

AUTO SOLDERING: AUTOMATION OF THE SOLDERING PROCESS FOR TRANSFORMER COIL TERMINALS

AUTO SOLDERING: AUTOMAÇÃO DO PROCESSO DE SOLDAGEM DOS TERMINAIS DAS BOBINAS APLICADAS A TRANSFORMADORES

AUTO SOLDERING: AUTOMATIZACIÓN DEL PROCESO DE SOLDADURA DE TERMINALES DE BOBINAS APLICADAS A TRANSFORMADORES



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ABSTRACT

This article describes the development of the AUTO SOLDERING project, the result of an PD&I initiative conceived and executed by B&Z International in the industrial context, with its scientific production coordinated by IITA. The project is aimed at the design and implementation of an automated tin immersion soldering system applied to transformer coil terminals used in cell phone chargers. The initiative stems from the need to replace the manual and semi-automatic process currently employed, which exposes operators to health and safety risks and presents instabilities regarding repeatability, reproducibility and control of critical parameters. The proposed solution is based on an integrated hardware and software prototype capable of automating the stages of insertion, handling, fluxing, immersion soldering and transfer of the product to the subsequent stage. The system includes control of essential variables (time, depth and immersion angle) and continuous monitoring of temperature, weld volume and cycle time. As a differential, it uses embedded intelligence for real-time decision-making, aiming at operational stability and quality standardization. Additionally, it allows the collection and availability of productive data for integration into the CMES system through XML files, supporting performance indicators and traceability. The development considers ergonomics, occupational safety and compliance with NR-12. As expected results, the elimination of operator exposure to the process, increased efficiency and availability, improved quality and greater control of production indicators stand out, characterizing incremental process innovation applied to the industrial context.

Keywords: Industrial Automation. Dip Soldering. Electronic Transformers. Occupational Safety. Process Control.

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RESUMO

O presente artigo descreve o desenvolvimento do projeto AUTO SOLDERING, fruto de uma iniciativa de PD&I concebida e executada pela B&Z International no contexto industrial, tendo sua produção científica coordenada pelo IITA. O projeto é voltado à concepção e implementação de um sistema automatizado de soldagem por imersão em estanho aplicado aos terminais de bobinas de transformadores utilizados em carregadores de telefones celulares. A iniciativa decorre da necessidade de substituir o processo manual e semiautomático atualmente empregado, que expõe operadores a riscos de saúde e segurança e apresenta instabilidades quanto à repetibilidade, reprodutibilidade e controle de parâmetros críticos. A solução proposta baseia-se em um protótipo integrado de hardware e software capaz de automatizar as etapas de inserção, manuseio, limpeza em fluxo, soldagem por imersão e transferência do produto à etapa subsequente. O sistema contempla controle de variáveis essenciais (tempo, profundidade e ângulo de imersão) e monitoramento contínuo de temperatura, volume de solda e tempo de ciclo. Como diferencial, utiliza inteligência embarcada para tomada de decisão em tempo real, visando estabilidade operacional e padronização da qualidade. Adicionalmente, permite coleta e disponibilização de dados produtivos para integração ao sistema CMES por meio de arquivos XML, suportando indicadores de desempenho e rastreabilidade. O desenvolvimento considera ergonomia, segurança ocupacional e conformidade com a NR-12. Como resultados esperados, destacam-se a eliminação da exposição do operador ao processo, aumento de eficiência e disponibilidade, melhoria da qualidade e maior controle dos indicadores produtivos, caracterizando inovação incremental de processo aplicada ao contexto industrial.

Palavras-chave: Automação Industrial. Soldagem por Imersão. Transformadores Eletrônicos. Segurança do Trabalho. Controle de Processos.

RESUMEN

Este artículo describe el desarrollo del proyecto AUTO SOLDERING, resultado de una iniciativa de PD&I concebida y ejecutada por B&Z International en el contexto industrial, cuya producción científica está coordinada por el IITA. El proyecto tiene como objetivo el diseño e implementación de un sistema automatizado de soldadura por inmersión de estaño aplicado a los terminales de bobina de transformador utilizados en cargadores de teléfonos móviles. La iniciativa surge de la necesidad de sustituir el proceso manual y semiautomático actualmente empleado, que expone a los operadores a riesgos para la salud y la seguridad y presenta inestabilidades en cuanto a repetibilidad, reproducibilidad y control de parámetros críticos. La solución propuesta se basa en un prototipo integrado de hardware y software capaz de automatizar las etapas de inserción, manejo, limpieza de flujos, soldadura por inmersión y transferencia del producto a la siguiente etapa. El sistema incluye el control de variables esenciales (tiempo, profundidad y ángulo de inmersión) y monitorización continua de la temperatura, el volumen de soldadura y el tiempo de ciclo. Como diferencial, utiliza inteligencia integrada para la toma de decisiones en tiempo real, con el objetivo de lograr la estabilidad operativa y la estandarización de calidad. Además, permite la recopilación y disponibilidad de datos productivos para su integración en el sistema CMES mediante archivos XML, apoyando indicadores de rendimiento y trazabilidad. El desarrollo tiene en cuenta la ergonomía, la seguridad laboral y el cumplimiento de la normativa NR-12. Como resultados esperados, destacan la eliminación de la exposición del operador al proceso, el aumento de la eficiencia y disponibilidad, la mejora de la calidad y un mayor control de los indicadores de producción, caracterizando la innovación incremental de procesos aplicada al contexto industrial.

Palabras clave: Automatización Industrial. Soldadura por Inmersión. Transformadores Electrónicos. Seguridad Laboral. Control de Procesos.

1 INTRODUCTION

The search for efficiency and safety in electronic manufacturing processes has driven the transition from manual methods to intelligent automation systems. This article presents the development of the AUTO SOLDERING project, whose objective is the design and implementation of an automated system for the immersion soldering of transformer coil terminals. The initiative is based on the need to replace manual and semi-automatic processes that, in addition to exposing operators to occupational risks, present technical instability. According to Rosário (2005), automation is essential in processes that require high repeatability, as active systems are capable of acting with optimal efficiency when processing information from the environment in real time.

Although the techniques of joining materials are ancestral, their technological evolution has allowed systemic integration in several global industrial segments, consolidating itself as a critical stage in sectors such as the two-wheeled pole, white goods, electronics and portable appliances. According to Rosário (2005), the evolution of these processes is driven by the need for precision and structural integrity, where automation acts as the link between conventional metallurgy and advanced manufacturing. As Groover (2011) points out, welding and other joining processes are fundamental in the assembly of complex products, requiring strict parameter control to ensure final quality in high-productivity environments.

The implementation of automation introduces a disruptive paradigm in production models, simultaneously boosting operational efficiency and the qualitative reliability of the final product. In addition to increasing production, the technological transition in critical processes acts as a fundamental agent in promoting the safety and health of the operator, by mitigating exposure to unhealthy environments or ergonomic risks. According to Rosário (2005), automation allows the active system to perform dangerous or exhausting tasks with precision superior to human accuracy, ensuring that the physical integrity of the worker is preserved without prejudice to throughput. In this sense, Groover (2011) reinforces that automation does not only aim to replace manual effort, but to create a work environment where control technology absorbs risk variables, resulting in a more humane, stable and safe industrial process.

This article aims to highlight the transition from the manufacturing model of an industrial welding process to the automated system, evaluating the effectiveness of the mitigation of production anomalies, as well as the increase in efficiency and quality as well as the reduction of risks to the health and physical integrity of the operator. As highlighted by Rosário (2005) and Groover (2011), this transition is essential to convert rigid systems into intelligent and safe manufacturing cells.

To achieve this central objective, the following specific objectives were established: technical survey through the realization of a detailed diagnosis of the current process and the identification of the root causes of its critical problems; proposal of a solution by exposing the architecture of the developed automated model, detailing its embedded intelligence and control mechanisms; comparative analysis with the execution of a quali-quantitative study between the manual and automated models, validating the performance gains and compliance with safety standards.

2 THEORETICAL FRAMEWORK

The theoretical framework of a study consists of a critical and systematized analysis of the literature pertinent to the theme, with the objective of providing the theoretical contextualization of the research and delimiting its fundamental concepts. The following topics present the main conceptual constructs that support and guide the development of this work.

2.1 INDUSTRY 4.0

Industry as it is known today is the result of numerous transformations over the decades, transformations resulting from revolutions, studies and technological evolution and modernity of societies. For Boettcher (2015), Industry 4.0 is the result of industrial revolutions and great technological advances.

2.1.1 First Industrial Revolution – Industry 1.0

The earliest forms of civilization produced goods strictly according to their immediate needs, through predominantly manual processes, characterized by artisanal production. With demographic growth, the need to settle in permanent housing and social organization in villages and small groups, a significant change in human behavior began, which resulted in the emergence of new demands and increased consumption.

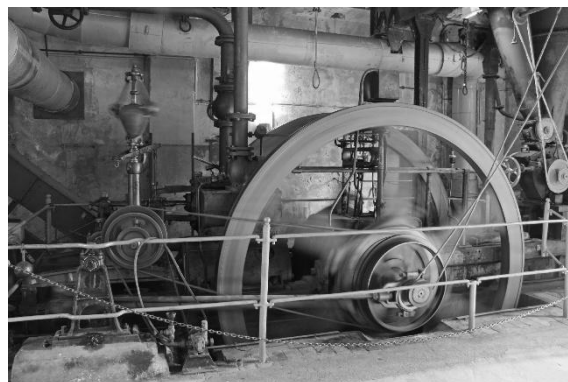
The migration of the population from the countryside to urban centers intensified this process, promoting transformations in the market with the aim of stimulating consumption. In this context, new services and activities aimed at the urban population have emerged, such as cinemas, clothing stores and the sale of low-cost electronics. The growing demand for consumer goods required the reformulation of production processes, since artisanal production was no longer able to meet large-scale production while maintaining the standardization of products. Thus, factories emerged as an alternative to boost the retail market, with the adoption of organized labor in industrialized processes.

According to Cavalcante and Silva (2011), in addition to being more agile, production began to occur on a larger scale, contributing to the transformation of social culture through the consolidation of capitalism, whose main objective is to obtain profits.

According to Boettcher (2015), this revolution began in England between the end of the eighteenth century and the beginning of the nineteenth century, later extending to other countries, such as the United States, France, Belgium, Russia, Germany, and the Netherlands. The main characteristic of the First Industrial Revolution was the improvement of the steam engine, initially applied to the textile industry and later expanded to several other production processes.

Figure 1

Depiction of the First Industrial Revolution and the Steam Engine



Source: The Electric Sector (2010).

2.1.2 Second Industrial Revolution – Industry 2.0

Boettcher (2015) states that the main factor that promoted the emergence of new revolutions was the evolution of technologies, as they provided growth and modernization and a significant increase in profits. Around 1870, the Second Industrial Revolution emerged, driven by technological demand.

This transition was marked by the discovery of electricity, transformation of iron into steel, operationalization and modernization of means of transport, advancement of communication systems, development of the chemical industry, etc. The main characteristics of this revolution were the search for greater profits, specialization of work and application of production (SILVA; GASPARIN, 2013).

Fordism begins, the name for mass production, with the objective of rationalizing production through technical innovations, stimulating a new chain of mass production VS mass consumption, with Henry Ford as a precursor in 1914 (BOETTCHER, 2015).

Figure 2

Henry Ford - Fordismo



Source: Business Insider (2012).

2.1.3 Third Industrial Revolution – Industry 3.0

In addition to the technological boost, there was also a renewal in the economic, political and social process, with great dynamism and high complexity in the twentieth and twenty-first centuries, according to Silva et al. (2012).

Also called the Third Revolution, Technical-Scientific and Informational, it was formed through processes of technological innovation, which are marked by advances in the fields of information technology, robotics, telecommunications, transportation, biotechnology, chemistry and nanotechnology (BOETTCHER, 2015).

Industry 3.0 has presented several outstanding characteristics, among which the use of multiple energy sources, the growing use of computer and automation resources, as well as the increase in environmental awareness, stand out. It was also observed the intensification of the replacement of human labor by increasingly modern machines, which contributed to the increase in structural unemployment. At the same time, there was the expansion of labor rights, the advance of the globalization process, the emergence of new industrial powers and the massification of technological products (SILVA et al., 2002).

2.1.4 Fourth Industrial Revolution – Industry 4.0

The concept of Industry 4.0 gained international visibility in 2011, when it was officially presented in Germany during the Hannover Messe. According to Kagermann et al. (2013), this initiative emerged as a strategic response to the need to increase the competitiveness of the German manufacturing sector in the face of technological transformations and the global economic scenario.

The following year, in 2012, those responsible for the development of the project, under the coordination of Siegfried Dais, representative of Robert Bosch GmbH, and Henning Kagermann, linked to acatech, prepared a document with guidelines and recommendations sent to the German Federal Government. This report served as the basis for the planning

and implementation of the new industrial model. In 2013, still at the Hannover Fair, the final version of the Industry 4.0 concept was consolidated and released (Silveira, 2017).

This new industrial paradigm is associated with the intensification of digitalization and automation processes in manufacturing, promoting increasingly integrated and intelligent production environments (Oesterreich; Teuteberg, 2016). As Silveira (2017) points out, the essence of Industry 4.0 lies in the ability to interconnect machines, systems, and productive resources, allowing the formation of autonomous networks capable of making decisions and optimizing processes without constant human intervention.

From this perspective, Zawadzki and Zywicki (2016) state that Industry 4.0 represents the convergence of recent technological advances with a new vision of production, in which cyber-physical systems connect the physical to the virtual environment, enabling automated, intelligent and highly adaptable operations.

Figure 3

Top Industry Technologies



Source: Tecnicon (2022).

2.1.5 Industry 4.0 in Brazil

In the Brazilian context, Industry 4.0 is still in the early stages of development when compared to more industrially advanced countries, such as Germany, the United States, and Japan. According to Hahn (2017), this technological delay is mainly evidenced by the low replacement of traditional production lines by automated systems, whose adoption rate remains lower than that observed in developed economies.

Despite this scenario, the national industry shows efforts to insert itself in this new productive paradigm. According to the National Confederation of Industry (CNI, 2016), initiatives aimed at Industry 4.0 in Brazil initially focus on product improvement and the development of new business models, seeking greater efficiency and competitiveness.

Zancul (2016) points out that, although many Brazilian industries have already incorporated some level of automation, digital manufacturing has not yet been fully achieved. The author points out that Industry 4.0 is based on two fundamental dimensions, integrated

processes and innovative products, in which Brazil still has limitations, reflected in the reduced number of competitive sectors on a global scale.

In addition, it is observed that several national companies are still in the process of transition to the Third Industrial Revolution, living with different levels of technological maturity. However, as Santos (2017) points out, there is the possibility of accelerating this process through the direct adoption of technologies associated with Industry 4.0, especially by small and medium-sized companies, which can obtain significant gains in productivity and competitiveness.

In this sense, the implementation of Industry 4.0 in Brazil must consider the particularities of the national reality, allowing the adaptation of concepts and the overcoming of traditional stages of industrial development. However, the dissemination of this model still faces obstacles, such as the lack of technical knowledge and resistance to the adoption of new technologies, factors that hinder the consolidation of this new industrial revolution in the country (Hahn, 2017).

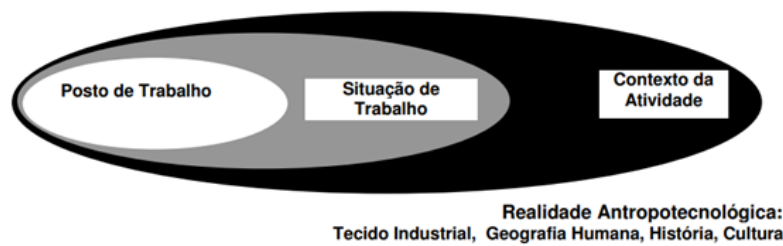
2.2 ERGONOMICS

The term Ergonomics was first used in 1857 by Wojciech Jastrzębowski, being derived from the Greek words *ergon* (work) and *nomos* (rules or laws). Ergonomics has its origin in the studies of Work Physiology, focusing on the identification of the causes of work fatigue and the proposition of solutions aimed at mitigating or eliminating it (Pinto, 2009).

According to Wisner (1982), ergonomics can be defined as the set of scientific knowledge related to the human being and necessary for the design of tools, machines, systems and devices that can be used with maximum comfort, safety and efficiency.

Ergonomics is directly related to the health and safety of the worker, through the adequacy of processes and working conditions, seeking to ensure the highest possible level of comfort and well-being. This concern began to gain greater relevance from the changes in the way workers were perceived within organizations, especially throughout the different industrial revolutions. As Chiavenato (2002) points out, "the more industrialized the society, the more numerous and complex the organizations become, which begin to exert a deep and lasting impact on the lives and quality of life of individuals".

In this context, ergonomics addresses aspects such as lighting, posture, limb and spine positioning, repetitive movements, load handling capacity, temperature, and other physical and organizational factors, which are essential to ensure that the work environment is considered adequate, safe, and healthy.

Figure 4*Types of Ergonomics*

Source: Federal Technological University of Paraná Londrina Campus (2019).

2.3 WELDING

Welding is a process of permanent joining of materials, predominantly metallic, carried out by means of heating and/or pressure, with or without the addition of filler material. In electrical and electronic applications, welding plays a critical role by directly impacting electrical conductivity, mechanical integrity, and product reliability throughout the life cycle.

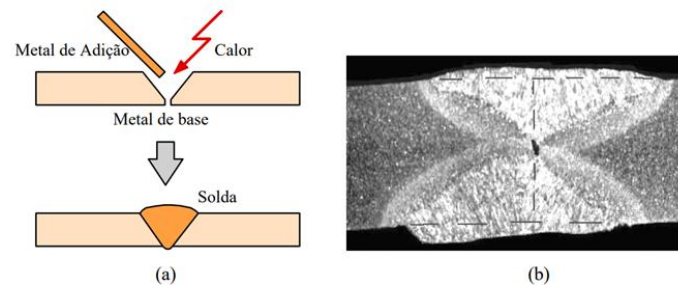
From the point of view of technological classification, welding processes can be organized into different groups, depending on the form of heat generation and the joining mechanism:

- Fusion welding: the base metal is fused, with or without filler metal, and the joint is formed after solidification of the metal bath. It is widely used in industry for its versatility and productivity.
- Solid state (pressure) welding: the union occurs without significant melting of the base metal, typically by the application of pressure, and there may be auxiliary heating. It stands out for its high-strength joints and for reducing metallurgical effects associated with melting.
- Resistance welding: heat is generated by the passage of electric current in the region of contact between the parts, combined with pressure. It is common in serial and highly repeatable applications.
- Concentrated energy welding: uses highly concentrated sources (e.g., laser or electron beam), allowing high precision, low thermally affected zone, and strict control of deformations.
- Gas welding (oxygen): uses the heat from the combustion of gases, and is traditionally applied in maintenance, repair and light welding operations.
- Brazing and soft welding: joining processes in which the base metal is not melted; The union occurs by melting the addition metal, with a melting point lower than that of the base metal. Brazing usually takes place above 450 °C, and soft welding below this value.

Historically, welding has accompanied the evolution of metallurgical techniques for centuries, with records of processes such as brazing and forging in different civilizations. Industrial consolidation intensified with the development of controllable energy sources and the use of electric arcs and combustible gases, increasing the precision and reliability of joining processes, especially after the great industrial demands of the twentieth century.

In this early stage of development, welding had limited application, being employed mainly in emergency repairs. Only after the First World War did this process begin to be used more widely and systematically, consolidating itself as an important method of industrial manufacturing. Currently, there are more than fifty distinct welding processes with application in the industrial sector, making it the main means of permanent joining of metals. The relevance of this process is evidenced by its presence in several segments of the industry and by the direct influence that weldability requirements exert on the development of new types of steels and other metal alloys.

In the present work, the focus is on tin immersion (tin bath) soldering, applied to metal terminals of miniaturized transformers. In this method, the previously prepared terminals, including the fluxing step, are immersed in liquid metal alloy for a controlled time, promoting proper wetting and joint formation after solidification. As it is a process that is highly sensitive to variables such as time, depth, and immersion angle, in addition to temperature and bath conditions, automation becomes a determining factor to ensure stability, repeatability, and reduction of defects in the production process.

Figure 5*Welding process*

Source: Federal University of Esp rito Santo (2009).

2.4 AUTOMATION

It is essential to distinguish automation from automation. While the first refers strictly to the mechanization of repetitive movements, characterized as a "blind action" because it lacks the processing of variables, automation is defined as a set of cyber-physical techniques. It enables the creation of active systems capable of processing information from the environment in real time to act with optimal efficiency. In short, automation provides intelligence to the process, allowing the system to make data-driven decisions.

In this context, modern industrial automation operates through computer systems that process signals from various measuring instruments on the factory floor. By confronting this data with optimal parameters (setpoints), the system performs complex mathematical operations in order to generate instantaneous correction signals. As stated by Groover (2011), automation is the technology by which a process or procedure is carried out without human assistance, being executed through an instruction program combined with a control system.

According to Ros rio (2005), industrial automation can be categorized into three main types, according to its versatility and production volume:

- **Fixed Automation:** It is characterized by operational rigidity, with little or no adaptability to changes. It is aimed at very high-volume processes and standardized models, where the sequence of operations is fixed by the configuration of the equipment. An example of this is the large-scale SMD insertion processes, where there is no internal variation or change of setup, and the lines are segregated by models due to the impossibility of changing to different processes.
- **Flexible Automation:** It is an evolution of programmable automation, being directed to medium production volumes. Its main feature is the ability to process different product models without wasting time with extensive tool changes or reprogramming, allowing for a varied and simultaneous production mix.

- **Programmable Automation:** It is used in production processes that have high product variability and lower production volumes. In this case, the sequence of operations is controlled by software, and can be changed to different product configurations, although it requires a setup time for the reprogramming and replacement of physical devices.

The evolution of manufacturing systems has been driven by the transition from mass markets to niche markets, where product variability becomes a competitive differentiator. According to Rosário (2005), the need for automation arises not only to increase productivity, but to ensure integrity and repeatability in scenarios where human error is enhanced by the diversity of models and processes.

In contexts of high variability, automation is no longer purely mechanical and becomes a tool for managing complexity. Rosário (2005) argues that fixed automation, although efficient for large volumes, becomes obsolete in the face of the need for customization, since "it is directed to production processes with little or no adaptability to changes" (Rosário, 2005, p. 11).

The implementation of flexible and programmable systems is justified by the ability to process different product configurations with minimal physical intervention. As the author points out:

"Flexible automation is an extension of programmable automation. [...] A flexible automation system is one capable of producing a variety of products (or parts) with reduced setup times, allowing the production of different models on the same assembly line." (Rosário, 2005).

Thus, the variability of products requires automation to be equipped with intelligent control systems and embedded software capable of recognizing and adjusting parameters autonomously. This transition to flexible automation minimizes losses from batch changes (setups) and reduces the incidence of critical failures, such as electrical insulation or structural integrity, which tend to occur more frequently when the process relies solely on memory and operator manual action in the face of multiple models.

In short, automation in high-variability environments is not just a technical choice, but a strategic necessity to enable throughput and regulatory compliance in modern production systems.

3 METHODOLOGY

The present research is characterized as applied and technological, as it is oriented to the solution of a real manufacturing problem and involves the development and evaluation of a prototype of industrial automation. As for the objectives, this is a descriptive and explanatory study, as it describes the immersion welding process currently used and explains the effects of automation on critical safety, stability, and performance variables (GIL, 2019).

Regarding the approach, a mixed design (qualitative-quantitative) is adopted, integrating qualitative evidence (mapping of occupational risks and compliance with safety requirements) and quantitative evidence (cycle time measurements, productivity indicators and quality metrics), a strategy recommended when seeking a more comprehensive understanding of the phenomenon by combining different types of data (CRESWELL; CLARK PLAN, 2017).

As a technical procedure, the work is configured as a case study in an industrial environment, suitable when investigating contemporary phenomena in the real context and intending to understand "how" and "why" process changes produce certain effects (YIN, 2018). The validation of prototype performance follows a comparative before-after logic (semi-automatic process versus automated prototype), incorporating chronoanalysis/study of times for estimates and comparison of standard time and cycle time (BARNES, 1977).

The evaluation of the performance of the automated system is carried out through a direct comparison between the semi-automatic process and the automated model, considering operational and productive indicators extracted from the equipment's own control system. The analysis includes variables such as cycle time, process stability, incidence of defects and operational availability, data that are automatically collected by the on-board software and made available for monitoring through the CMES system. To consolidate the overall performance of the equipment, the Overall Equipment Effectiveness (OEE) indicator is adopted, widely used in the industry for the integrated measurement of availability, performance and quality (NAKAJIMA, 1988).

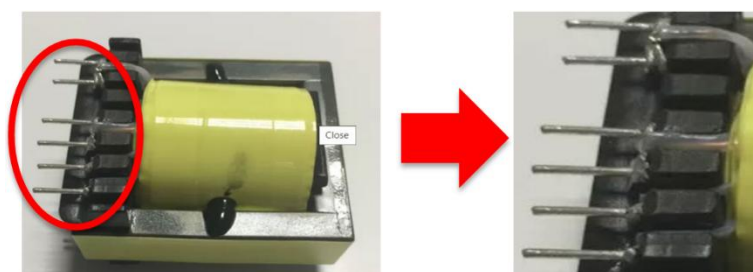
3.1 DIAGNOSIS OF THE NON-AUTOMATED PROCESS

The production process under study is a fundamental stage in the manufacture of cell phone chargers, focusing specifically on the welding of the terminals of a critical component: the transformer. This operation is technically called immersion welding, or "tin bath", and consists of submitting the terminals to the metal in a liquid state to promote the metallurgical union. To ensure joint quality and integrity, strict control of fluid temperature, immersion height accuracy, and alloy purity is imperative, as the presence of contaminants compromises conductive properties and process adhesion.

The current method for welding the terminals is based on a semi-automatic system with a high dependence on manual intervention and low ergonomic efficiency. The operational flow begins with the preparation of the fixing rod, which requires the manual application of adhesive tapes (double-sided and crepe) to support the components. After positioning the transformers with the pins vertically oriented, the terminals are subjected to fluxing, a process that requires frequent renewal of the chemical input every two tray cycles to ensure adequate deoxidation of the surfaces.

Figure 6

Comparative analysis of the morphology of the terminals: (A) Pre-welded in natura state and (B) Metal interface after the immersion tinning process



Source: RD&I Technical Report – B&Z International (2022).

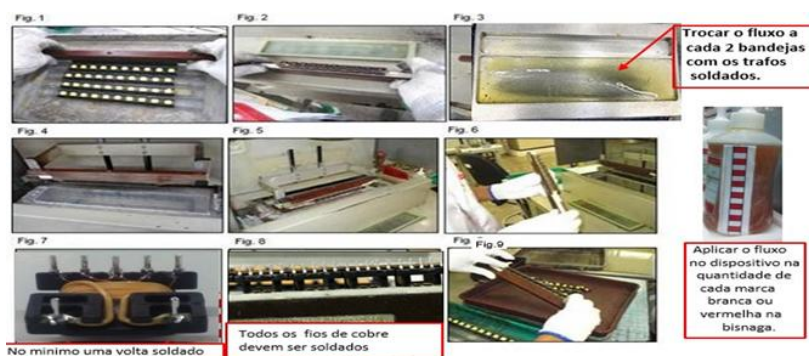
The critical welding step takes place by means of manual activation, after coupling the rod to the traction device. The process requires two consecutive immersion cycles in the molten tin alloy, with tightly established contact times of between 2.2 and 2.6 seconds. The second dip presents an additional technical complexity, as it must selectively target the Tex-E yarn. At the end of the immersion, a detailed visual inspection is carried out to validate the integrity of the welding and certify the absence of thermal degradation in the insulators or fasteners.

This flow is characterized by constant setup maintenance, requiring the replacement of the masking tape every 15 or 20 cycles, a frequency that varies according to the temperature and saturation of the flow. In the event of anomalies in the primary welding, the

components are segregated to a rework line with adjusted parameters, immersion times between 1.0 and 2.0 seconds and temperatures between 350°C and 370°C. The persistence of failures after this intervention results in definitive disposal (scrap), evidencing a manufacturing model with a high incidence of human manipulation and latent productivity bottlenecks.

Figure 7

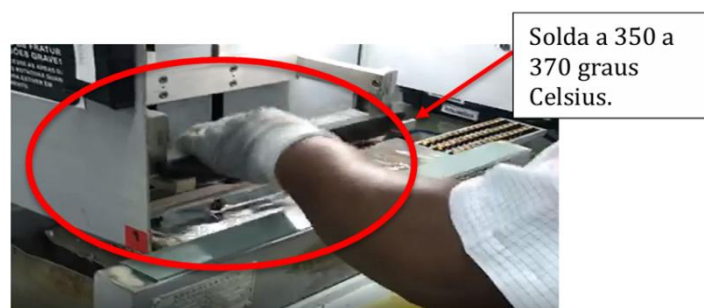
Flow of transformer assembly activity on dip rulers.



Source: RD&I Technical Report – B&Z International (2022).

Figure 8

Process of immersion of the transformers in the solder bath



Source: RD&I Technical Report – B&Z International (2022).

The analysis of this scenario reveals a matrix of critical risks to the physical integrity and occupational health of operators in the long term. The preponderant risk factor lies in the inhalation of metallic fumes composed of ultrafine particles (0.01 to 1 μ m) that, due to their small size, cross the barriers of the respiratory system. The toxicity of these effluents is potentiated by elements such as hexavalent chromium Cr(VI), manganese and nickel. According to Nederman technical data, continuous exposure to these agents is associated with severe pathologies, including systemic neoplasms, neurological damage, occupational asthma and other lung diseases.

In addition to the chemical risk, manual operation imposes immediate physical dangers, since the welding crucible operates at constant temperatures between 350°C and

370°C. This condition subjects the worker to intense thermal radiation, resulting in acute discomfort and early fatigue, factors that exponentially increase the probability of accidents and serious burns during the handling of the dipstick. From the perspective of production efficiency, the current model suffers from chronic instabilities in the repeatability and reproducibility of the process, since the control of fundamental variables, such as immersion time, depth and angle of attack, depends exclusively on the dexterity and physical resistance of the operator. The absence of digital records and the dependence on analog methods for monitoring make it difficult to manage performance and favor handling errors that compromise the final quality of the product. In view of this scenario, the automation of the process via the AUTO SOLDERING project presents itself as an imperative measure to ensure the biosafety and technical stability required by modern manufacturing.

The diagnosis of the current process revealed critical instabilities in the repeatability and reproducibility of the welding, mainly due to the manual variation of the immersion time and angle. In addition, the direct exposure of operators to metal fumes and high temperatures was identified, reinforcing the need for an automated solution in compliance with NR-12 and ergonomics standards.

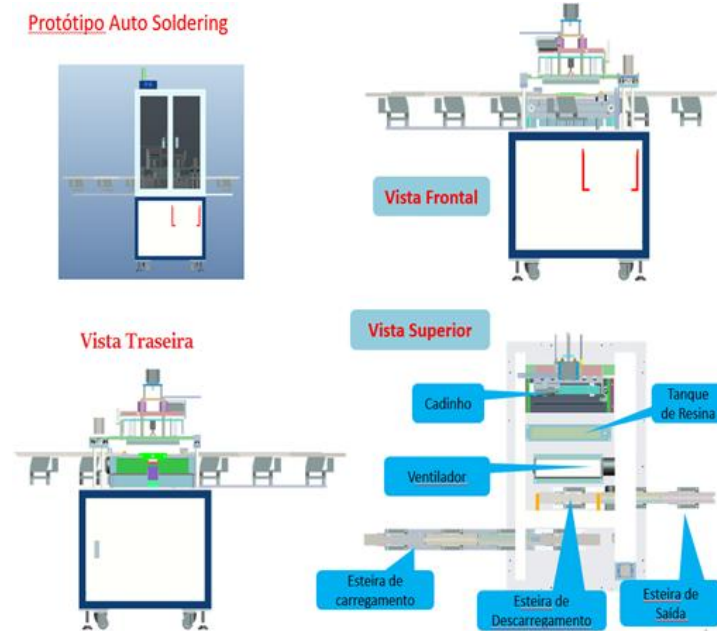
3.2 DETAILING OF THE AUTOMATED MODEL WITH EMBEDDED INTELLIGENCE AND CONTROL MECHANISMS

The proposed solution consists of a prototype of integral automation with embedded software, designed to manage the production cadence through real-time monitoring. The transition to the fully automated model eliminates the need for direct operator intervention in critical steps, substantially reducing the risks of occupational diseases and accidents. The technological scope of the system includes:

- **Product Life Cycle Automation:** The prototype performs the automatic insertion, handling and transport of transformers through customized pick and place systems, ensuring continuous production online.
- **Intelligent Treatment and Welding:** Includes automatic cleaning of terminals in flux tanks and immersion welding with strict control of bath height, angle and depth.
- **Safety and Biosecurity:** Implementation of an independent exhaust system to capture metal fumes at the source and compliance with NR-12 for operation in a zero-risk environment.
- **Digital Integration (Smart Manufacturing):** Collection of production indexes and equipment status for export via XML files, allowing direct integration with the company's CMES system.

Figure 9

Concept of the prototype



Source: RD&I Technical Report – B&Z International (2022).

The prototype was conceived from digital modeling elaborated in the SolidWorks software. In the construction phase, the mechanical structure was initially assembled and then the manipulation, transport, control and power devices were integrated, including sensors, actuators, PLC, pneumatic cylinders, among other components necessary for the operation of the system.

Figure 10

Module development



Source: RD&I Technical Report – B&Z International (2022).

The storage and control system of the flux and solder in the respective tanks was developed independently, depending on the technical particularities of each application. The resin-coated flow tank is intended for cleaning terminals, made of titanium alloy, and has been subjected to use and reliability tests.

Figure 11

Welding tank



Source: RD&I Technical Report – B&Z International (2022).

The main purpose of the use of solder flux is to facilitate the welding process, promoting the removal of oxides and impurities, in addition to improving the wettability of the metal surface. According to Frank et al. (1981), the welding flux can be composed of a non-reactive mixture, containing activators with at least one halogen atom, destabilizing components and acidic surfactants, such as polybasic carboxylic acids, their hydroxylated derivatives, acetoacids or combinations of these agents, whose function is to optimize the performance of the process.

Figure 12

Flow circulation tank (fluxer)



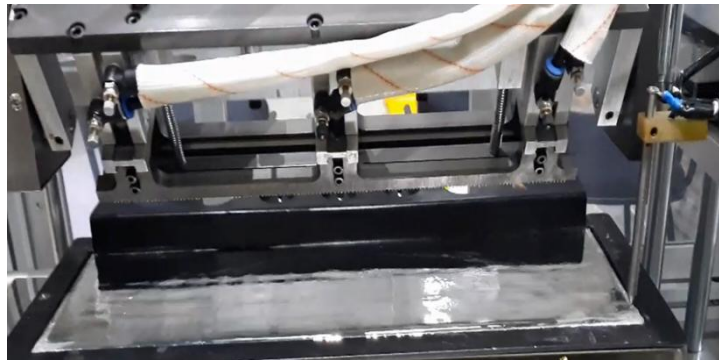
Source: RD&I Technical Report – B&Z International (2022).

To ensure that the chemical compound was kept in optimal operating conditions, especially in terms of temperature, wave height and applied volume, a system with a recirculation pump was designed, responsible for regulating the formation of the wave during

the cleaning process. Such a solution avoids the alteration of the viscosity of the flow, preventing its paste-like consistency, and allows the controlled adjustment of the operating parameters, ensuring stability and quality to the developed cleaning system.

Figure 13

Weld volume level sensor

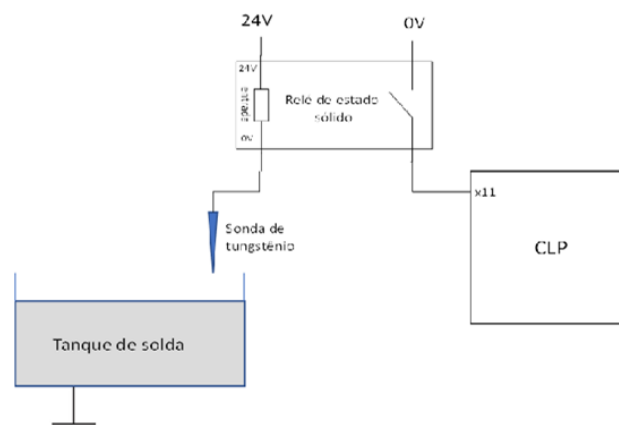


Source: RD&I Technical Report – B&Z International (2022).

One of the main solutions used in the system was the welding wave height sensor, developed from research carried out, a system was established (described in figure 14) that starts when the tungsten probe touches the surface of the liquid weld, this potential of 0V is transferred to the input of the solid state relay, which results in energization of the coil. At this moment, the contact of the solid-state relay switches, transferring the potential of 0V to the x11 terminal of the PLC. When the PLC detects the signal in x11, its internal program reads the height on the Z-axis encoder. The height read on the encoder is the weld level used as a reference in the welding process.

Figure 14

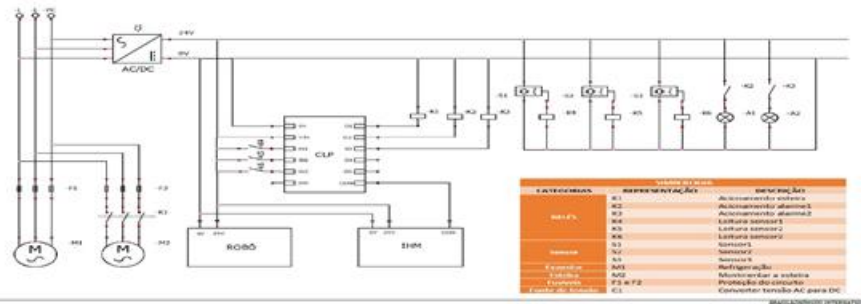
Level control functional diagram



Source: RD&I Technical Report – B&Z International (2022).

Figure 15

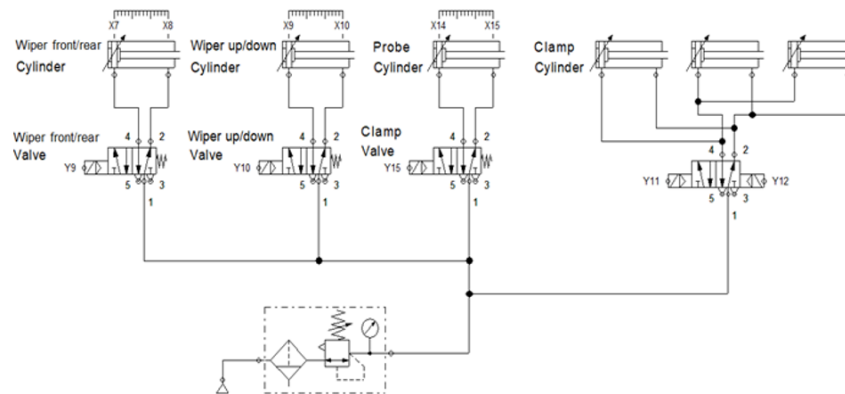
Electrical diagram



Source: RD&I Technical Report – B&Z International (2022).

Figure 16

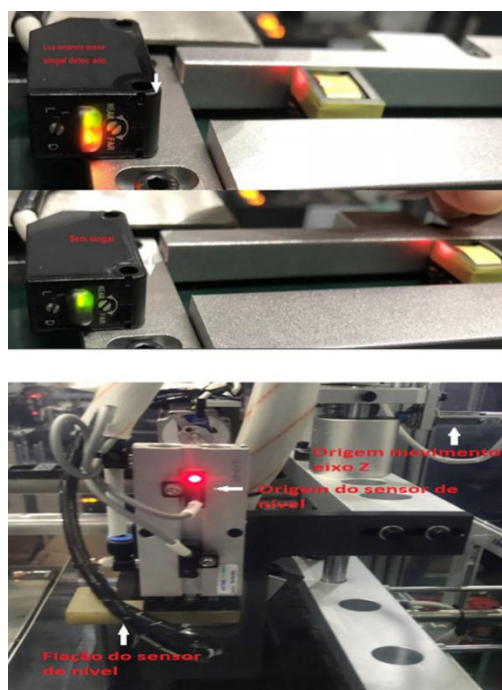
Pneumatic diagram



Source: RD&I Technical Report – B&Z International (2022).

Figure 17

Prototype sensors



Source: RD&I Technical Report – B&Z International (2022).

3.2.1 Software Architecture

The core of the system was developed in the C and C++ languages, using an architecture that processes field variables in milliseconds. The innovative differential lies in the implementation of an Artificial Intelligence that performs autonomous decision-making on the depth of immersion.

Through mathematical calculations processed by the computer, the system checks the volume of material available in the tanks and dynamically adjusts the position of the robotic arm. This mechanism automatically compensates for tin and flux consumption, ensuring that the level of contact with the terminals remains constant regardless of the amount of material in the crucible. In addition, the software calculates and makes available OEE, monitoring temperature, speed and defect indexes, demonstrating them in an intuitive human-machine interface (HMI) for technical supervision.

3.2.2 Incremental Innovation and Industrial Customization

Due to the lack of "off-the-shelf" solutions for the manufacture of miniaturized transformers, a market restricted to proprietary designs, the project represents an incremental process innovation. The equipment was designed with interchangeable accessories, allowing flexibility for future product design adjustments, aligning the robustness of fixed automation with the versatility of flexible automation, as recommended by Rosário (2005).

Table 1

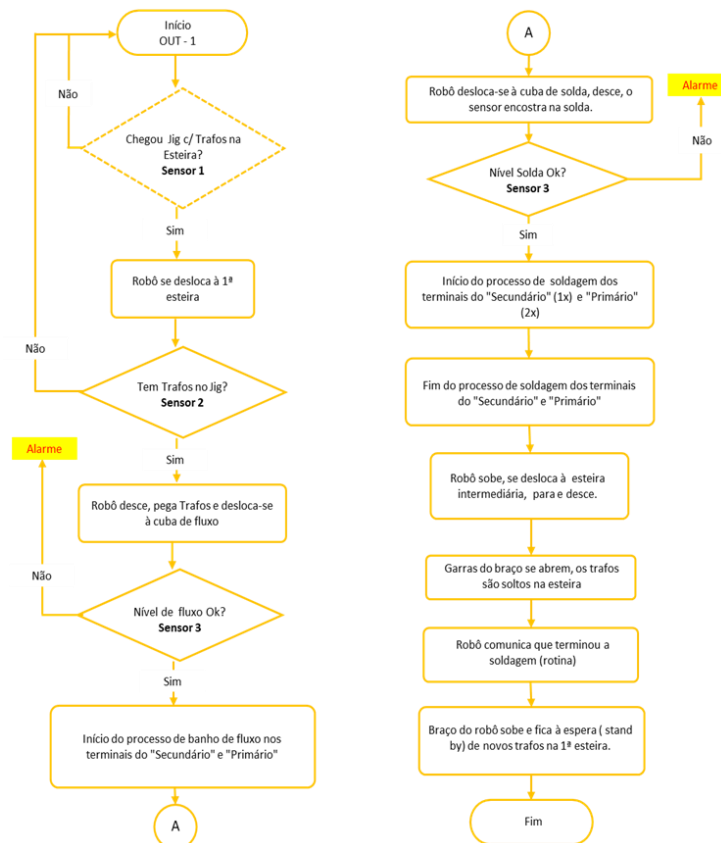
Technical knowledge matrix

Knowledge Component	Application in the AUTO SOLDERING Project
Artificial Intelligence (AI)	Dynamic calculation of immersion based on tank volume and level.
C/C++ and Ladder Language	Synchronization of cyber-physical systems and test variables.
Ultrasound Technology	Control of production parameters for metallurgical precision of the weld.
System Integration	Management of transport, welding and segregation in reduced space.

Source: Authors (2026).

Figure 18

Prototype operation flow

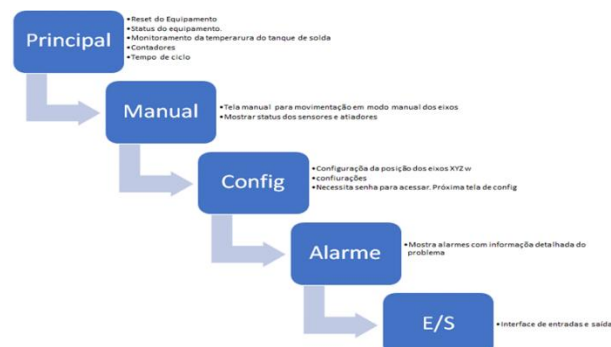


Source: RD&I Technical Report – B&Z International (2022).

The Human Machine Interface (HMI) used in the system was the WEINVIEW MT6071iP model. The programming was carried out in the EasyBuilder Pro software, in which the application files were developed, the operating parameters were defined and the communication devices were configured. The integration with the PLC used in the application was established through the parameterization of communication protocols, allowing the monitoring and management of movements and system functions in real time.

Figure 19

Interface requirements



Source: RD&I Technical Report – B&Z International (2022).

Based on the previously established requirements, the graphical interfaces of the system were elaborated, using the resources of the Drawing Tools library of EasyBuilder Pro. In this stage, elements such as buttons, light indicators, text fields, labels, images and tables were inserted and configured, organized in the project files in the extensions ".exob" and ".cxob", which make up the visual and functional structure of the HMI.

3.2.3 Negative Scope and Restrictions

To ensure the focus on the central objective of safety and welding quality, the project delimits that the following functionalities will not be contemplated: automatic identification of product change via code reading; direct integration with ERP (maintaining only the provision of data to the CMES via XML); and purely cosmetic or mechanical quality inspections outside the scope of the welded joint.

3.3 METHODOLOGY FOR THE QUALI-QUANTITATIVE STUDY BETWEEN THE MODELS

For the validation of the technological transition, this research adopts a mixed methodological approach, based on a quali-quantitative study that confronts the current scenario (semi-automatic) with the developed prototype (AUTO SOLDERING). The objective is to measure the impact of automation on the mitigation of occupational risks and the increase of production efficiency.

3.3.1 Qualitative Procedures (Health and Safety)

Qualitative analysis focuses on the assessment of biosafety and regulatory compliance. The methodology consists of mapping the risks of exposure to metal fumes and thermal irradiation (350°C - 370°C), based on the particle toxicity parameters (0.01-1µm) described in Nederman's technical literature. The effectiveness of the prototype is validated by the complete elimination of human interaction at the welding point, replacing manual handling with pick and place systems and independent exhaust, aiming to achieve the goal of zero accidents and absences.

3.3.2 Quantitative Procedures (Performance and Reliability)

The quantitative aspect uses chronoanalysis and comparison of operational indicators to evaluate productivity and quality between the semi-automatic process and the automated model (BARNES, 1977). The data collection follows the following criteria:

Evaluation of the stability and operational repeatability of the process by monitoring the critical parameters (time, depth and immersion angle), comparing the variation observed

in the manual model with the variation obtained in the automated system. While the manual model depends on the operator's skill, the automated model uses embedded intelligence (ANI), implemented in C/C++, to calculate and adjust the depth and angle of immersion in real time, compensating for variations in the process throughout the production cycle.

Overall Equipment Effectiveness (OEE): Automatic data collection via software, integrating cycle time, availability, and defect rate information directly into the company's CMES system via XML files.

Technical Parameters: Comparative monitoring of thermal stability and immersion time (set at 2.2s ~ 2.6s), evaluating the percentage of scrap reduction after rework.

3.3.3 Innovation Validation Framework

Given that there are no standardized "off-the-shelf" solutions for the specific design of the company's transformers, the development methodology follows the concept of incremental innovation. Validation occurs by verifying the system's ability to automatically adjust to the volume of molten tin and the cleanliness of the terminals, ensuring that the immersion soldering technology achieves the levels of precision required by high-scale manufacturing.

4 RESULTS AND DISCUSSIONS

The implementation of the AUTO SOLDERING project resulted in the development of a functional prototype of an automated tin immersion soldering station applied to the terminals of transformer coils used in mobile phone chargers. The results obtained were evaluated from the perspectives of occupational health and safety, process stability, production efficiency and welding quality, according to the objectives established in the project's work plan.

From the point of view of biosafety, the main evidence of the result was the total elimination of the operator's direct interaction with the weld bath, which operates at temperatures between 350 °C and 370 °C. The automated system integrated pick and place mechanisms, dedicated metal fume exhaust and enclosure as per the requirements of NR-12, completely mitigating the risks associated with inhaling ultrafine particles (0.01–1 µm) containing elements such as hexavalent chromium, manganese and nickel. In this way, the projected indicators of zero work accidents, zero absences and zero occurrence of occupational diseases became technically achievable, significantly surpassing the scenario of the semi-automatic process previously used.

Figure 20

Ergonomic evaluation methodologies

MOORE & GARD		OCRA		
< 3	Trabalho é seguro	VERDE	5,1 - 7,5	AUSENTE OU ACEITÁVEL
3 À 7	Trabalho pode apresentar riscos para membros superiores.	AMARELO	7,6 - 11	LIMITE
		VERMELHO LEVE	11,1 - 14	BAIXO
> 7	Trabalho perigoso e apresenta riscos.	VERMELHO MÉDIO	14,1 - 22,5	MÉDIO
		ROXO	> 22,5	ALTO

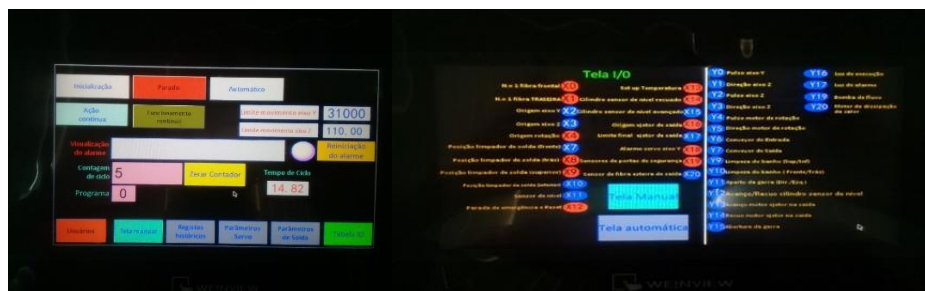
Source: RD&I Technical Report – B&Z International (2022).

Regarding the stability and reliability of the process, the results demonstrate a substantial evolution in relation to the manual model. The automated control of critical variables, immersion time, depth, angle of attack and bath temperature, eliminated the variability inherent to human action, which previously compromised the repeatability and reproducibility of the process.

The embedded intelligence, developed in C/C++ language, made it possible to dynamically calculate the immersion height based on the available volume of tin and flow in the tanks, automatically compensating for the consumption of material throughout the production cycle. This approach ensured metallurgical uniformity of the welding, regardless of the natural fluctuations of the process.

Figure 21

Control interfaces



Source: RD&I Technical Report – B&Z International (2022).

In terms of production performance, the data consolidated in the work plan indicate an estimated improvement of 10% in the availability of the equipment and an increase of approximately 20% in the efficiency of the workstation, both from the mechanical point of view and from the computer control system. Daily production went from 1340 units to 1900, meaning a 41% increase in production capacity.

Figure 22

Production data

Resultados Produção 2993 peças				
1ª Indutância	Teste Func.	Hipot	Tex-E	total ok
15 und	0 und	01 und	35 und	2942
			FPY	98,30%

51 peças em análise

Back Panel

Source: RD&I Technical Report – B&Z International (2022).

The integral automation of the cycle, insertion, cleaning, welding and transfer of the components, allowed continuous operation in an online regime, meeting the critical requirement of production time of approximately 2.86 seconds per part, through the collective welding of multiple transformers simultaneously.

Figure 23

Production performance report

RELATÓRIO OQC - Transformador								
MODELO:		ULC						
CÓDIGO:		FM 0201IH ULC			Qtd de Amostra: 2942 pcs			
LINHA/FORNECEDOR		LINHA PILOTO (PROJETO AUT. DE SOLDA)			Qtd Amostra: 160 pcs			
DATA: 05/04/2021		RESPONSÁVEL: CARLOS - ENGENHARIA			Índice NOK: 2,5% EMC acima do espec			
PEÇA	HIPOT	TESTE FUNC.		EMC (-70 ~ 40mV)	PEÇA	HIPOT	TESTE FUNC.	EMC (-70 ~ 40mV)
NUM.	STATUS	STATUS	STATUS	VALOR MEDIDO	NUM.	STATUS	STATUS	VALOR MEDIDO
1	OK	OK	OK	0	81	OK	OK	-30
2	OK	OK	OK	-30	82	OK	OK	70
3	OK	OK	OK	-60	83	OK	OK	0
4	OK	OK	OK	10	84	OK	OK	0
5	OK	OK	OK	40	85	OK	OK	-60

Source: RD&I Technical Report – B&Z International (2022).

The quality of the final product also showed significant gains. Reduced manual handling minimized thermal damage to insulators, weld wetting failures, and defects associated with rework. As a consequence, the project projects an improvement in welding quality of around 30%, directly reflecting on the reduction of scrap and the increase in the reliability of the component delivered to the subsequent stages of the production line. In addition, the automatic collection of production data enabled the continuous monitoring of indicators such as OEE, cycle time, stoppages and defect rates, allowing integration with the company's CMES system through XML files.

From the perspective of industrial innovation, the results confirm the character of incremental process innovation of the AUTO SOLDERING project. The lack of standardized "off-the-shelf" solutions for the automated welding of miniaturized transformers required the development of a customized solution, with interchangeable accessories and flexible architecture. This characteristic ensures the adaptability of the system to future variations in

product design, reconciling the robustness of fixed automation with the versatility of flexible automation, as recommended in the classic literature of industrial automation.

5 CONCLUSION

The development of the AUTO SOLDERING project has proven to be a technically and industrially viable solution for the automation of the tin immersion soldering process of transformer coil terminals applied to the manufacture of mobile phone chargers. The transition from the semi-automatic model to a fully automated system showed significant gains in occupational safety, process stability, production efficiency and quality of the final product.

The results obtained confirm that the elimination of human intervention in the critical stages of the process not only effectively reduces the risks of accidents and occupational diseases, but also contributes to the standardization of welding, ensuring high levels of repeatability and reproducibility. The use of embedded intelligence for real-time decision making proved to be fundamental for the dynamic control of process variables, automatically compensating for variations in weld volume and flux, and ensuring the metallurgical integrity of the welded joints.

In addition, the ability to collect and make available productive data in real time positions the AUTO SOLDERING system in line with the principles of industry 4.0, by allowing integration with corporate manufacturing systems and management based on performance indicators. This characteristic expands the potential of the equipment not only as an operational solution, but as a strategic tool to support industrial decision-making.

Finally, it is concluded that the project represents an applied incremental innovation, capable of raising the technological level of the production process without the need for complex restructuring of the industrial plant. The solution developed contributes to the modernization of electronic manufacturing, promoting a safer, more efficient and sustainable work environment, in addition to serving as a reference for future applications of intelligent automation in critical industrial processes.

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REFERENCES

- Barnes, R. M. (1977). Estudo de movimentos e de tempos: projeto e medida do trabalho (6ª ed.). São Paulo: Edgard Blücher.
- Boettcher, M. (2015). Revolução industrial: um pouco de história da indústria 1.0 até a indústria 4.0. LinkedIn. Disponível em: <https://pt.linkedin.com/pulse/revolu%C3%A7%C3%A3o-industrial-um-pouco-dhist%C3%B3ria-da-10-at%C3%A9-boettcher>
- Brasil. Ministério do Trabalho e Emprego. (s.d.). Norma regulamentadora nº 12 (NR-12): segurança no trabalho em máquinas e equipamentos. Brasília, DF.
- Cavalcante, Z. V., & Silva, M. L. S. da. (2011). A importância da revolução industrial no mundo da tecnologia. In Encontro Internacional de Produção Científica (7.). Maringá. Disponível em: https://www.unicesumar.edu.br/epcc-2011/wpcontent/uploads/sites/86/2016/07/zedequias_vieira_cavalcante2.pdf
- Chiavenato, I. (2002). Introdução à teoria geral da administração (6ª ed.). Rio de Janeiro: Campus.
- Confederação Nacional da Indústria (CNI). (2016). Desafios para indústria 4.0 no Brasil. Brasília: CNI.
- Creswell, J. W., & Plano Clark, V. L. (2017). Pesquisa de métodos mistos (3ª ed.). Porto Alegre: Penso.
- Frank, R. et al. (1981). Soldering flux (U.S. Patent No. 4,278,479). Washington, DC: U.S. Patent and Trademark Office.
- Gil, A. C. (2019). Como elaborar projetos de pesquisa (6ª ed.). São Paulo: Atlas.
- Groover, M. P. (2011). Automação industrial e sistemas de manufatura (3ª ed.). São Paulo: Pearson.
- Jastrzębowski, W. B. (1857). An outline of ergonomics, or the science of work based upon the truths drawn from the science of nature.
- Kagermann, H. et al. (2013). Recommendations for implementing the strategic initiative Industrie 4.0.
- Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitization and automation in the context of industry 4.0: a triangulation approach and elements of a research agenda for the construction industry. Computers in Industry.
- O Setor Elétrico. (s.d.). Da máquina a vapor aos softwares de automação. Disponível em: <https://www.osetoelettrico.com.br/da-maquina-a-vapor-aos-softwares-de-automacao/>

- Nakajima, S. (1988). Introduction to TPM: total productive maintenance. Cambridge: Productivity Press.
- Nederman. (s.d.). Catálogo técnico de soluções para extração de fumos de solda.
- Pinto, A. R. (2009). Ergonomia aplicada ao trabalho. São Paulo: Blucher.
- Rosário, J. M. (2005). Princípios de mecatrônica. São Paulo: Pearson Prentice Hall.
- Sakurai, R., & Zuchi, J. D. (s.d.). As revoluções industriais até a indústria 4.0. INFA – Revista de Inovação, Tecnologia e Sustentabilidade. <https://doi.org/10.31510/infa.v15i2.386>
- Santos, M., Manhães, A. M., & Lima, A. R. (2018). Indústria 4.0: desafios e oportunidades para o Brasil. In Simpósio de Engenharia de Produção de Sergipe (X SIMPROD). São Cristóvão, SE.
- Silva, D. B. da et al. (2012). O reflexo da terceira revolução industrial na sociedade. In Encontro Nacional de Engenharia de Produção (22.). Curitiba: ABEPRO. Disponível em: http://www.abepro.org.br/biblioteca/enegep2002_tr82_0267.pdf
- Silva, M. C. A. da, & Gasparin, J. L. (2015). A segunda revolução industrial e suas influências sobre a educação escolar brasileira. Disponível em: http://www.histedbr.fe.unicamp.br/acer_histedbr/seminario/seminario7/TRABALHOS/M/Marcia%20CA%20Silva%20e%20%20Joao%20L%20Gasparin2.pdf
- Silveira, C. B. (2017). O que é a indústria 4.0 e como ela vai impactar o mundo. Citisystems. Disponível em: <https://www.citisystems.com.br/industria-4-0/>
- Wisner, A. (1982). Ergonomie (2ª ed.). Paris: Presses Universitaires de France.
- Yin, R. K. (2018). Estudo de caso: planejamento e métodos (6ª ed.). Porto Alegre: Bookman.
- Zancul, E. de S. (2016). O Brasil está pronto para a indústria 4.0? Exame. Disponível em: <https://exame.abril.com.br/tecnologia/o-brasil-esta-pronto-para-a-industria-4-0/>
- Zawadzki, P., & Żywicki, K. (2016). Smart product design and production control for effective mass customization in the industry 4.0 concept. Management and Production Engineering Review.