Revista ARACÊ
ISSN: 2358-2472

INTELLIGENT AUTOMATION AND DIGITAL TRANSFORMATION IN TRANSFORMER MANUFACTURING: AN APPLIED STUDY OF THE TRAFO ULC PROTOTYPE AT FLEX INDUSTRIES

AUTOMAÇÃO INTELIGENTE E TRANSFORMAÇÃO DIGITAL NA FABRICAÇÃO DE TRANSFORMADORES: UM ESTUDO APLICADO DO PROTÓTIPO TRAFO ULC NA FLEX INDUSTRIES

AUTOMATIZACIÓN INTELIGENTE Y TRANSFORMACIÓN DIGITAL EN LA FABRICACIÓN DE TRANSFORMADORES: UN ESTUDIO APLICADO DEL PROTOTIPO TRAFO ULC EN FLEX INDUSTRIES

https://doi.org/10.56238/arev7n11-074

Submission date: 10/10/2025 **Publication Date:** 11/10/2025

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ABSTRACT

Digital transformation and Industry 4.0 principles have driven profound structural changes in global manufacturing, driving the integration of information technology and physical processes. This study presents the development and validation of the TRAFO ULC prototype, an automated system designed for the winding and application of high-insulation tape on high-frequency transformers, developed by B&Z Serviços de Automação in partnership with Flex Industries. The project incorporates embedded artificial intelligence (IAE) and cyber-physical systems (CPS) to optimize production efficiency, reduce errors, and eliminate ergonomic risks. The methodology adopted combined agile project management practices (Scrum and PMI) with applied research and experimental development, using 3D modeling, PLC control, and intelligent algorithms to coordinate sensors and actuators. The results demonstrated a 99.85% increase in process compliance, a reduction in failures from 6.7% to 0.5%, and the elimination of absences due to occupational hazards. These advances demonstrate that intelligent automation is a strategic driver of competitiveness and sustainability in the Manaus Industrial Hub (PIM), directly contributing to technological innovation, improved production efficiency, and improved working conditions in regional industrial plants.

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Revista ARACÊ
ISSN: 2358-2472

Keywords: Industry 4.0. Intelligent Automation. Cyber-Physical Systems. Transformers. Manaus Industrial Pole.

RESUMO
A transformação digital e os princípios da Indústria 4.0 impulsionaram profundas mudanças estruturais na manufatura global, impulsionando a integração da tecnologia da informação e dos processos físicos. Este estudo apresenta o desenvolvimento e validação do protótipo TRAFO ULC, um sistema automatizado projetado para o enrolamento e aplicação de fita de alto isolamento em transformadores de alta frequência, desenvolvido pela B&Z Serviços de Automação em parceria com a Flex Industries. O projeto incorpora inteligência artificial embarcada (IAE) e sistemas ciberfísicos (CPS) para otimizar a eficiência da produção, reduzir erros e eliminar riscos ergonômicos. A metodologia adotada combinou práticas ágeis de gerenciamento de projetos (Scrum e PMI) com pesquisa aplicada e desenvolvimento experimental, utilizando modelagem 3D, controle de CLP e algoritmos inteligentes para coordenar sensores e atuadores. Os resultados demonstraram um aumento de 99,85% na conformidade do processo, uma redução nas falhas de 6,7% para 0,5% e a eliminação de ausências por riscos ocupacionais. Esses avanços demonstram que a automação inteligente é um impulsionador estratégico da competitividade e sustentabilidade do Polo Industrial de Manaus (PIM), contribuindo diretamente para a inovação tecnológica, melhoria da eficiência produtiva e melhoria das condições de trabalho nas plantas industriais regionais.

Palavras-chave: Indústria 4.0. Automação Inteligente. Sistemas Ciberfísicos. Transformadores. Polo Industrial de Manaus.

RESUMEN
La transformación digital y los principios de la Industria 4.0 han impulsado profundos cambios estructurales en la manufactura global, fomentando la integración de la tecnología de la información y los procesos físicos. Este estudio presenta el desarrollo y la validación del prototipo TRAFO ULC, un sistema automatizado diseñado para el bobinado y la aplicación de cinta aislante de alta eficiencia en transformadores de alta frecuencia, desarrollado por B&Z Serviços de Automação en colaboración con Flex Industries. El proyecto incorpora inteligencia artificial integrada (IAE) y sistemas ciberfísicos (CPS) para optimizar la eficiencia de la producción, reducir errores y eliminar riesgos ergonómicos. La metodología adoptada combinó prácticas de gestión de proyectos ágiles (Scrum y PMI) con investigación aplicada y desarrollo experimental, utilizando modelado 3D, control PLC y algoritmos inteligentes para coordinar sensores y actuadores. Los resultados demostraron un aumento del 99,85 % en el cumplimiento del proceso, una reducción de fallos del 6,7 % al 0,5 % y la eliminación de las ausencias por riesgos laborales. Estos avances demuestran que la automatización inteligente es un motor estratégico de la competitividad y la sostenibilidad del polo industrial de Manaus (PIM), contribuyendo directamente a la innovación tecnológica, la mejora de la eficiencia de la producción y la mejora de las condiciones laborales en las plantas industriales regionales.

Palabras clave: Industria 4.0. Automatización Inteligente. Sistemas Ciberfísicos. Transformadores. Centro Industrial de Manaus.

Revista ARACÊ
ISSN: 2358-2472

1 INTRODUCTION

The so-called Fourth Industrial Revolution, or Industry 4.0, is characterized by the strategic integration of digital technologies, automated systems, and computational intelligence, resulting in significant changes in the organization and operation of production systems (Schwab, 2016; Hermann et al., 2016). In the Brazilian context, the Manaus Industrial Pole (PIM) stands out as a crucial ecosystem for the adoption of these technologies, both for its consolidated technological base and for the tax and regulatory incentives that stimulate research, development, and innovation initiatives (SUFRAMA, 2023).

In 2020, the electronic payments sector in Brazil recorded a significant growth of 8.2% compared to the previous year, totaling R$2 trillion in transactions with credit, debit, and prepaid cards. With the impact of the emergency aid, this increase was increased to 11.1%, reflecting a significant increase in financial transactions. This scenario has driven the demand for equipment such as card machines, which require high-tech components, such as ferrite transformers produced by Flex Industries in the PIM.

The company manufactures these transformers, which are essential for increasing the switching frequency of POS (point of sale) machines, and to meet this growing demand, it needs to ensure large-scale production while maintaining strict quality standards. To this end, all transformers undergo quality control tests, using low conductivity materials and specific insulation techniques, such as class H varnish and adhesive polyester, which help minimize power losses. Despite the advantages, ferrite cores present challenges, such as low saturation flux density and sensitivity to mechanical shocks, which need to be mitigated to ensure product reliability and efficiency.

The literature points out that automation projects are potential strategies to increase production efficiency and quality in industrial processes, especially in contexts that demand high precision and control (Zuehlke, 2010; Kusiak, 2017). Automation, by integrating digital technologies and intelligent systems, offers significant opportunities for reducing human error, optimizing processes, and improving the consistency of final products. In this scenario, the automation of precision electromechanical processes, such as winding and the application of insulators in transformers, has shown particular promise.

The present research seeks to investigate the feasibility of implementing automation solutions in the manufacturing process of high-frequency transformers, through the development of a prototype of an automated station with embedded software, aiming to improve the accuracy of the production process, reduce non-conformities and minimize ergonomic risks in the manufacturing environment, in line with the principles of Industry 4.0.

Its specific objectives are: the critical analysis of failures in the manual production process, seeking to identify points of improvement that can be applied in the development of automated solutions; the development of the automated prototype, based on the identified failures, aiming to improve the efficiency, quality and safety of the production process, based on the concept of Industry 4.0; and the realization of a comparison between the production process with and without the automated prototype, in order to evaluate the gains in efficiency, quality and safety.

With this, it is expected not only to optimize the production of transformers, but also to improve working conditions, with the reduction of repetitive and physically demanding tasks, promoting a safer environment in line with the requirements of Industry 4.0.

2 THEORETICAL FRAMEWORK

In this section, the theoretical foundation that supports the research will be presented, covering the key concepts, theories and previous studies that guide the analysis and implementation of the project. The main academic references related to Industry 4.0, process automation, energy efficiency and the use of ferrite transformers will be discussed. Through this review, we seek to contextualize the research theme within the state of the art, highlighting the most relevant approaches and the gaps identified in the literature, which justify the application of automation in the specific context of the manufacture of transformers for electronic payment systems.

2.1 ECONOMIC AND TECHNOLOGICAL CONTEXT

In recent years, the use of electronic means of payment has grown exponentially, driven both by the digitalization of consumption and by the expansion of banking access via mobile devices. According to the Brazilian Association of Credit Card and Services Companies (Abecs, 2020), the volume of transactions with credit, debit, and prepaid cards reached R$ 2 trillion, representing 30.9% of the national GDP. This growth is due not only to technological adoption, but also to the impact of public policies such as emergency aid, which have intensified the use of digital accounts and prepaid cards.

Authors such as Schwab (2016) and Kagermann et al. (2013) highlight that this advance is directly associated with Industry 4.0, which proposes the integration of physical and digital systems, resulting in more intelligent, flexible, and interconnected production processes. In the context of payment terminal manufacturing companies, such as those that produce chargers and transformers for card machines, automation is a strategic factor to increase productivity, reduce costs, and ensure quality and traceability.

2.2 TECHNICAL FUNDAMENTALS OF TWO TRANSFORMERS

The ULC_FSP05 transformer, the focus of this study, is an essential component in credit card machine chargers. According to Petrescu et al. (2019), ferrite transformers (mainly Mn-Zn) have advantages for high frequency applications (10 kHz to 100 kHz), due to their low magnetic loss, high resistivity and efficient insulation. These properties allow for miniaturization of converters and reduction of hysteresis losses, which is critical in compact, high-efficiency feeding systems, often in excess of 99%.

However, the low magnetic saturation density (0.3T) and the mechanical fragility of ferrites require rigorous and controlled production processes, avoiding cracks and misalignments. As Flynn (2008) and Binns et al. (1992) point out, geometry, air gap and inductance control are determinants for the electromagnetic performance of the transformer. Thus, the automation of steps such as winding and application of insulating tapes becomes crucial to eliminate human variations and ensure repeatability in the process.

2.3 ENERGY EFFICIENCY, AUTOMATION AND CYBER-PHYSICAL SYSTEMS

The literature on manufacturing automation highlights the growing role of cyber-physical systems (CPS) in the integration between logical and mechanical control. According to Lee (2020) and Monostori (2014), a CPS combines sensors, actuators, and embedded software to create intelligent production systems capable of self-tuning and incremental learning. In the case of the automated winding prototype project, this integration is done through C/C++ and Ladder languages, associated with the control of Cartesian manipulators and servo motors, ensuring precision, speed and safety.

The use of Artificial Intelligence (AI) in the architecture of embedded software allows real-time monitoring of critical variables (temperature, torque, speed, cycles), promoting autonomous decisions and reducing human errors. According to Siciliano & Khatib (2016), the concept of repeatability and reproducibility is central in automated systems, as it ensures consistency in final quality, especially in high-precision processes, such as transformer winding.

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2.4 TECHNOLOGICAL INNOVATION AND INDUSTRIAL COMPETITIVENESS

Modern industrial automation is based on the integration between physical and digital systems. Monostori (2014) highlights that Industry 4.0 is based on production systems with high operational autonomy, capable of modifying their behavior according to the data continuously processed during operations. Effective interaction between the physical and digital environments is made possible by the adoption of cyber-physical systems (CPS) and the Industrial Internet of Things (IIoT), which connect physical components, such as sensors and actuators, to digital platforms responsible for the supervision and control of processes (Kagermann et al., 2013).

The development of the described prototype configures an incremental process innovation, according to the concepts of Tidd, Bessant and Pavitt (2018). This category of innovation seeks to improve existing processes, increasing their efficiency, reliability, and safety without substantially altering the final product. In the context of Flex-Industries and B&Z International, the creation of an automated station with embedded software represents the introduction of an unprecedented system in the domestic market, which contributes to the strengthening of Brazilian technological competitiveness.

The integration of the system with the CMES (Manufacturing Execution System) and the use of AI to control production variables are aligned with the smart factory paradigm, in which information is used as a productive resource. Such a practice is in line with the principles of Industry 4.0, especially with regard to digitalization, connectivity, and operational autonomy.

2.5 OPERATOR BENEFITS OF AUTOMATION

Historically, automation has been seen primarily as a way to increase productivity and reduce costs. However, the evolution of studies on automation has also focused on more humanistic aspects, especially with regard to the well-being and safety of the operator. Traditionally, operators have not been the central focus of shop floor improvements. However, with the increasing emphasis on innovation and the evolution of automated systems, the focus has broadened, considering the impact of automation on workers' health and safety.

Research by Dul and Weerdmeester (2008) and Iida (2016) highlights that automated processes, especially those involving repetitive and high-precision tasks, can significantly reduce ergonomic risks and problems related to excessive physical exertion, such as repetitive motion injuries. The automation of steps such as the winding of transformers and the application of insulating tapes contributes to reducing the physical effort of operators, reducing absenteeism and improving working conditions. This focus on improving health and safety conditions is also in line with occupational safety guidelines, such as those established by NR12.

3 METHODOLOGY

3.1 ANALYSIS OF FAILURES IN THE PRODUCTION PROCESS

To perform the data collection and critical analysis of the failures in the non-automated production process, a quali-quantitative and observational diagnostic approach was adopted, with data collection directly on the coiling line under study. Direct observation techniques, semi-structured interviews with technicians and process engineers, as well as documentary analysis of quality, production and maintenance reports were used.

The analysis focused on identifying the causes of nonconformities, inductance variations and ergonomic failures in the manual winding process and application of electrical tape. The production process is a complex and dynamic system, in which several factors interact, such as people, processes, raw materials and time. The identification of failures aimed to carry out a detailed analysis of the factors involved, allowing to know the process in depth and obtain concrete data to support decisions that can generate changes. Such decisions, if not well planned, can cause chain effects that impact other interconnected systems.

The collected data were analyzed using tools such as cause and effect analysis (Ishikawa Diagram) and FMEA (Failure Modes and Effects Analysis), enabling the mapping of the main bottlenecks: ferrite breakage, inadequate assembly of the electrical tape and dimensional variation of the winding. This stage guided the development of the prototype's conceptual planning, guiding decisions related to mechanical architecture, logical control and performance parameters (production ≥ 2000 pieces/hour and compliance ≥ 99.85%).

The results of the analysis are presented in the discussion section, where production performance before and after automation is compared, with an emphasis on reducing failures and improving ergonomic conditions for operators.

3.2 AUTOMATED PROTOTYPE DEVELOPMENT

The development of the automated prototype was guided by the flaws identified in the

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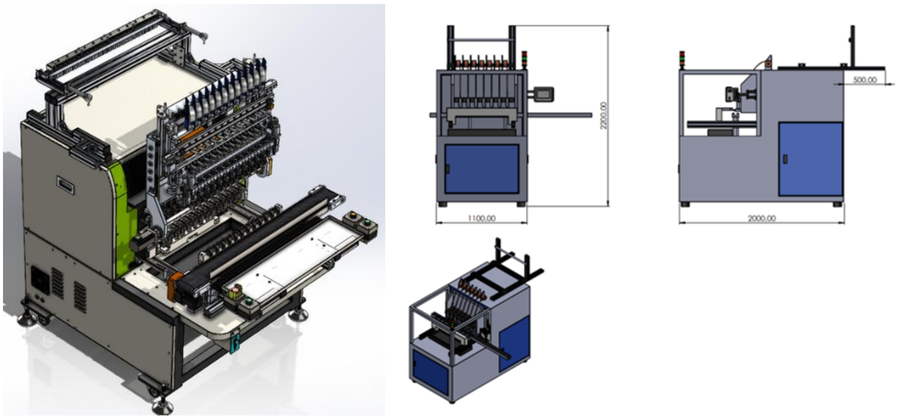
manual production process, with the objective of improving the efficiency, quality and safety of the process, aligning it with the concepts of Industry 4.0. The methodology adopted was divided into three main stages: planning and design, prototyping and implementation, and testing and performance adjustments.

- Planning and Conception

In the first step, the prototype requirements were defined based on the identified critical failures, such as inductance variations and ergonomic failures. The planning involved defining the scope of automation, taking into account the integration of cyber-physical systems (CPS), embedded intelligence (IAE) and industrial interconnectivity (IIoT), aiming at a more efficient and accurate winding process. The choice of components was guided by the needs of high precision and repeatability, considering the best practices of industrial process automation.

Figure 1

Prototype design



Source: Authors, 2025.

- Prototyping and Implementation

The second stage focused on the physical construction and implementation of the automated system. Suitable technologies were selected, including high-precision servo motors, sensors for continuous monitoring, and a programmable logic control (PLC) system. The prototype was designed to automate the winding and application of electrical tape steps, in addition to integrating a feedback system for automatic adjustments in real time, based on embedded AI. The prototype control was developed with a focus on adaptability, allowing quick adjustments to production parameters.

- Performance Testing and Tuning

In the last stage, the prototype was subjected to a series of tests to evaluate its performance in terms of efficiency, quality and safety. The evaluation involved direct comparisons between the manual and automated process, measuring output per hour, compliance with quality parameters, and the reduction of failures. The tests also focused on analyzing the ergonomic conditions for operators, ensuring that automation minimized negative impacts on workers. Based on the results, fine-tuning was made to optimize system performance, utilizing feedback from the prototype to make continuous improvements.

The results obtained during the tests and implementation will be presented in a comparative way, highlighting the gains in terms of productivity, quality and safety. In addition, a detailed flowchart will be provided to illustrate the differences between the manual and automated process, highlighting the improvements in the production chain.

3.3 COMPARISON BETWEEN MANUAL AND AUTOMATED PROCESS

For the third objective, to compare the performance between the manual process and the automated process with the TRAFO ULC prototype, a controlled experimental method was adopted. The design consisted of measuring performance indicators (KPI) before and after automation, maintaining the same conditions of input, product and line operator.

The tests were carried out in a real factory environment, with daily samples of approximately 2,000 pieces, produced under continuous monitoring. The dependent variables were:

(i) Repeatability and reproducibility (R&R);
(ii) Process compliance index;
(iii) Failure rate per batch;
(iv) Average cycle time and absenteeism.

The data were statistically treated by descriptive analysis and percentage comparison.

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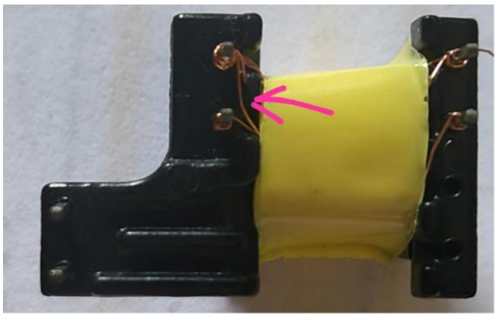
4 RESULTS AND DISCUSSIONS

4.1 ANALYSIS OF THE COLLECTED DATA

The initial stage of the research focused on the characterization of the winding process and manual application of the high insulation tape in the transformers ULC_FSP05. Direct observation and data collection in the field showed three predominant failures: inadequate assembly of the insulation tape, cracks caused in the ferrite core and dimensional variations in the winding, resulting in an average of 6.7% of non-conformities per batch and work leaves due to repetitive efforts.

Figure 2

Assembly failures



Source: Authors, 2025.

Quality tools such as the Ishikawa Diagram and the Analysis of Failure Modes and Effects (FMEA) were applied, which pointed to human variability and the absence of dynamic control of torque and wire tension as the main causes.

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Figure 3

Manual manufacturing process

Source: Authors, 2025.

These findings confirm what Groover (2019) and Lee et al. (2020) describe about the stochastic nature of manual processes, in which human intervention directly impacts repeatability and dimensional accuracy. Zuehlke (2010) and Monostori (2014) highlight that the replacement of these steps by cyber-physical systems is decisive to achieve stability and standardization in high-precision manufacturing. Thus, the diagnosis validated the need for an automated approach, with integrated control and continuous feedback, in line with the principles of Industry 4.0.

4.2 EVALUATION OF THE FINISHED PROTOTYPE

The second phase comprised the development of the automated prototype called TRAFO ULC, designed as a winding station and application of high insulation tape, equipped with embedded artificial intelligence (IAE) and cyber-physical architecture (CPS). The equipment was designed according to NR-12 and NBR ISO 12100 standards, with a total area of less than 3 m², integration of Fuji Electric GYB401D7-RC2 servo motors, programmable logic control (PLC) system and EasyBuilder Pro human-machine interface (HMI).

During the project, innovative solutions were incorporated, such as the Anti Pig Tail device, which eliminated ties and wire breaks; the intelligent needle holder, which improved the positioning of the conductors; and the real-time torque and speed monitoring system, ensuring autonomous corrections by the on-board software.

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Figure 4

Layout of the developed prototype

Source: Authors, 2025.

This is the mechanical appearance developed to improve the production process of the company under study, it has the following dimensions:

- Length =1100 mm;
- Height = 2200 mm;
- Largra = 2500 mm

After inserting the iron cores into the locks, they attach them to perform the embolbinamento and then tapping, with greater precision, agility, maintaining the same execution pattern.

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Figure 5

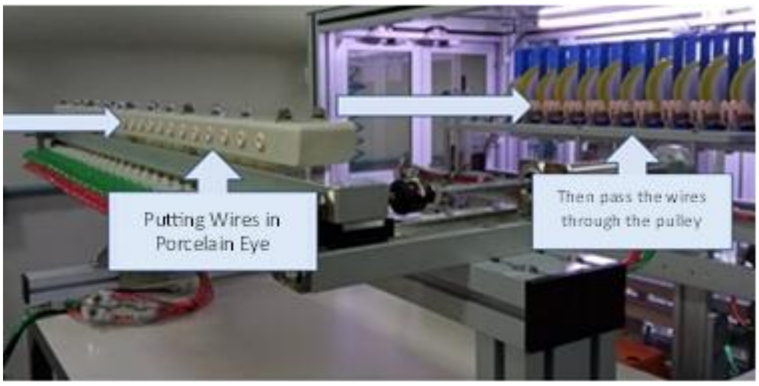
Iron core entrapment latches

Source: Authors, 2025.

To carry out the coiling, it is necessary to feed the material into the prototype. The following image evidences this copper wire feeding process:

Figure 6

Copper wire feed flow



Source: Authors, 2025.

In order to ensure operational safety, the prototype was fully enclosed, avoiding any contact between the employee and the machine, which operates in continuous cycles and performs 360° movements. In addition to the enclosure, disconnector devices were installed, responsible for interrupting the machine cycle whenever the door is opened, allowing the restart only by means of a two-hand operation.

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Figure 7

Door locking sensor - light curtain

Source: Authors, 2025.

For the operation of the prototype, an interface was developed through the HMI (Human Machine Interface), which manages the control of the movement of the grippers, the speed of winding and taping, the monitoring of the states of the safety sensors, as well as the communication with the emergency sectioning system. This interface optimizes the process, providing greater agility and precision in the management of operations, in addition to ensuring the integrity of the system through real-time monitoring of critical parameters.

Figure 8

Prototype manipulation interface – HMI (In portuguese)

Source: Authors, 2025.

Validation tests have proven repeatability and reproducibility greater than 99%, a compliance rate of 99.85% and productivity equal to or greater than 2,000 pieces per hour, exceeding the manual standard of 1,200 pieces/hour. These results characterize development as an incremental process innovation, according to the Oslo Manual (OECD, 2018).

In addition to quantitative performance, automation has provided relevant ergonomic and environmental gains: elimination of leaves due to repetitive strain injuries, reduction in the consumption of insulating material and reduction of scrap. According to Dul and Weerdmeester (2008) and Iida (2016), ergonomic improvement is directly associated with increased production efficiency and process sustainability.

4.3 QUALITATIVE-QUANTITATIVE EVALUATION BETWEEN MODELS

The experimental comparison between the manual and automated processes was conducted in a controlled factory environment, with a sampling of 2,000 pieces per production cycle. Performance indicators such as compliance, cycle time, repeatability (R), reproducibility (R'), productivity and absenteeism were evaluated.

Table 1

Quantitative performance evaluation

Rated Parameter	Before Implementation	After Implementation	Variation/Improvement
Compliance Index	93,3 %	99,85 %	↑ +6,55 p.p. (Significant improvement in quality)
Failure rate	6,7 %	0,5 %	↓ –6,2 p.p. (Drastic reduction of failures)
Repeatability and reproducibility (R&R)	—	≥ 99 %	Excellent levels of consistency and accuracy
Productivity	1.200 Parts/h	2.000 Parts/h	↑ +800 Parts/h (+66,7 %)
Absenteeism due to physical exertion	Existent	Zero	Total elimination of leaves due to physical exertion
Capability (Cp e Cpk)	—	> 1,67	Statistically stable and highly capable process

Source: Authors, 2025.

The results showed a significant improvement in all parameters: the compliance index went from 93.3% to 99.85%; the failure rate reduced from 6.7% to 0.5%; repeatability and reproducibility reached levels ≥99%; productivity rose from 1,200 to 2,000 pieces/h; and absenteeism due to physical exertion was reduced to zero. The capability analysis indicated Cp and Cpk values higher than 1.67, evidencing statistical stability of the process. These

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performance gains confirm the effectiveness of the cyber-physical system in replacing critical manual steps, according to Siciliano and Khatib (2016) and Carvalho, Costa and Teixeira (2022).

5 CONCLUSION

The development of the TRAFO ULC FLEX prototype has proven the technical and operational feasibility of intelligent automation in the manufacturing process of high-frequency transformers. The results obtained demonstrated substantial improvements in efficiency, precision and safety of the production process, fully meeting the general objective and the specific objectives established.

The automated system achieved repeatability and reproducibility above 99%, compliance of 99.85% and productivity of more than 2,000 parts per hour, eliminating failures and absences due to ergonomic causes. Direct benefits include dimensional standardization, digital control of torque and tension, and integration with intelligent monitoring systems. From an ergonomic and economic point of view, the reduction of human effort and waste reinforces the sustainability of the process.

The limitations observed are concentrated in the need for continuous adjustments of the embedded software to adapt to different models of transformers and in the absence of direct integration with MES or ERP systems. As recommendations for future work, it is proposed to expand the system to multiple production lines, incorporate machine learning for dynamic self-tuning, and evaluate energy efficiency on an industrial scale.

It is concluded that the TRAFO ULC prototype represents a significant advance in the context of Brazilian Industry 4.0, consolidating a replicable model of automation applied to the manufacture of electronic components in the Manaus Industrial Pole.

ACKNOWLEDGMENTS

We express our gratitude to the programs and institutions that made this project possible. In particular, to B&Z International, responsible for the technical development and execution; to Flex Industries, the proponent and institutional partner of this initiative; and to the Instituto de Inovação e Tecnologia da Amazônia (IITA – Institute of Innovation and Technology of the Amazon), for its scientific support and contribution to the theoretical foundation of this work.

This project was developed under Lei nº 8.387/1991 (Lei de Informática – Informatics Law), which aims to promote Research, Development, and Innovation (R&D&I) Projects. Its implementation was made possible through the collaboration of the Centro Internacional de Tecnologia de Software (CITS – International Center for Software Technology), the Comitê das Atividades de Pesquisa e Desenvolvimento na Amazônia (CAPDA – Committee for Research and Development Activities in the Amazon), SUFRAMA (Superintendência da Zona Franca de Manaus – Superintendence of the Manaus Free Trade Zone), and the Ministério do Desenvolvimento, Indústria e Comércio (MDIC – Ministry of Development, Industry, and Commerce) — institutions that, together, foster technological innovation in the industrial sector and facilitate access to the incentives provided by the legislation.

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