

Article



Enhancing an Automatic Automotive Cable Assembly Line: A Design Science Research Approach to Improve OEE

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How To Cite: Lopes, R.; Campilho, R.D.S.G.; Pinto, A.G.; et al. Enhancing an Automatic Automotive Cable Assembly Line: A Design Science Research Approach to Improve OEE. *Journal of Mechanical Engineering and Manufacturing* 2026. <https://doi.org/10.53941/jmem.2026.100033>

Received: 26 November 2025

Revised: 23 May 2026

Accepted: 22 June 2026

Published: 28 September 2026

Abstract: The automotive industry demands high standards of efficiency and reliability in order to remain competitive. This study addresses the optimization of an automatic production cell (“Line X”) dedicated to the manufacture of cables for automotive latches, which initially presented critical performance levels, with an average Overall Equipment Effectiveness (OEE) of 42%, significantly below the strategic target of 85%. Adopting the Design Science Research (DSR) methodology, the research diagnosed the root causes of inefficiency, mainly associated with the electric cutting process, cable insertion, and component feed stability. Targeted technical interventions were designed and implemented, including the development of copper-beryllium electrodes with tungsten tips to reduce wear, a new symmetrical electrode opening system to eliminate burrs, and a spiral cleaning tool to prevent insertion failures. The results demonstrated a substantial improvement in operational stability: corrected OEE stabilized above 80%, reaching a peak value of 87.7%, clearly highlighting the effectiveness of the implemented technical improvements, while performance consistently exceeded the 95% target. Additionally, there was a dramatic reduction in non-compliance rates (ppm), validating the effectiveness of the engineering solutions. This work confirms that technical redesign focused on critical process steps is decisive in recovering the productivity and availability of automatic assembly lines.

Keywords: overall equipment effectiveness (OEE); automotive industry; electric cable cutting; design science research; process optimization

1. Introduction

The automotive industry currently operates in a highly complex and competitive global ecosystem, where the efficiency and flexibility of production processes are key to business success. The integration of new production and assembly concepts, capable of responding to demand variability and mass customization, requires robust systems that minimize waste and maximize operational reliability [1]. In this context, the continuous improvement of critical equipment, such as tire manufacturing machines or rubber components, demonstrates that direct technical optimization has a profound impact on the overall productivity of factories [2]. The transition to Industry 4.0 and the adoption of digital technologies, such as digital twins, now make it possible to simulate scenarios and anticipate constraints before physical implementation, ensuring more agile product lifecycle management [3].



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To address these challenges, the automation of complex manual operations, particularly in the production of Bowden cables, emerges as an essential strategy for increasing safety and flexibility, reducing dependence on the human factor in repetitive tasks [4]. However, automation alone does not guarantee efficiency; it is necessary to ensure process stability, as seen in the injection of ZAMAK components, where small technical improvements can result in significant quality gains [5]. Intelligent industrial systems, enabled by digital technologies, are essential for monitoring and controlling these variables in real time, promoting more resilient and adaptable production [6].

Monitoring industrial performance through Overall Equipment Effectiveness (OEE) has established itself as a standard practice for identifying losses and guiding improvement actions on assembly lines [7]. Studies show that the application of productivity models focused on OEE, even in component machining processes for molds, increases resource availability and efficiency [8]. The sustainability of these results often depends on the implementation of autonomous maintenance strategies, which involve operators in equipment maintenance and early detection of anomalies [9]. In addition, the careful design of transfer and internal logistics systems is crucial to ensure the continuous flow of materials and avoid downtime that penalizes OEE [10].

Reducing setup times is another critical factor for competitiveness, with the Single Minute Exchange of Die (SMED) methodology widely validated in industry, where it has increased production flexibility without compromising production capacity [11]. The combination of cost reduction and quality improvement also reinforces the importance of an integrated approach to production management [12]. Tools such as the A3 methodology have proven effective in structuring improvement projects, facilitating the resolution of complex problems on assembly lines [13]. To ensure long-term reliability, preventive maintenance management must be optimized, ensuring that assets operate under ideal conditions [14]. Operational safety and productivity also benefit from the application of SMED, which, by simplifying procedures, reduces the risk of accidents and human error [15]. This methodology is applicable across a range of processes, from tire calibration [16] to steel cable assembly, where the frequency of reference changes requires short response times [17]. Rath et al. [18] and Zehra et al. [19] are examples of the SMED application in the automotive industry, with tangible results.

To sustain these gains, the implementation of Total Productive Maintenance (TPM) provides the organizational structure necessary to maximize equipment effectiveness [20]. Strategic maintenance plans based on TPM enable a shift from a reactive approach to proactive management, aligned with business objectives [21]. Continuous improvement in maintenance, supported by Lean tools, is thus an indispensable pillar of operational excellence in the automotive industry [22]. The manufacture of control cables presents specific challenges related to the nature of the materials and the precision required. Optimizing the process of injecting terminals into Bowden cables is critical to ensuring the functionality and durability of the component [23]. The development of dedicated equipment, such as double spiral cutting machines [24] or fully automated manufacturing cells [25], demonstrates the need for advanced engineering solutions to overcome the limitations of traditional processes. The quality of materials, subject to phenomena such as oxidation in zinc-coated steel cables, must be strictly controlled to prevent service failures [26]. The automatic handling of deformable components, such as wires in overmolding machines, requires accurate and reliable feeding systems [27]. The implementation of TPM, supported by 5S, has proven effective in improving the availability of automotive production lines, reducing the incidence of breakdowns [28]. Automation also extends to product testing and validation, with the development of new concepts for long and flexible product transfer systems [29] and for the automatic introduction of lubricant into control cables [30].

Despite the widespread adoption of automated assembly systems in the automotive industry, many production lines continue to suffer from efficiency losses caused by process instability, wear-sensitive tooling, and handling difficulties associated with flexible components such as Bowden cables. In practice, even small defects in cutting quality, cable alignment, or insertion stability can generate frequent micro-stoppages, reject accumulation, and significant reductions in OEE. These issues are particularly critical in fully automatic lines, where the absence of direct operator intervention increases sensitivity to mechanical and process deviations. However, the literature remains predominantly focused either on the development of entirely new automated systems or on generic Lean/TPM methodologies, with little attention dedicated to targeted engineering retrofits capable of recovering the performance of existing industrial lines through low-cost but high-impact technical interventions.

In this context, the present study addresses the optimization of “Cable Line X”, a fully automatic production cell dedicated to the manufacture of automotive latch cables. Prior to the intervention, the line operated under severe instability conditions, characterized by average OEE values of around 42%, frequent unplanned stoppages, burr formation during electric cutting, cable insertion failures, electrode wear, and recurring process interruptions associated with spiral misalignment and contamination. These problems significantly compromised productivity, product quality, and operational reliability, which prevented the line from achieving the target production rate of 450 units/hour. To address these limitations, this work proposes a structured Design Science Research (DSR) approach combining Lean Manufacturing principles, OEE-driven diagnostics, and engineering redesign of critical

process stages. The novelty of the study lies in the development and industrial validation of integrated retrofit solutions for electric cutting stabilization, spiral calibration and cleaning, electrode redesign, symmetrical electrical discharge systems, and precision positioning devices, implemented directly in an operating industrial environment without complete line replacement. The proposed approach demonstrates how focused engineering interventions can substantially recover the performance of existing automated assembly systems with reduced investment and operational risk.

2. Case Study Context and Existing Issues

Before the implementation of the proposed improvements, the “Line X” automatic cable assembly system operated under critical efficiency conditions, presenting significant instability in production performance, availability, and quality indicators. The line was dedicated to the manufacture of automotive latch cables and was expected to consistently achieve a production target of 450 units/hour with only one operator.

However, the initial diagnosis revealed severe operational inefficiencies between calendar week (cw) 45 of 2024 and cw11 of 2025. As summarized in Table 1, the corrected Overall Equipment Effectiveness (OEE corr) consistently remained far below the strategic target of 85%, fluctuating within critically low values that reflected the instability of the production system. The Availability (AV) indicator also presented significant variability, demonstrating the frequent occurrence of machine stoppages and extended downtime periods throughout the analyzed weeks. Although the Performance (PF) indicator generally remained closer to the expected target values, the instability observed in Availability and Quality (Q) significantly compromised the overall effectiveness of the line. Quality levels fluctuated considerably due to recurrent non-conformities associated mainly with failures in the electric cutting process and cable insertion operations. In parallel, the non-compliance indicator (ppm: conversion of failures into parts per million) reached very high values during several production weeks, confirming the strong impact of process instability on product conformity and operational reliability. These results demonstrated that the main limitations of Line X were not exclusively related to production speed, but primarily to process stability, equipment reliability, and defect generation.

Table 1. OEE Line X before-interventions.

	cw45	cw46	cw47	cw48	cw49	cw50	cw51	cw01	cw02	cw03	cw04	cw05	cw06	cw07	cw08	cw09	cw10	cw11
OE	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85
(obj)	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
AV	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
(obj)	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
PF	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95	95
(obj)	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Q	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
(obj)	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
OEE	87.67	96.98	91.28	121.37	122.12	106.22	99.98	93.50	69.31	50.20	39.46	57.31	87.14	63.23	65.45	58.04	51.20	41.78
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
OE corr	29.22	32.42	30.43	40.46	40.71	35.41	33.33	31.17	23.10	46.02	36.38	57.31	55.00	60.06	61.70	55.69	48.45	40.81
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
AV	72.18	76.88	63.95	84.34	66.12	76.51	71.43	74.90	64.44	68.98	53.53	57.31	60.31	71.60	61.94	66.33	60.20	80.32
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
PF	43.52	44.19	51.47	51.17	48.43	48.95	51.75	44.25	38.84	72.80	73.66	103.20	100.00	88.95	105.69	87.53	85.10	52.02
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Q	93.01	95.42	92.44	93.75	97.61	94.54	90.18	94.04	92.29	91.64	92.27	96.90	91.35	94.31	94.26	95.92	94.58	97.67
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
PPM	69,884	45,786	75,597	62,476	23,905	54,628	98,208	59,577	77,130	83,577	77,329	30,979	86,540	56,897	57,444	40,779	54,245	23,300

Table 2 presents a brief description of OEE and its three indicators, as well as the formulas used for their respective calculations.

Detailed production monitoring and failure analysis revealed that the electric cable cutting station represented one of the most critical bottlenecks in the system. Excessive electrode wear, asymmetric electrical discharge, burr formation, and cutting instability frequently generated defective cuts, requiring repeated interventions and causing significant production interruptions. Additionally, dimensional inconsistencies and burrs inside the metal spiral compromised the cable insertion process, resulting in insertion failures, machine stoppages, and increased rejection rates. Other relevant issues included instability in component positioning during injection operations, accumulation of residues in critical areas of the equipment, and excessive dependence on auxiliary production lines to compensate for the low productivity of Line X. Pareto analysis of failures demonstrated that a small number of recurrent technical problems were responsible for a substantial percentage of production losses and downtime.

Table 2. Formulas and brief description of OEE, AV, PF and Q.

OEE: key performance indicator used in industry to measure the productivity and efficiency of equipment or production lines	$\text{OEE gross} = \frac{\text{good actual production}}{\text{ideal production}}$ $\text{OEE corr} = \text{AV} \times \text{PF} \times \text{Q}$
AV: measures the actual run time against planned production time	$\text{AV} = \frac{\text{operating time}}{\text{planned time}}$
PF: measures the total parts produced against the theoretical maximum output	$\text{PF} = \frac{\text{real production}}{\text{production time} \times \text{hourly capacity}}$
Q: measures the proportion of good products compared to the total produced	$\text{Q} = \frac{\text{good parts}}{\text{total production}}$

Given this scenario, a structured improvement approach based on Design Science Research (DSR) was adopted to identify root causes, prioritize interventions, and implement technical solutions aimed at increasing operational stability, improving OEE, reducing defect generation, and recovering the expected productivity and reliability levels of the automatic assembly system.

3. Methodology

3.1. DSR Approach

This work was developed following the DSR methodology, which is particularly suitable for industrial engineering problems requiring the creation, implementation, and validation of practical technical solutions in real operating environments [31]. Unlike purely observational research approaches, DSR focuses on the development of artifacts or engineering interventions capable of solving identified industrial problems while simultaneously generating scientific knowledge. In the present study, the DSR methodology was applied through an iterative process composed of five main stages:

- Problem identification and diagnosis: Analysis of the production line was carried out through direct observation, OEE monitoring, maintenance records, production data analysis, and discussions with operators and technicians. This stage enabled the identification of critical failures associated with electric cutting, cable insertion, spiral alignment, and electrode wear;
- Definition of improvement objectives: Based on the diagnosed problems, specific operational targets were established, including increasing OEE to values above 85%, reducing production stoppages, minimizing burr formation, and improving process stability and productivity;
- Design and development of solutions: Engineering solutions were conceived and developed to address the identified limitations. These included the redesign of electrodes, implementation of symmetrical electrical discharge systems, development of spiral finishing tools, creation of positioning gauges, and mechanical modifications to the production cell;
- Implementation and validation: The proposed solutions were implemented directly in the industrial environment and evaluated under real production conditions. Their effectiveness was assessed using OEE indicators and their associated components (Availability-AV, Performance-PF, and Quality-Q), as well as ppm levels and operational stability metrics;
- Evaluation and knowledge generation: The results obtained were analyzed and compared with previous studies reported in the literature, which allowed the validation of the effectiveness of the proposed interventions and demonstrating the applicability of the developed approach for similar automated manufacturing systems.

3.2. Proposed Interventions

In this initial phase of the process of improving the automatic cable production line, data was collected and analyzed, generating ideas with the potential to solve the main problems identified in the operation of the line. The analysis was based on key performance indicators, including OEE components (availability, performance, and quality), as well as failure frequency and downtime records. Root cause analysis tools, such as Pareto analysis and direct observation, were used to prioritize critical issues. Suggestions arose both from direct observation at the workplace and through brainstorming with operators, maintenance technicians, and engineers from the company. The prioritization of interventions considered criteria such as expected impact on OEE, implementation complexity, cost, and risk, enabling a structured decision-making process aligned with performance improvement objectives.

Table 3 presents a summary of the different interventions proposed, with a brief description and the respective implementation decision.

Table 3. Summary of proposed interventions for Line X.

Intervention	Description	Decision
Improvement in the manufacture of the spiral	Development of a specific drill bit to clean and calibrate the internal hole of the spiral.	Implement
Change in the inner hole of the spiral terminal	Reduction of the diameter of the spiral fitting hole in the terminal to prevent misalignment.	Implement
Development of new electrodes	Introduction of copper-beryllium electrodes with tungsten tips to reduce wear.	Implement
Implementation of electrode opening system	Automatic spring-loaded opening to reduce burrs in electric cutting.	Implement
Changing the electrical connections of the electrodes	Reconfiguration of electrical connections to ensure symmetrical discharge on both sides of the cable.	Implement
Application of liquid in cleaning electrodes	Fluid cleaning system to remove residues.	Do not implement
Vacuum placement in electrode cleaning	Vapor and residue extraction system, preventive in case of cleaning fluid use.	Do not implement
Gauges for electrode placement	Creation of positioning devices to facilitate precise electrode assembly.	Implement
Adjusting the force of the cutting jaws	Tests to vary the clamping force on the cables during cutting, evaluating the impact on quality.	Do not implement
Anti-mass accumulation system in the first flower	Prevent mass from entering the flower machine	Do not implement
Rear door replacement	Redesign of the door to facilitate access to the machine's collection and cleaning area.	Implement
Direct drop of cables to the customer's box	Automation of packaging, eliminating manual final inspection.	Do not implement

3.3. Exclusion of Ideas

Although several of the proposed ideas showed potential, not all of them were put into practice. The decision not to implement some interventions was mainly due to three factors: the effectiveness of improvements already implemented, the complexity or risk associated with the proposal, and the lack of need or urgency after analysis.

This subtopic lists and explains the ideas that were excluded after a selection process.

3.3.1. Application of Liquid to the Electrodes

An intervention initially planned in the process of improving the electric cut consisted of applying a liquid cleaning system to the electrodes, with the aim of extending their useful life and ensuring cutting efficiency over time. This solution was designed as a preventive measure in case the expected improvements with the implementation of new electrodes did not materialize in practice.

The liquid electrode cleaning system works by applying a specific fluid in a controlled manner, which removes metal residues, carbonized particles, and other contaminants that accumulate on the conductive surfaces during the cutting process. This type of dirt can increase contact resistance, affect cutting accuracy, and accelerate electrode wear, thus compromising process stability.

The installation of such a system would involve the integration of a fluid distribution circuit, applicator nozzles directed at the active zone of the electrodes, as well as the implementation of an automated cleaning cycle, possibly synchronized with machine downtime or with sensors that detect degradation in electrical performance. Despite the additional investment and complexity of the system, this measure could prove advantageous in scenarios where electrodes are replaced frequently or in intensive production environments.

However, after the implementation of the new copper-beryllium electrodes with tungsten tips, as described above, there was a significant improvement in durability, cutting stability, and resistance to surface wear. The quality of the material, in particular the high hardness and thermal resistance of the tungsten tip, substantially reduced the accumulation of conductive residues and minimized the appearance of cutting defects.

Given the proven effectiveness of the new electrodes, the installation of the liquid cleaning system proved unnecessary, and the idea was shelved as it did not justify the investment or the alteration of the machine's infrastructure.

3.3.2. Vacuum Placement in Electrode Cleaning

In addition to the proposal to clean the electrodes using liquid, the implementation of a vacuum system was also considered as a complementary safety measure. This intervention aimed to ensure the immediate removal of flammable vapors or suspended particles resulting from the application of the cleaning fluid, preventing potential fire risks inside the machine.

During the electric cutting process, the electrodes operate at high temperatures due to the electrical discharge generated between the poles. If a cleaning liquid were introduced, it would be subject to intense heating upon contact with the hot electrodes, which could give rise to combustible vapors, especially in the case of organic solvents or mixtures with a low flash point. In addition, fine metal particles released during cutting or cleaning—such as copper filings or carbonized residues—could remain suspended in the air, creating a potentially explosive environment in the presence of sparks or heat.

The main function of a vacuum system would be to continuously extract these vapors and particles from the cutting area, promoting forced ventilation of the compartment and preventing their accumulation. The vacuum would be directed through ducts positioned next to the active zone of the electrodes, possibly with filters suitable for fine particles and gas detection sensors, ensuring that a safe environment is maintained inside the machine.

However, as mentioned above, the liquid cleaning solution was discarded due to the high performance of the copper-beryllium electrodes with tungsten tips, whose resistance to wear and residue accumulation eliminated the need for active cleaning. Thus, there was no need to implement the vacuum system, since the risk it was intended to mitigate no longer existed. The idea was therefore considered redundant and was not pursued.

3.3.3. Adjust the Contact Area with the Cable in the Clamps

Another preventive intervention considered in the context of the electric cutting process was to conduct tests with different levels of clamp tightness on the cable, with the aim of assessing the impact of this variable on cutting performance and electrode durability. This idea arose as part of an experimental approach that sought to explore multiple factors influencing defect generation and electrical discharge stability.

The jaws are the components responsible for securing the cable in the correct position during the cutting process. Their function is to ensure the alignment of the cable with the electrodes and to limit any unwanted movement that could compromise the accuracy of the cut. The hypothesis under analysis consisted of testing variations in the clamping force of the jaws, clamping the cable with more or less intensity, to verify whether this would result in better electrical current conduction between the electrodes or a cleaner separation of the material, reducing premature wear of the electrodes.

A stronger grip could, theoretically, better stabilize the cable, facilitating the formation of a straighter and more predictable cutting path. On the other hand, excessive tightening could also deform the cable or introduce mechanical stresses that interfere with how it reacts to the electrical discharge. Conversely, a looser grip would allow greater freedom of movement for the cable, which, despite reducing mechanical stress, could cause oscillations and impair cutting efficiency.

Despite the potential technical interest of this approach, the intervention was ultimately not implemented. The introduction of the new electrodes proved effective in resolving the main problems associated with electric cutting, particularly with regard to burr generation and the need for frequent maintenance. Therefore, it was not considered necessary to proceed with this idea, as the improvement objectives had already been achieved without the need for additional adjustments to the jaws.

3.3.4. System to Ensure That the Mass Does Not Enter the Machine That Makes the First Flower

Another intervention planned during the observation and diagnosis phase of the process concerned the prevention of failures related to the insertion of mass into the spiral, namely the possible accumulation of mass inside the machine responsible for making the first flower in the cable. It was identified that, in certain situations, the punching station incorrectly inserted the mass into the spiral, leaving it poorly fixed or poorly positioned.

When this occurred, the cable that then entered the spiral ended up pushing this poorly inserted mass, expelling it from the spiral in the opposite direction to that of the cable's insertion. As a result, this displaced mass began to accumulate in the internal structure of the machine that made the first flower—a sensitive and automated piece of equipment. Over time, it was feared that this accumulation of material would interfere with the machine's mechanism, affecting the correct positioning of the cable, damaging internal components, or even causing unexpected line stoppages.

The proposed intervention therefore consisted of creating and installing a control or protection system that would prevent mass from entering the flower machine. This system could involve physical barriers, obstruction detection sensors, or automatic collection mechanisms for the expelled mass.

However, after the implementation of significant upstream improvements, namely in interventions related to the preparation and cleaning of the spiral (as detailed above), this type of error ceased to occur. With the spiral correctly calibrated and cleaned, the mass was properly inserted and kept inside, eliminating the risk of accumulation at the next station. After continuous monitoring of the process, it was concluded that there was no evidence of mass accumulation in the flower machine, so the intervention was considered unnecessary and did not proceed to the implementation phase.

3.3.5. Ensure That Cables Fall Directly into the Customer's Box

One of the interventions planned in the continuous improvement process of the line was related to the possibility of having the finished cables fall directly into the customer's box, making them immediately ready for storage or shipment. This solution aimed to eliminate intermediate handling steps and speed up production flow.

However, after further analysis, the proposal was rejected for two main reasons. Firstly, with the prospect of the line producing several different references in the future, including cables of different lengths, it would be necessary to frequently adjust the destination boxes according to the reference in production. This variation would entail additional logistics associated with the constant replacement of boxes, which could hinder the fluidity of the line, cause delays, or even lead to product separation errors.

The second, more important reason relates to quality control at the end of the process. To allow the finished cables to be sent directly to the customer's box, it would be essential to ensure that they were completely free of defects. This would require complete reliance on the effectiveness of the automatic testing station, which, at the time, did not guarantee a 100% defect detection rate. For this reason, visual inspection by the operator, who visually analyzes each finished cable before sending it for packaging, was still essential. The elimination of this inspection would only be feasible by modernizing the test station, using more robust verification systems, something that was not planned for implementation.

Therefore, taking into account the logistical constraints associated with the diversity of references and the need to maintain a reliable final inspection stage, the proposal did not proceed to the development phase.

3.4. Explanation and Implementation of Selected Ideas

The ideas that proved viable and relevant were developed, tested, and successfully implemented. The improvements achieved had a positive impact on line efficiency, process reliability, and defect reduction.

3.4.1. Improvement in the Manufacture of the Spiral

Although the manufacturing of the metal spiral does not occur directly on the production line of the model under study, it is a critical component for the quality of the final product, with a direct impact on the performance of line X. During the diagnostic phase, a recurring problem was identified: the presence of burrs, imperfections, or even obstructions in the inner hole of the spiral.

These irregularities significantly compromised the efficiency of the line, causing rejections due to difficulties or even failures in cable insertion, leading to frequent stoppages and productivity losses.

The source of the problem lay in the fact that, until then, all the factory's spirals were subject to a single type of common internal finish, regardless of the destination line. In other words, although all spirals already came with an axial hole, this often had diameters outside tolerance, irregular cuts, or internal burrs, which were incompatible with the requirements of line X.

As a solution, a dedicated finishing drill was developed, designed specifically to run through the existing hole along the entire spiral. This tool is not intended to drill the spiral, but rather to perform a precision finish on the inside, eliminating residual burrs, correcting minor deformations, and ensuring a uniform and clean cross-section. The modelled drill bit, illustrated in Figure 1, consists of three distinct pieces, which are assembled as shown in Figure 2. The technical drawings of the individual components, which constitute essential documentation for the manufacturing processes and subsequent maintenance of the drill, are partially presented in Figure 3.

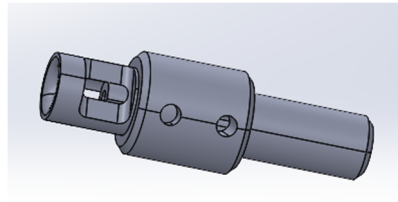


Figure 1. 3D model of the drill bit.

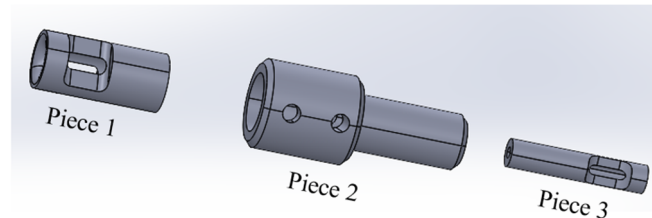


Figure 2. Exploded view of the modelled drill bit.

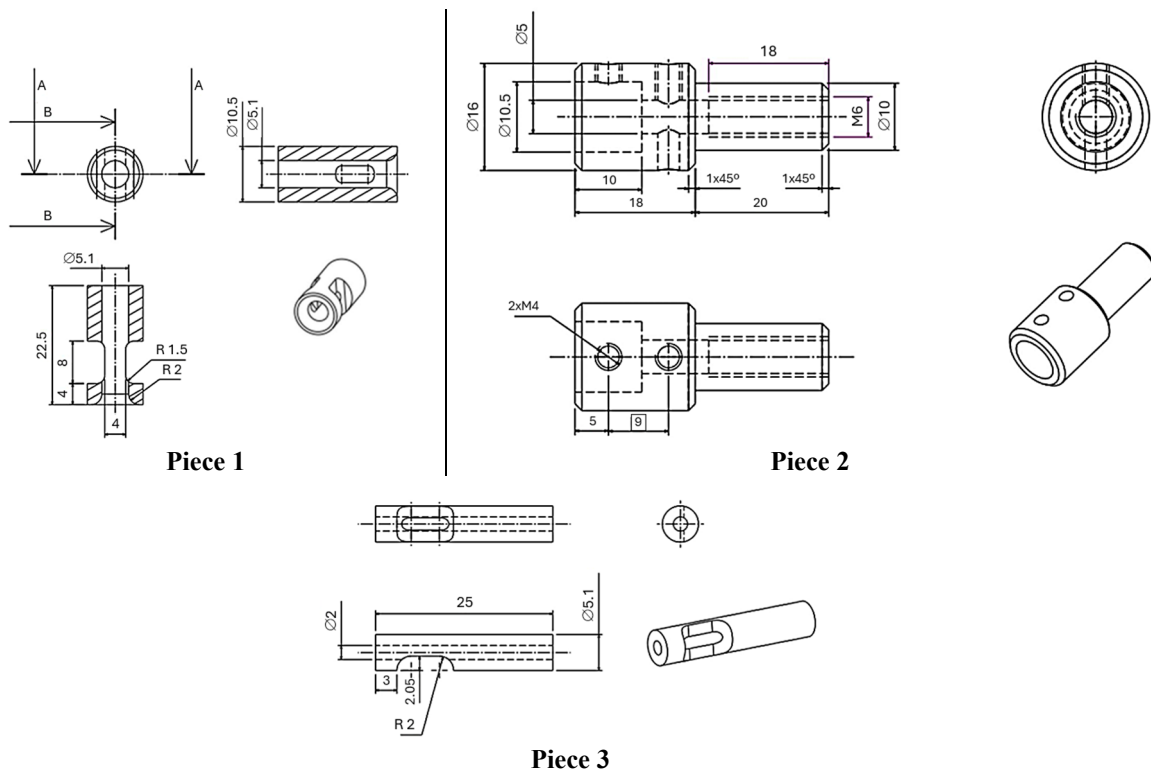


Figure 3. Technical drawings of each of the parts (dimensions in mm).

Figures 4 and 5 illustrate the actual drill bit, already manufactured from the above model. The internal finishing operation of the spiral is then performed at a dedicated station, illustrated in Figure 6. At this station, after the spiral has been cut to the correct length, it is positioned on a support and fixing structure and aligned axially between two drive motors. Two rotary drills are then installed, positioned at opposite ends of the spiral. Each drill is coupled to a servomotor, given the need for precise control of the rotation speed and angular position during the process. These motors are mounted on linear pneumatic cylinders, which allow controlled movement of the drill along the longitudinal axis of the spiral.

Once the spiral is correctly fixed and aligned, the pneumatic cylinders are activated, promoting the simultaneous advancement of the two motors in opposite directions until the drills smoothly enter the existing hole within the spiral. During this advance, the drills remain in constant rotation, ensuring uniform roughing and the removal of burrs or internal irregularities along the spiral channel.



Figure 4. View 1 of the created drill.



Figure 5. View 2 of the created drill.

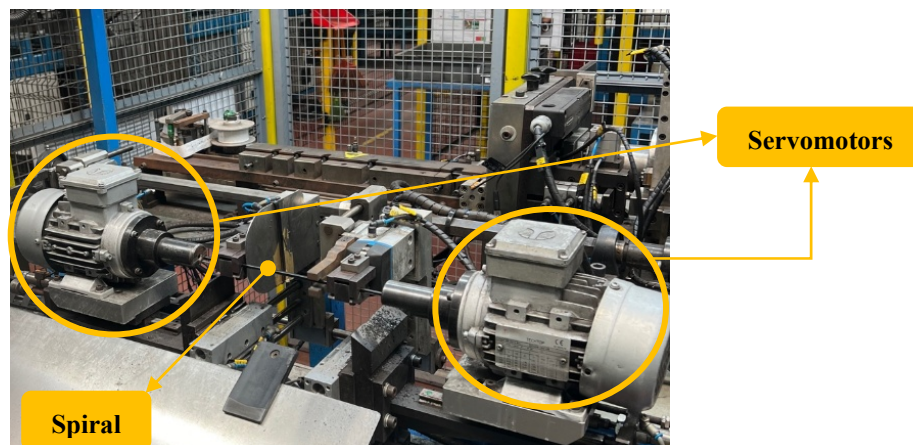


Figure 6. Internal spiral finishing station.

This synchronized bilateral finishing process ensures a clean, continuous, and geometrically controlled interior section, adapted to the dimensional specifications required by the X line references. The use of two drills reduces cycle time and ensures better symmetry in the final finish, increasing the efficiency of the operation.

This simple but highly effective intervention has contributed to an increase in line cadence and a reduction in non-compliance failures, having a positive impact on productivity and quality indicators.

3.4.2. Change in the Inner Hole of the Spiral Terminal

One of the most critical flaws identified in the cable line was the poor fastening of the metal spiral inside the plastic terminal. This terminal has two holes: one with a smaller diameter, for the cable entry, and another with a larger diameter, designed for the spiral to fit into. After fitting, a punching operation is performed to secure the spiral to the terminal before the cable is inserted. Figure 7 shows the spiral terminal seen from above, with the two holes clearly visible.

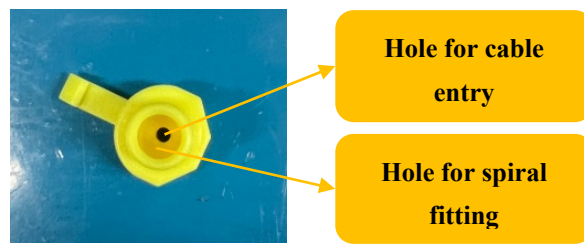


Figure 7. Spiral terminal holes.

After constant observation, it was noted that the hole for the spiral had an excessive diameter in relation to the diameter of the spiral itself. This created significant slack, preventing the spiral from remaining correctly positioned in the terminal. As a result, there was often a misalignment between the internal channel of the spiral and the hole through which the cable is inserted. This problem is illustrated, as a mere example, in Figures 8 and 9.

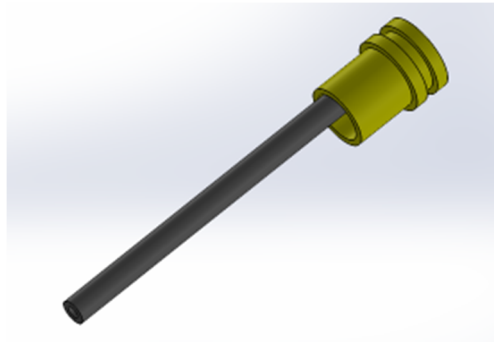


Figure 8. 3D model of misalignment between spiral and terminal.

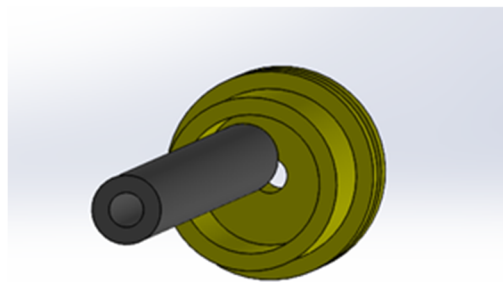


Figure 9. Detail of the 3D model showing the misalignment between the spiral and the terminal.

Thus, when inserted, the cable collided with the wall of the spiral, unable to pass through it. This failure caused assembly errors and forced the line to stop, compromising production cadence. In Figure 10, it is possible to see the spiral terminal from another perspective, highlighting the hole where the spiral should fit. Figure 11 illustrates the end of the metal spiral, highlighting its internal hole.



Figure 10. Spiral terminal.



Figure 11. Spiral end.

To rectify this situation, it was necessary to intervene directly in the manufacturing process of the terminal, which is produced by plastic injection. The hole where the spiral fits is formed during injection by a metal needle integrated into the mold, whose geometry defines the interior cavity of the terminal. Thus, to reduce the diameter of the hole, the needle was reworked on a lathe, adjusting its outer dimension.

This process consisted of mounting the needle on the lathe chuck, placing it in controlled rotation, and then uniformly removing material from its side surface using a cutting tool. The operation was performed with high precision, respecting the dimensional tolerances necessary to ensure that the needle remained functional and compatible with the existing mold. This approach made it possible to reduce the diameter of the terminal hole simply and effectively, without the need to manufacture a new mold part.

With the intervention made, the terminals now have a tighter hole, allowing for a proper fit of the spiral, with minimal clearance and guaranteed alignment between its internal channel and the cable entry hole. Figure 12 shows a cable already assembled with the terminal and the spiral correctly fixed, demonstrating the success of the intervention.



Figure 12. Correctly assembled end cable.

This intervention eliminated the recurring cable insertion error and restored the reliability and continuity of the assembly line.

3.4.3. Development of New Electrodes in Electric Cutting

After stabilizing the mechanical alignment and cable insertion conditions, attention was directed toward the electric cutting process, which remained one of the main sources of quality defects and unplanned stoppages. The following interventions focused on improving cutting consistency, reducing burr formation, and increasing electrode durability, all of which were critical to ensuring stable automatic operation. The electrical cutting process is essential for separating the cable accurately. However, metal burrs were often observed on the cable after cutting, which caused interference in subsequent stages of the line, potentially compromising the fitting of components and affecting the final quality of the product.

After analyzing the process, it was found that the electrodes used, composed of copper and beryllium, showed significant wear after relatively short periods of operation. This excessive wear reduced the effectiveness of the cut and directly contributed to the formation of burrs. Figure 13 illustrates a CAD model of two pairs of copper-beryllium electrodes in the positions they take when cutting.

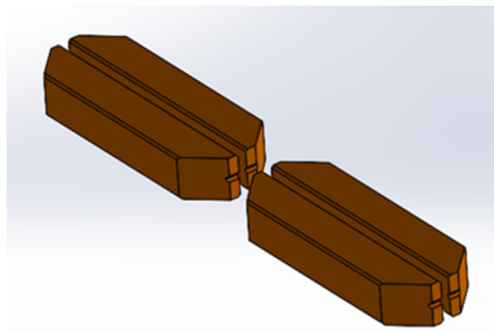


Figure 13. CAD model of copper-beryllium electrodes.

To eliminate this problem, a new version of electrodes was developed, also composed of copper and beryllium, but with a tungsten tip. Tungsten, being a material with high hardness and wear resistance, allowed for significantly greater durability of the active end of the electrode, ensuring cleaner and more consistent cuts, with less need for downtime for maintenance and replacement. The choice of tungsten for the electrode tips was also reinforced by the fact that it was already being used successfully in spot welding operations on other company lines, where it had proven to be highly effective and reliable. Based on these good results, it was decided to apply this type of electrode to the electric cutting process, which was an innovative idea within the company. In addition to these electrodes, two other types were also developed and tested, one made of molybdenum and the other of a mixture of tungsten and copper, with the aim of assessing their viability as even more effective alternatives.

Although the new electrode materials significantly improved durability, additional instability was still observed during cable separation. This indicated that the problem was not exclusively related to electrode wear, but also to the dynamics of the cutting mechanism itself. Consequently, a redesign of the electrode opening concept was investigated.

3.4.4. Implementation of an Electrode Opening System in Electric Cutting

Following improvements made to the line's electric cutting station, it was determined that the cutting concept in use needed to be changed, specifically with regard to electrode opening. The opening of the electrodes refers to the movement of separation between the two electrodes of each pair (located opposite each other and arranged laterally in relation to the cable), in the longitudinal direction of the part. This movement, when correctly timed, contributes to a cleaner and more effective cut, significantly reducing the formation of metal burrs.

Initially, the cutting process on this line operated without any electrode opening. This configuration can be effective on manual assembly lines, where the operator can actively intervene, holding the cable during cutting, maintaining its alignment, and helping to separate it at the exact moment the electrical discharge occurs. However, on a fully automatic production line, as is the case with the line in question, the absence of opening often resulted in defective cuts, as the cable was not stretched or separated optimally at the moment of breakage.

To overcome this limitation, a mechanical electrode opening system using springs was implemented. The new system now includes two fixed electrodes (one on each side of the cable) and two movable electrodes, positioned next to the fixed ones. The movable electrodes are mounted on structures that include compression springs, which are responsible for generating the opening movement at the exact moment of cutting.

In terms of operation, during the approach phase of the two pairs of electrodes, both remain in the closed position, slightly compressing the cable and ensuring the necessary contact for the electrical discharge. At the moment of discharge, when the cable begins to yield to the break caused by the high intensity of the current, the springs exert force on the movable electrodes, promoting a slight separation from the fixed electrodes. This movement helps to stretch and separate the cable better, preventing the wires from overlapping or deforming irregularly, which previously caused burrs to form. The timing and extent of the opening are automatically and passively controlled by the springs themselves, ensuring that the movement occurs exclusively at the right moment of the cut—neither too early, which would compromise electrical contact, nor too late, which would prevent proper separation.

This new concept proved to be a significant improvement over the previous version, especially for automatic lines, where the absence of human intervention requires mechanisms that consistently and repetitively guarantee the quality of the cut. In addition to substantially reducing the number of cables with burrs, this solution also contributed to increasing the reliability of the process and reducing downtime due to errors.

Figure 14 shows the cutting section in the electric cutting machine, illustrating the two pairs of electrodes, the blocks that support them, and indicating the direction of opening of the movable electrodes.

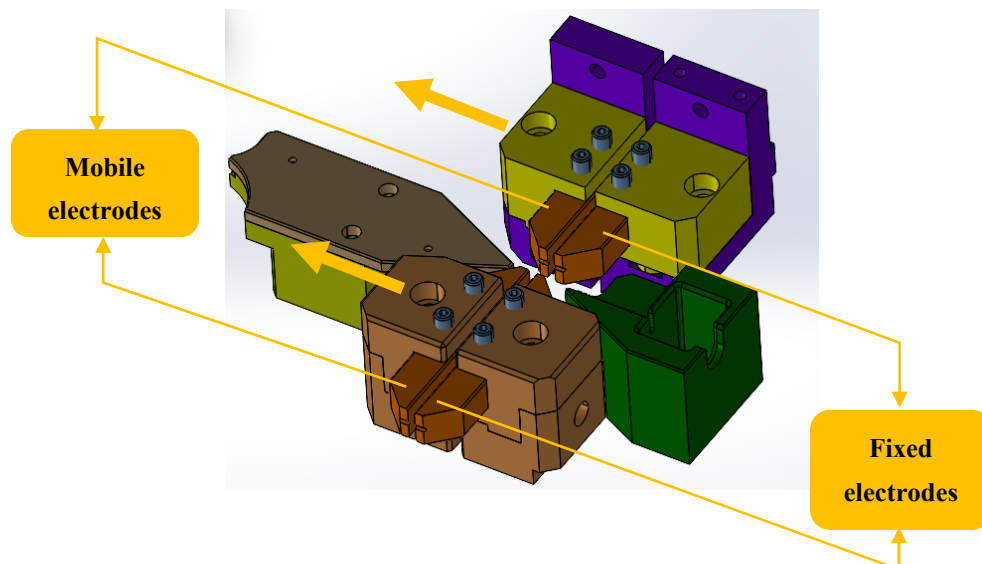


Figure 14. 3D model of the cut section in Line X.

3.4.5. Changing the Electrical Connections of the Electrodes

This intervention focused on how electrical connections were made to the electrodes. As is well known, electrical cutting is based on the discharge between two conductive electrodes. For this discharge to occur, one of the electrodes must be connected to the positive pole and the other to the negative pole of the power supply, allowing a high-intensity current to pass through the cable, melting it and causing it to separate.

In the original configuration of the line, this electrical connection was present in only one of the pairs of electrodes, more precisely in the mobile pair, which moves closer to and further away from the cable in the transverse direction. The second pair of electrodes, which was fixed, had no electrical connection, functioning solely as a mechanical support and point of contact with the cable. This configuration allowed the cut to be made, as the current could still be closed, but it generated an asymmetrical electric field. This asymmetry often resulted in slanted or irregular cuts, as the electrical discharge started preferentially on the powered side, causing uneven wear and melting of the cable.

Figure 15 is a diagram illustrating the situation before the intervention, where only one pair of electrodes has an electrical connection.

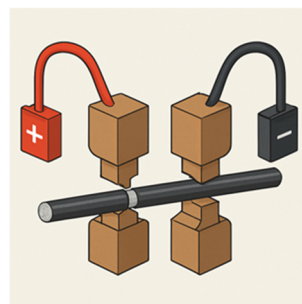


Figure 15. Pre-intervention electrical connection diagram.

To solve this problem, the intervention consisted of replicating the electrical connection on both sides of the cable. This was done by electrically connecting each electrode of the already connected pair (mobile) to the corresponding electrode of the opposite pair (fixed), thus ensuring that both sides of the cable were subject to a direct and balanced electrical discharge.

In Figure 16, you can see the four electrodes with the connections already made. The two upper electrodes are connected directly to the power supply by the red cables, functioning as the main electrodes. The two lower electrodes are connected to the upper ones by additional connecting cables, allowing the current to flow between the lower pair as well, thus completing the circuit and ensuring a discharge on both sides of the cable.

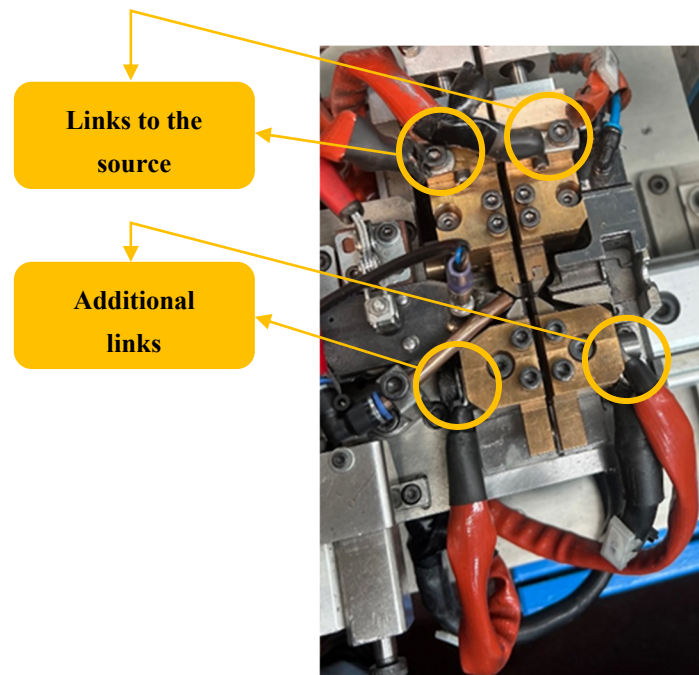


Figure 16. Post-intervention electrode connections.

With this change, there is now a symmetrical discharge in the two pairs of electrodes, one on each side of the cable, ensuring that the electric field generated in the process is uniform and centered. This balance in the electric field brought several advantages, including cleaner cuts with less burrs, cutting sections more perpendicular to the cable axis (elimination of unwanted tilt), more uniform electrode wear, and greater predictability and repeatability of the process, which is essential in an automatic line.

This intervention thus proved decisive in ensuring the quality and reliability of the electric cut, improving process performance and drastically reducing the need for corrective stoppages caused by cutting defects.

3.4.6. Creation of Gauges for Electrode Placement

Another important intervention carried out at the electric cutting station was the creation and implementation of electrode positioning gauges, with the aim of optimizing the process of replacing or cleaning them. Before this improvement, whenever the electrodes were removed, whether for maintenance, replacement due to wear, or cleaning, it was also necessary to dismantle the metal supports where they were fixed and then manually and imprecisely reposition the electrodes in relation to the support. This process was not only time-consuming, but also carried the risk of misaligning the electrodes, which compromised the quality and precision of the electric cut and could lead to defects such as slanted cuts or burrs.

To solve this problem, a set of placement gauges was developed, specifically modelled for each position of the electrodes in the machine. These gauges consist of a single, custom-machined part into which the bracket and electrode are inserted. Both are placed against high-precision machined reference surfaces inside the gauge and then secured with screws in their final position. This approach ensures that the distance from the tip of the electrode to the end of the support is always exactly the same, eliminating margins of error and ensuring the correct functioning of the electrical cut immediately after assembly.

Figure 17 shows the three-dimensional model of one of the gauges developed, highlighting its functional simplicity and geometry adapted to the dimensions of the electrodes and holders. Figure 18 shows a holder and its respective electrode fitted inside the gauge, ready to be fixed in the correct position.

Regarding the material used in its production, tempered RL 200 was selected, a choice justified by the material's high mechanical strength, dimensional stability, and surface hardness. These characteristics make the gauges robust and wear-resistant, ensuring that they maintain their dimensions and functionality even after multiple cycles of assembly, disassembly, and contact with tools or industrial oils.

With this solution, electrode replacement time has been significantly reduced and process accuracy ensured, directly contributing to the stability and efficiency of the electric cutting station.

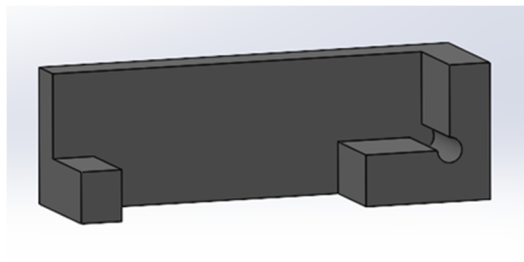


Figure 17. CAD model of a developed gauge.

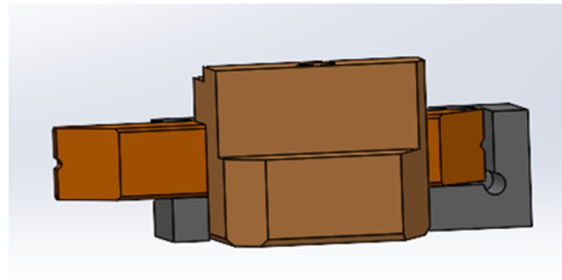


Figure 18. CAD model of an electrode and holder in the respective gauge.

3.4.7. Modification of Rear Door for Cable Removal and Cleaning

This intervention consisted of improving the rear door of the production line, through which the operator accesses the interior of the machine to remove cut cables and clean the equipment. Originally, the existing door was small and opened vertically, limiting access and significantly hindering the cleaning operation. This situation is shown in Figure 19, where it can be seen that the usable area of the plate was not fully utilized.

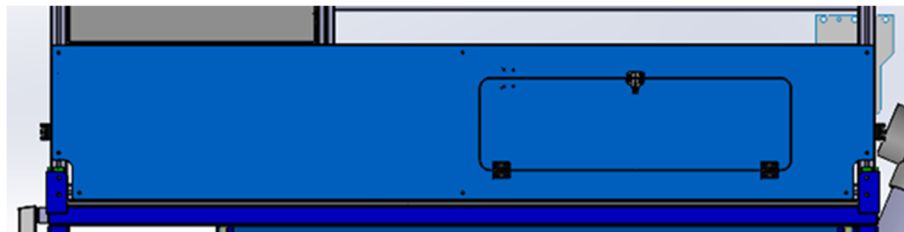


Figure 19. Rear door of the X Line.

With the aim of increasing operator comfort and operational efficiency, a new solution was implemented: a larger side-opening door that occupies virtually the entire available area of the sheet metal. This new door was designed by reusing part of the existing structure—namely, the aluminum profiles, handle, and hinges already used in the previous version (in the 3D model of the initial door, the hinges differ from the actual ones, as the company's existing 3D model was outdated).

The execution involved cutting the original sheet in half, keeping the left half and replacing the right half with a functional door and a small additional fixed sheet. The holes necessary for the correct fitting and operation of the new door were included, as well as the elements for fixing it to the aluminum structure. The new configuration is illustrated in Figures 20–22, which show the CAD model of the final door, open and closed, as well as the reuse of components.

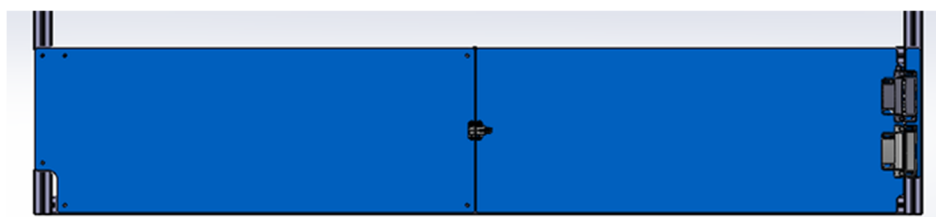


Figure 20. Rear door of the X Line after intervention.

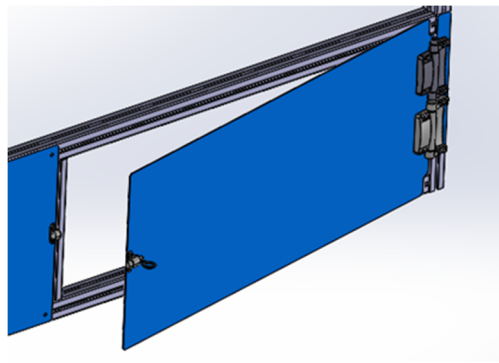


Figure 21. Rear door of the X Line opened after intervention.



Figure 22. Structure of the rear door of the X Line after intervention.

This intervention made it possible to substantially improve the operator's access and operating conditions, without the need for major investments, using simple and functional solutions based on the efficient reuse of resources already available in the company.

4. Results—Guidelines/Concept Development

After implementing the proposed mechanical and process improvements, a monitoring phase was initiated to evaluate their impact on production stability and operational efficiency. This monitoring was conducted between calendar weeks 14 and 18 of 2025. The effectiveness of the interventions was assessed primarily through OEE and its associated indicators, allowing quantitative validation of the developed solutions. This indicator summarizes the three fundamental parameters, Availability (AV), Performance (PF), and Quality (Q), and is the most relevant metric for assessing the real impact of the improvements implemented on the line. Although the other indicators continue to be monitored for the purposes of controlling production levels and identifying critical points for continuous improvement, it is through OEE that an integrated view of overall performance is obtained, allowing a direct comparison of results before and after the interventions.

Figure 23 shows the evolution of OEE (gross and corrected values) in the post-intervention period, while Table 4 summarizes the data that gave rise to the graphs presented. This table also presents the objectives (obj) that are intended to be achieved for the various indicators.

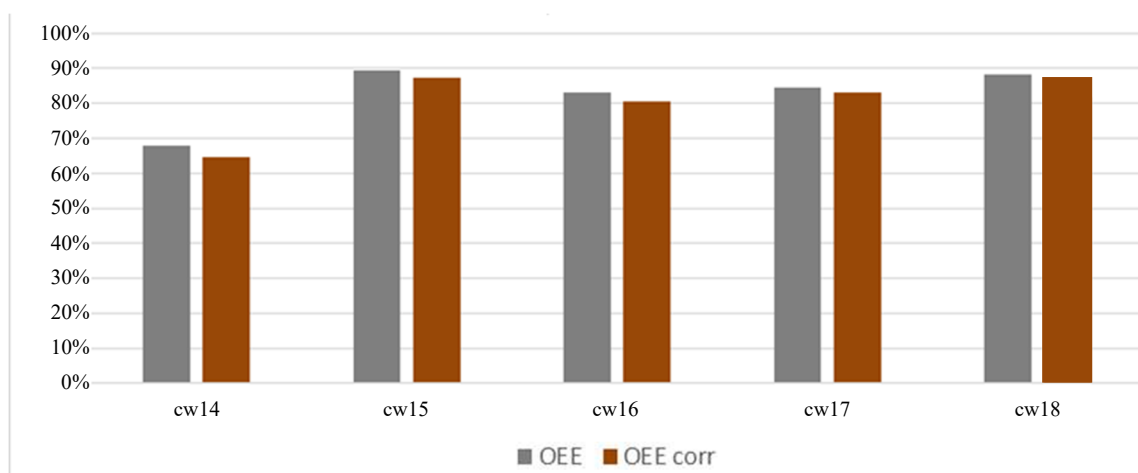


Figure 23. OEE chart for Line X after interventions.

Table 4. OEE Line X post-interventions.

	cw14	cw15	cw16	cw17	cw18
OEE (obj)	85%	85%	85%	85%	85%
AV (obj)	90%	90%	90%	90%	90%
PF (obj)	95%	95%	95%	95%	95%
Q (obj)	99%	99%	99%	99%	99%
OEE	68.00%	89.40%	83.20%	84.40%	88.30%
OEE corr	64.63%	87.25%	80.52%	82.99%	87.67%
AV	67.50%	82.00%	79.20%	81.00%	80.70%
PF	100.00%	109.00%	105.00%	104.20%	109.40%
Q	95.74%	97.61%	96.83%	98.32%	99.30%
PPM	44.000	23.900	31.700	16.800	7.000

There has been a significant improvement compared to the pre-intervention period. The corrected OEE, which previously had an average value of 42%, is now mostly above 80%, even reaching 87.7% in cw18. The weekly consistency of the results shows that the line has regained operational stability, achieving values significantly close to the defined overall target (85%).

In cw14, however, slightly lower values are observed, which can be explained by the fact that it was the first week of operation after the implementation of the interventions. During this period, several changes introduced required a short adaptation period on the part of technicians and operators, temporarily affecting overall performance. The main changes implemented, already presented in subsection 2.4, and which required some adaptation from technicians and operators in cw14, were:

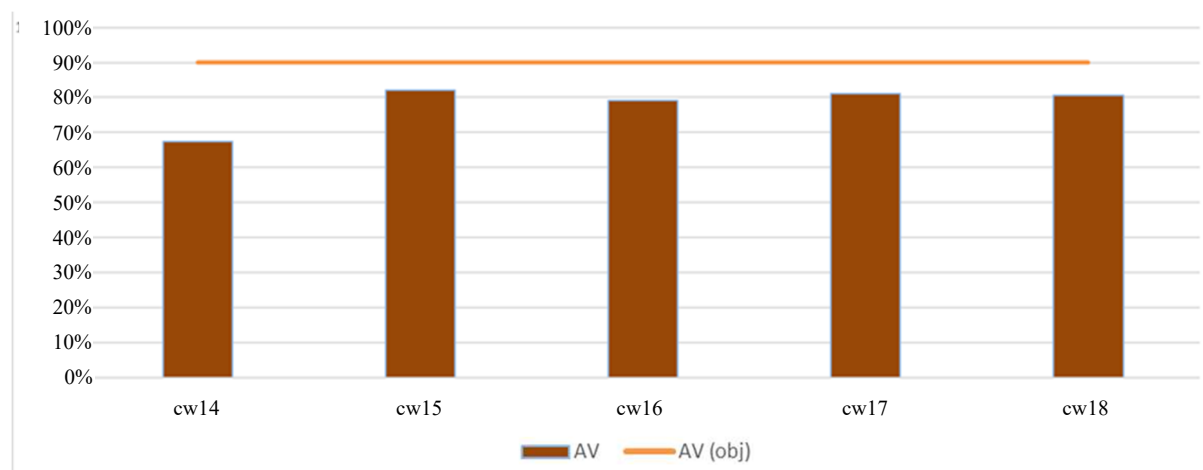
- the application of a roughing drill for the spiral, which helped reduce cable insertion failures;
- the correction of the misalignment between the spiral and the terminal, eliminating associated rejections;
- the optimization of the electric cutting process with new electrodes, gauges, opening system, and electrical connections, ensuring more stable and durable cuts, and improving process performance while drastically reducing the need for corrective stoppages caused by cutting defects;
- the improvement of the rear door of the line, increasing safety, operator access, and operating conditions.

The evolution presented in Figure 23 and Table 4 demonstrates that the actions implemented were effective in eliminating critical losses that previously heavily penalized the line. Still, to understand the origin of this overall improvement, it is necessary to analyze the three components of OEE individually, starting with Availability.

Although it has not yet reached the 90% target, Availability is substantially higher than in the period prior to the interventions, when it fluctuated between 53.5% and 84.3%, with sharp drops in critical weeks. After the improvements, the indicator stabilized between 67.5% (cw14) and 82.0% (cw15), remaining close to 80% in the following weeks. Once again, cw14 represents the lowest value, a natural consequence of the initial adaptation phase after the interventions. After that transition week, Availability showed greater stability.

Having analyzed Availability, it is pertinent to observe the behavior of Performance, which showed great instability in the previous period (see Table 1).

Figures 24 and 25 present the results of the Availability indicator and the evolution of Performance after the interventions, respectively.

**Figure 24.** Graph showing Line X Availability after interventions.

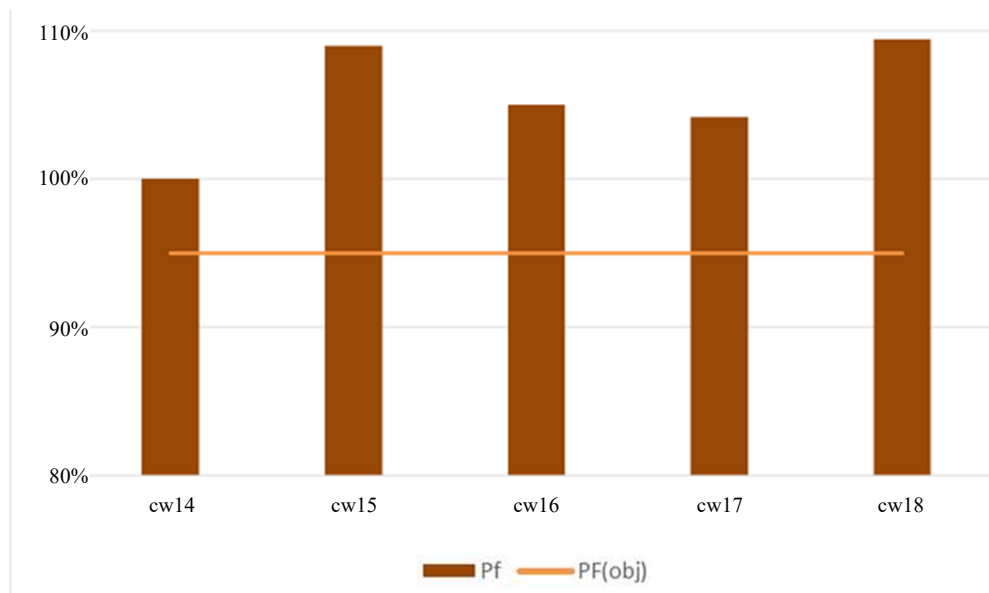


Figure 25. Line X Performance Chart after interventions.

The PF indicator shows a notable improvement. Before the interventions, performance was highly unstable, ranging between 38.8% and 105.7% (with an average value of 66.2%), and only occasionally approached or exceeded the 95% target. After the actions were implemented, the target was systematically exceeded, with values between 100% and 109.4%, reflecting gains in speed and process efficiency.

In cw14, performance recorded the minimum value for the period analyzed (100%), which still represented a significant improvement in the situation prior to the interventions. This slightly lower value may also be associated with the initial adaptation phase of the operators.

With a clearly consolidated Performance, it remains to evaluate the last OEE parameter, Quality, shown in Figure 26.

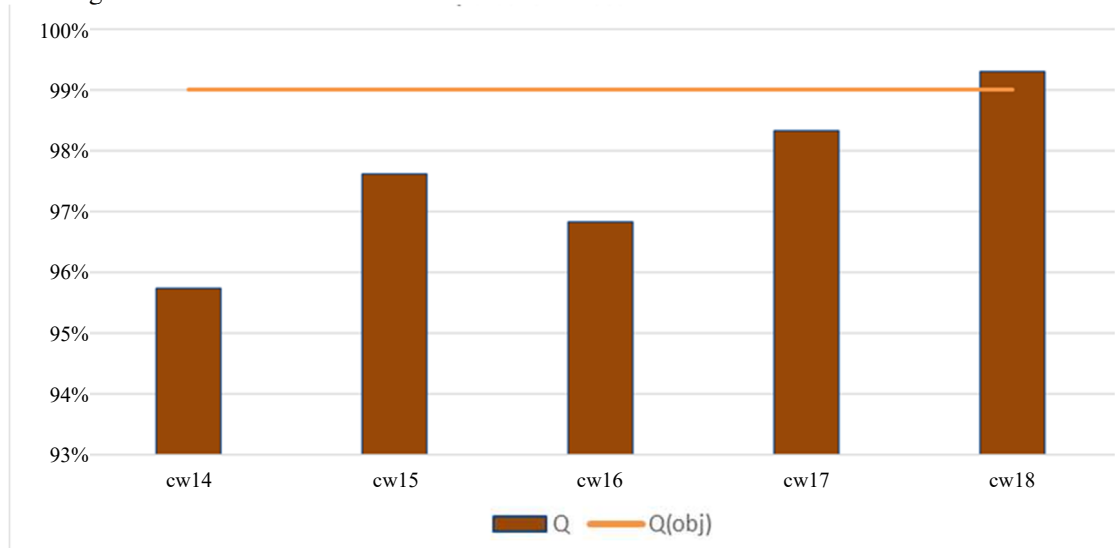


Figure 26. Line X Quality Chart after interventions.

Quality was already high in the pre-intervention period, remaining above 90%. After the improvements, there was a further increase, with values ranging from 95.7% (cw14) to 99.3% (cw18), approaching the target of 99%.

Here too, cw14 corresponds to the lowest value (95.7%), which is consistent with the context of the first week after the line started up, when operational adjustments were still being assimilated. From the following week onwards, quality stabilized at levels close to the target.

Thus, having analyzed each component individually, it is possible to summarize the results obtained and relate them to the overall performance of the line.

Table 5 presents a comparative summary of the average pre- and post-intervention values of OEE and its three associated indicators. The comparison clearly demonstrates the effectiveness of the implemented solutions,

particularly regarding the substantial increase in corrected OEE to stable levels above 80%, very close to the target (85%). Availability increased and became more consistent, although still slightly below the target (90%). Performance showed the most significant improvement, systematically exceeding the target (95%), while Quality consolidated at close the target (99%). The non-compliance rates (ppm) are discussed in the following section. It should be noted that the values from cw14 might not be considered in this comparison, as this was the first calendar week following the intervention carried out on Line X, which reflects the team's adaptation period to the new context. If this calendar week were excluded, the results would be much better, since it was in cw14 that the worst indicators were recorded. Overall, the results confirm that the actions implemented had a positive and sustained impact on the performance of line X.

Table 5. Comparison of pre- and post-intervention performance indicators.

	Pre-intervention cw45/2024–cw11/2025			Post-intervention cw14–cw18/2025		
	Minimum	Maximum	Average	Minimum	Maximum	Average
OEE corr	23.10%	61.70%	42.09%	64.63%	87.67%	78.85%
AV	53.53%	84.34%	68.40%	67.50%	82.00%	77.43%
PF	38.84%	105.69%	66.20%	100.00%	109.40%	104.55%
Q	90.18%	97.67%	94.01%	95.74%	99.30%	97.13%
PPM	23,300	98,208	59,905	7000	44,000	29,100

5. Discussion—Validation of the Concept through a Case Study

To validate and contextualize the results achieved in the optimization of Line X, it is essential to establish a basis for comparison with similar studies documented in the literature, where technical and methodological interventions were applied to resolve inefficiencies in automotive assembly lines.

A relevant example is the study conducted by Pereira et al. [13], which applied the A3 methodology to improve the efficiency of an assembly line. In this work, the structured identification of problems allowed for the implementation of actions that significantly increased productivity. In the present study, the approach followed a similar logic of diagnosis and resolution (via Design Science Research), but with a more pronounced technical focus on process failures (cutting and insertion). When comparing the scenarios, it can be observed that Line X started from a critical scenario (corrected OEE average of 42%) to achieve corrected OEE values above 80% (with a peak of 87.7% in cw18), as evidenced in the results. This evolution of more than 35 percentage points validates the premise that, in complex automatic systems, technical stabilization is a prerequisite for operational efficiency.

The relevance of automation and stabilization of processes with flexible components, such as Bowden cables, is also discussed by Martins et al. [25] and Eiras et al. [4]. These authors demonstrated that the introduction of fully automatic concepts for handling and assembling these cables drastically reduces the variability associated with the human factor and handling defects. The present work corroborates these conclusions: the introduction of the spiral cleaning tool and the new electrode opening system eliminated recurring insertion and burr failures. While Eiras et al. [4] focused on the development of new equipment from scratch, this study demonstrates that it is possible to achieve comparable productivity gains by reengineering critical components in existing lines (retrofit), a strategy that is often more economically viable for the industry.

Analyzing specifically the Performance indicator (PF), the results obtained (above 100%, reaching 109.4% in cw18) deserve particular mention when compared to the work of Reis et al. [32], which addresses the implementation of TPM strategies. Performance values above 100% indicate that optimizations in the electric cutting cycle and in the synchronization of machine movements made it possible to exceed the initially defined theoretical nominal cadence. This suggests that the elimination of micro-stops and the optimization of setup times (SMED), as advocated by Sousa et al. [11] in the cork industry and transposed here to the automotive sector, have freed up hidden production capacity, allowing the line to operate more smoothly and quickly.

With regard to quality and waste reduction, the comparison with the study by Pereira et al. [5] on improvements in ZAMAK injection machines is pertinent. Just as Pereira et al. [5] managed to stabilize the process through improvements in component design, in Line X, the replacement of conventional electrodes with tungsten-tipped copper-beryllium electrodes resulted in a drastic drop in non-compliance rates (ppm). The reduction from 44,000 ppm in the start-up week (cw14) to 7000 ppm in cw18 demonstrates a trend toward quality stabilization compatible with the demanding requirements of the automotive sector. This result reinforces the thesis of Pinto et al. [26], who warns of the need for strict control of material properties (such as oxidation or wear) to avoid functional failures.

However, there is an important difference to notes in Availability. Although there was a substantial improvement (stabilizing at around 81%), this indicator remained slightly below the 90% target. Comparing with

the study by Santos et al. [33], who improved an APEX machine through mechanical interventions, it appears that full recovery of availability is often the slowest parameter to achieve, requiring a period of maturation of preventive and autonomous maintenance routines. The persistence of some stoppages in Line X suggests that, despite the success of the main interventions, there is still room for the application of continuous improvement tools to iron out the remaining rough edges.

In summary, discussion of the results in light of the literature confirms that combining diagnostic methodologies (DSR) with precision engineering solutions (new electrodes and tools) is a highly effective strategy. The study not only replicates the efficiency gains reported in previous works [13], but also adds value by demonstrating the effectiveness of specific solutions for electrical cutting, contributing to the body of knowledge on the optimization of control cable assembly lines. Although this study focused on an automotive cable assembly line, the methodology and engineering approach adopted can be generalized to other industrial sectors involving automated assembly, precision cutting, deformable component handling, or repetitive high-cycle operations. Industries such as electronics manufacturing, appliance assembly, medical device production, and wire-processing systems may benefit from similar strategies combining OEE-driven diagnostics, targeted mechanical redesign, predictive maintenance principles, and process stabilization techniques. Therefore, the proposed framework represents not only a case-specific optimization strategy but also a transferable model for improving efficiency and reliability in complex automated manufacturing environments.

Despite the positive results obtained, some limitations should be acknowledged. As mentioned earlier, the methodology used in this study can be applied to other industrial sectors; however, the effectiveness of the proposed interventions may still vary when applied to different production environments or scales. Additionally, while the implemented solutions demonstrated strong short-term performance improvements, their long-term sustainability depends on continuous monitoring, maintenance practices, and operator engagement. From an economic perspective, although the interventions were relatively low-cost and focused on critical process points, scaling these solutions to larger production systems may require additional investment and adaptation. Future work should therefore focus on evaluating the long-term performance stability and cost-effectiveness of these solutions in different industrial settings.

6. Conclusions

The analysis conducted in this investigation demonstrated that the structured application of continuous improvement methodologies, supported by Lean Manufacturing principles, Total Productive Maintenance (TPM), and Overall Equipment Effectiveness (OEE) monitoring, is a highly effective approach to optimizing production lines in the automotive sector. The line under study showed structural flaws in the areas of productivity, availability, and quality, which compromised the achievement of the strategic goals set by the organization (Pieces per Human Hour (PHH) = 450 units/hour and $OEE \geq 85\%$). Through a carefully designed technical and organizational intervention, it was possible to transform the line's operational performance, scientifically validating the effectiveness of the adopted model. The main measures implemented, including the development of a roughing drill to optimize cable insertion, the correction of mechanical misalignments between the spiral and terminal, the improvement of electrical cutting with customized electrodes and gauges, and structural optimization of the production cell, made it possible to eliminate the main causes of unplanned downtime and significantly reduce the number of rejects. These improvements not only resolved the identified failures but also promoted a significant increase in operational indicators. The corrected OEE, which initially ranged between 23.1% and 61.7% (average close to 42%), now reaches stable values around 80%, representing an average gain of more than 35 percentage points. This result brings the line closer to the world-class levels reported in the literature and confirms the relevance of the strategy adopted. Hourly performance (PHH) approached the benchmark of 450 units/hour, with production peaks of 445 units/hour achieved with only one operator, confirming the feasibility of the defined objective. The analysis of the OEE components also allowed for the verification of simultaneous improvements in Availability, Performance, and Quality, demonstrating that the gains obtained were consistent and sustainable from an operational standpoint. From a scientific point of view, this study validates the effectiveness of incremental interventions based on real operating data, demonstrating that engineering improvements conducted in a structured manner can generate results equivalent to or superior to those obtained through complete reengineering, but with significantly lower costs and risks. From an industrial perspective, the results show that the use of Lean tools, combined with systematic failure analysis and rigorous control of indicators, represents a high-return strategy for companies in the automotive sector that operate under highly competitive pressure and sustainability requirements.

In addition, the results achieved create a solid foundation for future optimization actions, including the integration of digital solutions and Industry 4.0 technologies, which could further enhance line performance by

ensuring data traceability, real-time monitoring, and predictive capabilities. Thus, this work proves the effectiveness of the interventions implemented and establishes a replicable model for other production lines with similar characteristics.

In summary, the objectives initially defined were largely achieved. The study contributes to the advancement of scientific knowledge on continuous improvement in the automotive industry, reinforces the practical applicability of Lean + OEE methodologies, and demonstrates that operational excellence is achievable through the balanced integration of engineering, data analysis, and organizational involvement. Unlike previous studies primarily focused on the development of new automated systems, the present work demonstrates the effectiveness of targeted retrofit engineering interventions applied directly to an existing industrial production line operating under real manufacturing constraints. Future developments should focus on the integration of Industry 4.0 technologies to support a data-driven continuous improvement strategy. In particular, the implementation of smart sensors in critical stations, such as the electric cutting and cable insertion systems, would enable real-time monitoring of variables including electrode wear, cutting temperature, insertion force, vibration, and cycle time deviations. The acquisition of these operational data could support predictive maintenance and machine learning models capable of anticipating failures before the occurrence of stoppages or quality defects. In parallel, the development of digital dashboards and predictive analytics tools would allow dynamic monitoring of OEE components, facilitating faster decision-making and reducing response times to process deviations. A digital twin of the production line could also be implemented to simulate operating conditions, optimize machine parameters, and evaluate process modifications before physical deployment.

Author Contributions

R.D.S.G.C.: conceptualization; I.M.P., A.G.P. and R.L.: methodology; A.G., I.P.F. and M.B.: data curation, visualization; R.L.: writing—original draft preparation; A.G.P. and M.B.: investigation; R.D.S.G.C.: supervision; A.G., I.P.F. and I.M.P.: validation; I.M.P. and A.G.P.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data will be made available upon request.

Conflicts of Interest

The authors declare no conflict of interest. Given the role as Senior Consulting Board Member, Raul D. S. G. Campilho had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used an AI tool, ChatGPT, to revise the document. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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