant, Gisbert, Pérez, & Perez-Bernabeu, 2020).

The one-minute setup time methodology and other lean production tools such as 5S, visual management, and work standardization could be applied to reduce the setup times observed at the beginning of the project (Saravanan, Nallusamy, & Balaji, 2018).

Considering that every wasted minute represents inefficiency, rapid changeover times are very important in manufacturing and are a necessity today in all types of industries to address issues such as a changing demand environment and a need for high-quality product differentiation and rapid delivery at low prices. One-minute changeover time reduction (SMED) is a methodology developed by Shigeo Shingo in 1985, which seeks to reduce machine setup time to less than ten minutes (Shingo, 1985).

It provides a fast and efficient way to convert a manufacturing process from one running product to the next (Tharisheneprem, 2008), with the goal of reducing setup time for industrial machinery, given the flexibility of the product and its characteristics. Among the benefits reported by implementing the SMED methodology are reduced changeover time, reduced waste, and increased quality, as well as the possibility of flexible and low-cost operations (Cakmakci, 2007).

Quick setup changeovers (SMED) and other alternative methodologies aim to reduce the time required for equipment setup, minimizing shop floor downtime. It is an efficient way to shift a manufacturing process from producing a current job to producing a subsequent job. This, in turn, enables the production of increasingly smaller batches.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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Single-minute die exchange (SMED) focuses primarily on recognizing internal and external activities (Talekar, Patil, Shinde, & Waghmare, 2019). Taking two consecutive operations as a reference, the setup time is the time that elapses between the output of the last product of A and the output of the first product B, recognized as SMED (single minute exchange of die). Its distinction in lean manufacturing is relevant, according to (Saravanan, Nallusamy, & Balaji, 2018) the phrase "one minute" does not mean that the configuration or change is carried out in one minute, but that the change is carried out within a period of one digit in minutes, that is, in ten minutes.

There are two types of setups: internal and external. Internal setup activities are those that can only be performed while the machine is stopped, such as mounting and dismounting dies, etc., and external setup activities are those that can be performed while the machine is running, such as transporting dies, collecting wrenches and bolts, etc. The basic idea is to perform as many activities as possible internally.

Both shot peening and sandblasting are leading methods among modern surface treatment methods. They are generally used for surface treatment of various objects, structures, and installations before applying an anticorrosive coating. They are also used for removing old protective coatings, removing corrosion, obtaining the desired surface texture, treating injection molds, deburring molding machine parts, etc. (Woźniak, 2013).

The abrasive media used are selected to ensure that the abrasives are so soft that they can remove layers of the surface without affecting its structure; they are selected to ensure that they are harder than the removed layer, but softer than the surface (Woźniak, 2013).

Methodology

Object

The object under study was the preventive maintenance process that is carried out every 25 days in the T-50 Guyson Sandblaster in the plating area.

Materials

During the method development stage, different materials and tools were used with the purpose of documenting the process under study, as well as measuring different magnitudes, among which are:

- A digital stopwatch was used to time the activities performed in the preparation processes.

- Microsoft Office was used to create spreadsheets with the times and the layout of the study area.

- A measuring tape was used to measure the area of the process under study.

- A 25-day preventive maintenance process instruction sheet was used to understand the process under study.

- A Setup Operations Analysis Chart format sheet was used to facilitate the organization of the information obtained through the time study.

Procedure

The selection of the procedure to be used was obtained from Shingo (1985), García and Pantoja, (2007) and finally Agustiady and Cudney, (2016).

1. **Examine the process under study:** The preparation process carried out by the technicians was identified using the instruction sheet that describes the preventive maintenance procedure. With the information obtained, a flowchart was created that summarizes the process under study.

2. **Break down the preparation process activities:** The activities described above were broken down into their component steps, resulting in a list of all the activities carried out during the preparation process.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

3. **Measure the current preparation process time:** Time measurements were taken for each of the activities that make up the preparation process, using the Freivalds and Niebel criterion (2014), which considers timing three cycles for those activities that last more than 40 minutes. The result was a table with the times required to carry out the preparation process, as well as the times of the individual activities that make up the same, along with a spaghetti diagram.

4. **Identify internal and external activities of the preparation process:** The activities obtained in the previous step were examined and together with the analysis carried out on site, it was identified under Shingo's criterion (1985) whether the activities are internal, external or non-value-added activities, in order to facilitate the process of converting from internal to external.

5. **Convert internal to external activities in the preparation process:** An evaluation was conducted of the activities identified as internal to be converted to external activities. An attempt was made to reduce the time of internal activities by considering whether the activity could be modified. Furthermore, activities that did not provide added value were eliminated. The result was a list of proposed activities to form a new work procedure.

6. **Develop a new work method for the preparation process:** Once the improvement proposals for conforming the work procedure were identified, they were organized in a certain order according to the specifications of the organization under study, as well as documented under specific criteria, as a result, a new work instructions manual was obtained.

7. **Apply the new work method to the preparation process:** The equipment preparation process was carried out using the new work method, and time measurements were taken for the activities comprising the procedure. As a result, the times for each activity comprising the new work method were obtained on a time study sheet.

8. **Verify if the new method meets the expected results:** A comparison was made between the current and proposed procedures in relation to the execution time to conclude if the expected results were met, a spaghetti diagram was used to visualize the transfers, as well as a financial analysis was carried out evaluating the feasibility of the proposal.

Results

Below are the results obtained from each of the steps established in the method, necessary to achieve the objective of this research.

1. **Examination of the process under study:** The process under study was analyzed by finding its main activities using the instruction sheet that the company already had. Figure 1 shows the diagram obtained (see Figure 2).

Box 2

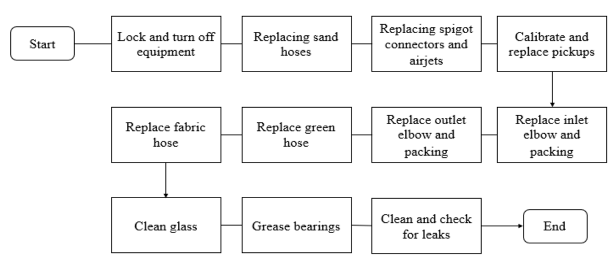

Figure 2
Flowchart of the process under study.
Source: Own elaboration.

Figure 2 shows the process under study defined in a flow diagram, the process is performed by a single maintenance technician, all activities related to the process are performed on the same day, at the same time. The process begins with the technician arriving in the morning, locking the equipment with a padlock to prevent accidental activation. Then, he replaces the hoses and their respective connectors. Calibrating the pickups is absolutely necessary, so the technician is responsible for this. When the technician replaces the inlet and outlet elbows, the cyclone is removed. Using through-bolt hardware, it won't tighten without the corresponding nut, making it necessary to insert a hand into the cyclone to connect the nut to the bolt. After this, the green and fabric hoses are replaced, the cabin window is cleaned, and the motor is greased. The final step is to clean the area and ensure the machine is leak-free.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

2. Breakdown of preparation process activities: Of the general activities of the process, each of them was broken down and the following list was obtained.

1. Turn off and lock out equipment
2. Clean the booth
3. Cut sand hoses
4. Replace sand hoses
5. Replace barb connectors
6. Replace airjets
7. Connect pickup
8. Replace door gasket
9. Replace glass gasket
10. Check handle
11. Replace inlet elbow
12. Replace cyclone door gasket
13. Replace fabric hose
14. Replace outlet elbow
15. Replace upper hopper gasket
16. Replace green hose
17. Empty sand
18. Replace lower hopper gasket
19. Add sand
20. Grease bearings
21. Clean equipment
22. Check wiring
23. Perform leak test

In addition to the previous activities, each of these activities is composed of smaller activities but which would be represented in such a short time that it was considered to include them so that they are integrated into the activities previously described.

3. Current process time: Once time measurements were made on three dates in which the activities of the process under study were executed (see appendix 1), the results obtained were condensed in the following table (see Table 1).

Box 3

Table 1

Total time required to carry out the process under study

Moments when times were taken	Total time in hours
First day	10:03 (ten hours and three minutes)
Second day	8:04 (eight hours and four minutes)
Third day	8:00 (eight hours)

Source: Own Elaboration

Table 1 shows the time required to carry out the process under study. There is a two-hour reduction in time, since the first-time measurement was performed on activities belonging to another process. In addition to the above, it must also be considered that a good part of the time taken by the process is used in unnecessary trips by personnel, the same trips shown in the spaghetti diagram in Figure 3.

Box 4

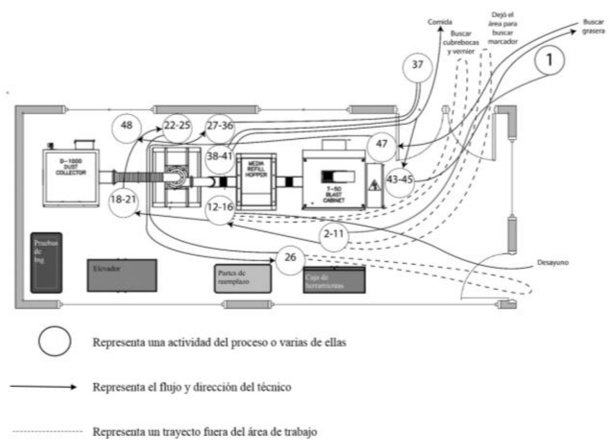

Figure 3

Spaghetti diagram of the process under study

Source: Own Elaboration.

Figure 3 shows the study area in an elevation view. The sandblaster is located at the top of the diagram, while the cabinets containing the replacement parts are located at the bottom. The diagram begins with activity number one of the processes, which consists of bringing in the replacement parts and arranging them. The technician then works in the booth where activities two through eleven are displayed, where the red hoses are replaced. The dotted lines represent when the technician leaves the area to retrieve tools or instruments, and the arrows indicate the direction. It is important to note that the spaghetti diagram was created based on the time readings taken on the second day of timekeeping.

4. Identification of internal and external activities: Time tracking provided a better view of the activities involved in the process under study. The Setup Operations Analysis Chart format in Excel was used to identify each activity as internal, external, or waste.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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In the current state of the preparation process, it is found that of the 49 total activities that make up the process, 42 are internal, which means that most of the activities are done with the equipment stopped, no activity is external and seven are waste, that is, activities that do not add value to the process (see appendix 2).

5. Conversion of internal activities to external ones: Using the previous format and with the help of the maintenance supervisor, ideas were generated to improve the process under study, which are observed in appendix 2.
The elements fall into three distinct categories: Eliminate, Internal to External, and Reduce. Under Shingo's (1985) methodology, all activities that can be performed outside the setup process should be performed in advance, and all those that, due to their nature, require the machine to be shut down should be reduced, as they cannot be performed before starting the setup process or eliminated.

Some of the ideas established for improving the process under study conclude that fetching replacement parts or, in general, moving from the area to look for a tool is a waste of time and therefore should be eliminated. Other activities, such as cutting replacement hoses, can be done in advance by another technician or the technician himself, leaving the parts ready in the area the day before. The same applies to connectors and calibrations of external parts.

6. Development of a new work method: With the improvements established, a new procedure manual was created, eliminating all unnecessary activities. This manual was approved by the maintenance supervisor. The cover of the manual is shown in Figure 4.

Box 5

Figure 4
New procedure manual
Source: Own Elaboration

In Figure 4, there is a screenshot of the first three pages that make up the new manual for the process under study. For confidentiality reasons, it was not possible to include the entire document.

7. Application of the new work method: The new work method was applied in the preparation process two months after the third time measurement. This led to a new time study in which a difference in the number of activities carried out by the technician can be seen, with fewer of them now, going from 49 activities to 26. In addition, thanks to the improvements introduced, the activities that are unavoidable now have a shorter duration (see appendix 3).

8. Verify whether the new method meets the expected results: Comparing the times of the process under study before and after applying the new method, the following table was obtained (see Table 2).

Box 6

Table 2
Comparison between the times of the process under study before and after applying the new method

Current time	Time with the new working method
8:00 (eight hours)	4:29 (four hours and twenty-nine minutes)

Source: Own elaboration.

With the information shown in Table 2, it is possible to appreciate the gap that exists between the current time and the time used with the new method. The process time with the improvements represents a reduction of 44%, thus meeting the established objective of at least 20%. Since the process changed, the spaghetti diagram was also updated as shown below in Figure 5.

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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Box 7

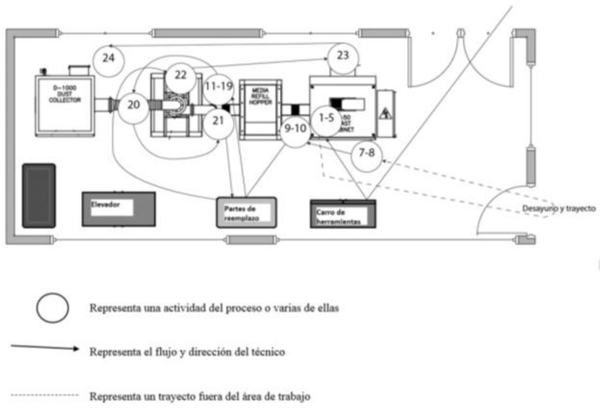

Figure 5

Updated spaghetti diagram.

Source: Own Elaboration.

Figure 5 above shows an elevation plan of the sandblasting area, where the sandblaster is located, and the processes performed are shown in order from 1 to 24. The main difference between the current spaghetti diagram and the previous one is that there are no transfers outside the area, except for lunch breaks. This was achieved by preparing all the materials and tools necessary for the process in advance and making them available. For this reason, the technician does not spend his time searching for tools and accessories. Transfers within the area follow a relative order from right to left, minimizing unnecessary transfers and creating a constant flow.

To determine the project's feasibility, a benefit-cost analysis was developed, considering all costs associated with the project over the 16-week completion time. The project costs are shown in Table 3.

Box 8

Table 3

Costs associated with the project

Factor	Units used	Unit cost MXN	Total cost MXN
Man hours	480	$ 100.00	$ 48,000.00
Breakfast	80	$ 40.00	$ 3,200.00
Meal	80	$ 17.00	$ 1,360.00
Screws	100	$ 4.51	$ 451.00
Machuelo	2	$ 77.54	$ 155.08
Drill bit	2	$ 29.00	$ 58.00
Given 10 mm	1	$ 34.85	$ 34.85
Given 13 mm	1	$ 38.00	$ 38.00
Rotary hammer	1	$ 5,599.00	$ 5,599.00
Total			$ 58,818.39

Source: Own Elaboration

Table 3 describes the cost drivers for the organization under study, as well as the tools used to solve the problem. Over the course of the 16 weeks, approximately 480 man-hours were worked; both breakfast and lunch were covered by the organization, as well as the materials that were proposed as an improvement to the current method, giving a total of $58,818.39 MXN. The benefits were calculated over a 12-month horizon. The following table 4 shows the detailed information on the benefits.

Box 9

Table 4

Annual savings perceived

Method	Setups per year	Hours per setup	Hours per year	Line downtime cost per hour USD	Total annual cost USD	Total annual cost MXN
Current	12	8	96	$ 52.77	$ 5,065.92	$ 95.087.32
Improved	12	4.5	54	$ 52.77	$ 2,849.58	$ 53.486.62
Saving						$ 41,600.70

Source: Own Elaboration

Table 4 describes the main benefits of the project, saving $41,600.70 MXN directly from the reduced time, in addition to the above, there are also savings from the equipment consumables, more specifically those of the self-adhesive packaging that can be seen below in table 5.

Box 10

Table 5

Savings on consumables

Method	Consumable	Units used per year	Unit cost	Total cost MXN
Current	Self-adhesive packaging	90	$ 540.00	$ 48,600.00
Improved	Self-adhesive packaging	40	$ 540.00	$ 21,600.00
Saving				$ 27,000.00

Source: Own Elaboration

Using Table 4 and Table 5, a total value of $68,600.7 MXN is obtained in terms of direct benefit, and using Table 8, a total cost of $82,818.39 MXN is obtained. With the help of this information, the benefit-cost analysis was performed as follows:

$$B/C = \frac{\$68,600.7}{\$58,818.39} = 1.16$$

ISSN: 2523-6806
RENIECYT-SECIHTI: 1702902

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With the analysis described above, it was concluded that for every peso invested in the project, the organization obtains one peso and sixteen cents of profit, thus making the present project profitable.

Conclusions

The current procedure achieved the project objective by reducing the setup time for the sandblasting process, which used to take an average of eight hours. Now, with the updated method, it takes approximately four and a half hours. This means the equipment is more readily available.

The benefit of increased equipment availability brings economic benefits to the organization because more parts can be produced in the same amount of time. An economic study determined the project to be viable for the organization.

The SMED tool is versatile; it can be easily adapted, as in the current project, to preventive maintenance work, since the actions performed can be adjusted to the different steps of the methodology.

It is advisable to monitor this type of project, as it is often forgotten by staff and, over time, the same problem arises. It is essential that all staff be involved in the improvement actions taking place throughout the plant.

Author contribution

Roberto Cáñez Barraza: Contributed to the development of the method to achieve the results and documentation of the project.

Manuel Antonio González Mendivil: Contributed to the bibliographic and format review.

René Daniel Fornés Rivera: Contributed to the structure of the method and alignment of results obtained.

Adolfo Cano Carrasco: He contributed with the idea of the project, the method and the research technique.

Abbreviations

NADCAP (National Aerospace and Defense Contractors Accreditation Program)
SMED (single minute exchange of die
TPM (Total Productive Maintenance)
VSM (Value Stream Map)

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Appendix 1. Time taking of the current process in three days

Box 11

Table 6

Time taking of the current process performed on day 1			
#	**Time (min)**	**Operation**	**Comments**
1	00:16:00	Remove red hoses	
2	00:05:00	Remove the 4 airjets from the guns	
3	00:43:00	Breakfast and journey	
4	00:10:00	Remove brass pin connectors	
5	00:20:00	Replace airjets with new ones	
6	00:18:00	Install new pin connectors	
7	00:22:00	Install new red hoses	
8	00:15:00	Place hoses in pickups and these in the feed hopper	
9	00:26:00	Put red hoses on guns	
10	00:03:00	Put airjets on the guns	
11	00:08:00	Arrangement of red hoses inside the cabin	
12	00:25:00	Calibrate pickups	
13	01:30:00	Remove packaging from the cabin door	
14	00:35:00	Mealtime and journey	
15	00:09:00	Putting the cabin door gasket on	
16	00:10:00	Remove cabin window packaging	
17	00:11:00	Install cabin window gasket	
18	00:11:00	Remove cabin door gasket	
19	00:05:00	Install cabin door gasket	
20	00:27:00	Remove plastic hose	
21	00:05:00	Remove cabin discharge	
22	00:10:00	Remove the reservoir and plastic hose discharge	
23	01:53:00	Install blue plastic hose (cabin discharge and reserve hopper discharge were also installed)	Two people required
24	00:23:00	Install 90° elbow in sandblasting booth	
25	00:05:00	Install reserve hopper discharge hose	
26	00:23:00	Place 45° elbow of sandblasting booth	Two people required
27	00:05:00	Adjusting cabin elbow clamps	
28	00:10:00	Check for leaks	

Box 11

Table 7

Time taking of the current process carried out on day 2			
#	**Time (min)**	**Operation**	**Comments**
1	00:25:00	Go for replacement parts and a tool cart	
2	00:02:00	Clean cabin	Did not put lock (padlock)
3	00:01:00	Search for tools	
4	00:11:00	Cut red hoses	He went out to look for a marker to put a line on the hoses
5	00:02:00	Remove pin connectors	
6	00:01:00	Search for tools	Answered a call on your cell phone
7	00:10:00	Remove airjets and prepare hose outlet	Can't find key to remove
8	00:02:00	Place airjets	
9	00:06:00	Prepare pin connectors and connect them (apply lubricant)	Changing gloves
10	00:08:00	Insert red hoses and tighten clamps	No change will be made for shortages
11	00:02:00	Connect airjets to router and tighten	
12	00:01:00	Disconnect pick up	
13	00:04:00	Clean and remove funnel	Get face masks and change gloves
14	00:05:00	Empty hopper	
15	00:06:00	Calibrate pick ups	Go for vernier and leave it
16	00:02:00	Remove pickups	
17	00:48:00	Breakfast and journey	
18	00:04:00	Remove fabric hose	
19	00:06:00	Unscrew the filter cabinet outlet	
20	00:07:00	Remove packaging and place a new one	
21	00:12:00	Install the filter booth outlet	
22	00:02:00	Remove cyclone cover	
23	00:14:00	Remove outlet elbow	
24	00:02:00	Remove blue plastic hose	
25	00:06:00	Remove inlet elbow	
26	00:22:00	Search for tools	He left the area
27	00:11:00	Remove cyclone	
28	00:09:00	Remove old packing and install cyclone packing	
29	00:17:00	Place cyclone	
30	00:14:00	Put on new jacket and new packaging	
31	00:17:00	Place outlet elbow	
32	00:05:00	Place the inlet elbow gasket	
33	00:11:00	Place inlet elbow	
34	00:09:00	Remove and replace the new cyclone cover gasket.	
35	00:05:00	Place cyclone cover	
36	00:05:00	Lubricate outlet elbow and blue plastic pipe, place	
37	00:10:00	Cutting and preparing fabric hose	
38	00:14:00	Place fabric hose	
39	00:07:00	Replace hopper cover filter	
40	00:09:00	Replace filter cover under hopper	
41	00:09:00	Place pick ups	
42	00:58:00	Food and journey	
43	00:18:00	Remove the door gasket and replace it with a new one.	
44	00:09:00	Clean window and remove packaging and replace with new one.	
45	00:09:00	Remove the cabin gasket (below) and replace it with a new one.	
46	00:06:00	Go for materials	
47	00:05:00	Grease bearing and check oil level	
48	00:10:00	Add sand to hopper	
49	00:06:00	Perform leak test	

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Box 12

Table 8

Time recording of the current process carried out on day 3			
#	Time (min)	Operation	Comments
1	00:02:00	Search for tools	The tools should be ready
2	00:03:00	Clean cabin	
3	00:08:00	Cut sand hoses x4	Pipe cutter is dull, the space is too narrow, a knife is used
4	00:34:00	Breakfast and journey	
5	00:21:00	Replace red hoses	Cable ties were cut, hoses were labeled, and other activities were carried out.
6	00:24:00	Replacing pin connectors	
7	00:20:00	Replace air jets	Getting thinner Teflon
8	00:16:00	Connect pick up	
9	01:03:00	Change cabin door gasket and glass	There are no packages upstairs, he went to the bathroom and for packages
10	00:01:00	Check handle	A special knife is needed to remove the packaging.
11	00:01:00	Check clamps under the cabin	
12	00:04:00	Replace 1 forgotten airjet	
13	00:21:00	Remove inlet elbow and packing	
14	00:08:00	Remove cyclone door and change packing	
15	00:48:00	Food and journey	
16	00:03:00	Remove fabric hose	
17	00:08:00	Remove outlet elbow	
18	00:27:00	Place outlet elbow and new gasket	
19	00:11:00	Place inlet elbow	
20	00:07:00	Install cyclone door	
21	00:10:00	Bathroom	
22	00:27:00	Place blue fabric hose	Cut the wire should not be the same length
23	00:57:00	Replace green hose and clamps	It doesn't take long to change every month
24	00:03:00	Replace upper hopper packing	
25	00:35:00	10-minute break	
26	00:18:00	Replace lower hopper packing	

APPENDIX 2 Set-up Operations Analysis Chart Format

Box 13

Table 9

		Operating time		Categories				Goal of the improvement plan		
Passed	Element	Duration (min)	Accumulated (min)	Internal	External	Waste	Improvement plan	Eliminate	Internal to external	Reduce
1	Go for replacement parts and a tool cart	25	25			x	Have replacement parts ready beforehand	x		
2	Clean cabin	2	27	x						
3	Search for tools	1	28			x	Create a small toolkit	x		
4	Cut red hoses	11	39	x			Cut hoses a day in advance when necessary		x	
5	Remove pin connectors	2	41	x						
6	Search for tools	1	42			x		x		
7	Remove airjets and prepare hose outlet	10	52	x						
8	Place airjets	2	54	x						
9	Prepare pin connectors and connect them (lubricate them)	6	60	x			Prepare spigot connectors one day before		x	
10	Insert red hoses and tighten clamps	8	68	x			Use butterfly clamps			x
11	Connect airjets to router and tighten	2	70	x						
12	Disconnect pick up	1	71	x						
13	Clean and remove funnel	4	75	x						
14	Empty hopper	5	80	x						
15	Calibrate pick ups	6	86	x			Calibrate pick-ups one day before		x	
16	Remove pickups	2	88	x						
17	Breakfast and journey	48	136			x				
18	Remove fabric hose	4	140	x						
19	Unscrew the filter cabinet outlet	6	146	x			Use smart hardware			x
20	Remove packaging and place a new one	7	153	x						
21	Install the filter booth outlet	12	165	x			Use smart hardware			x
22	Remove cyclone cover	2	167	x						
23	Remove outlet elbow	14	181	x						
24	Remove blue plastic hose	2	183	x						
25	Remove inlet elbow	6	189	x						
26	Search for tools	22	211			x		x		
27	Remove cyclone	11	222	x			It is not necessary to remove the cyclone if thread-seeking screws are used, for that it is necessary to make guides with a tap.			x
28	Remove old packing and install cyclone packing	9	231	x				x		
29	Place cyclone	17	248	x				x		
30	Put on new jacket and new packaging	14	262	x						
31	Place outlet elbow	17	279	x						
32	Place the inlet elbow gasket	5	284	x						
33	Place inlet elbow	11	295	x						
34	Remove and replace the new cyclone cover gasket.	9	304	x						
35	Place cyclone cover	5	309	x						
36	Lubricate outlet elbow and blue plastic pipe, place	5	314	x						
37	Cutting and preparing fabric hose	10	324	x			Prepare fabric hose one day in advance	x		
38	Place fabric hose	14	338	x						
39	Replace hopper cover filter	7	345	x						
40	Replace filter cover under hopper	9	354	x						
41	Place pick ups	9	363	x						
42	Food and journey	58	421			x				
43	Remove the door gasket and replace it with a new one.	18	439	x						
44	Clean window and remove packaging and replace with new one.	9	448	x						
45	Remove the cabin gasket (below) and replace it with a new one.	9	457	x						
46	Go for materials	6	463			x	Have grease trap available one day before setup preparation	x		
47	Grease bearing and check oil level	5	468	x						
48	Add sand to hopper	10	478	x						
49	Perform leak test	6	484	x						
	Total	**484**								

APPENDIX 3 Time recording after improvement

Box 14

Table 10

#	Time	Operation	Comments
1	00:03:00	Clean cabin	
2	00:30:00	Replace red hoses	Hose 3 was not changed
3	00:17:00	Replacing pin	Use 26.9 mm 11 /16
4	00:06:00	Connect red hose to	
5	00:07:00	Replacing airjets part 1	
6	00:56:00	Breakfast and journey	
7	00:06:00	Replacing airjets part 2	
8	00:04:00	Accommodate red	
9	00:05:00	Connecting pickups	
10	00:16:00	Replace cabin gasket	
11	00:10:00	Remove inlet elbow	
12	00:01:00	Remove cyclone door	
13	00:16:00	Remove outlet elbow	
14	00:08:00	Place outlet elbow	
15	00:17:00	Place outlet elbow	
16	00:04:00	Place the inlet elbow	
17	00:08:00	Place inlet elbow	
18	00:08:00	Replace cabin door	
19	00:06:00	Install cyclone door	
20	00:10:00	Replace fabric hose	
21	00:05:00	Place plastic hose	
22	00:04:00	Replace upper hopper	
23	00:07:00	Grease bearings	
24	00:03:00	Leak test	
25	00:12:00	Clean and tidy	

ISSN: 2523-6806
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Cano-Carrasco, Adolfo, González-Mendivil, Manuel Antonio, Fornés-Rivera, René Daniel and Cañez-Barraza, Roberto. [2024]. Reducing setup times in the sandblasting process of an aerospace industry. 9[22]1-11: e4922111.
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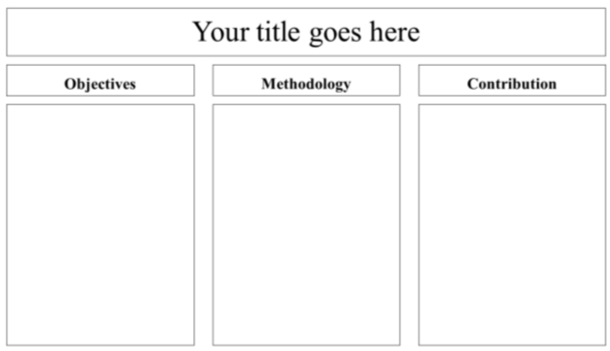

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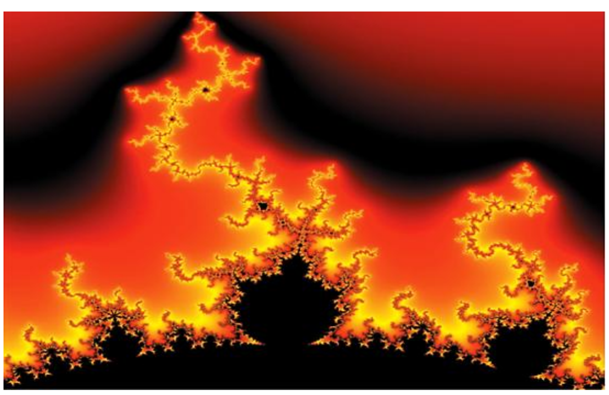

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