DIGITAL TRANSFORMATION IN THE MANAUS INDUSTRIAL HUB: INCREASED EFFICIENCY IN THE PRODUCTION OF LITHIUM BATTERIES THROUGH INDUSTRY 4.0

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ABSTRACT

The lithium battery industry faces increasing challenges in terms of demand and expectations for sustainability and efficiency. In the context of the Manaus Industrial Pole, this study explores the application of Industry 4.0 technologies to overcome these challenges and increase production efficiency. The research implemented integrated cyber-physical systems, advanced automation, and real-time data analysis on a lithium battery assembly line, replacing manual processes with automated solutions. The results demonstrated a significant improvement in production accuracy and speed, with a 40% reduction in cycle time and a 75% decrease in product rejection rate, highlighting the potential of digitalization to optimize industrial operations and meet the demands of a competitive global market. This study contributes to the literature on digital transformation in manufacturing, offering practical insights into the implementation of emerging technologies in complex industrial environments.

Keywords: Industry 4.0. Lithium Batteries. Manaus Industrial Pole. Industrial Automation. Cyber-Physical Systems.

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INTRODUCTION

Industry 4.0 marks a technological revolution, characterized by the integration of cyber-physical systems (CPS) that connect the physical and digital worlds, facilitating automation and real-time monitoring of production processes. According to Lee et al. (2015), this technological evolution allows efficient communication between machines and equipment, increasing flexibility and safety in industrial environments. In addition, technologies such as the Internet of Things (IoT), Big Data, and artificial intelligence not only improve the monitoring of operations, but also optimize planning and minimize waste, promoting more efficient and sustainable resource management (Hermann et al., 2016; Xu et al., 2018). In this context, the transformation in the Manaus Industrial Pole stands out as a significant example of industrial adaptation to new technologies, essential to sustain competitiveness in a dynamic global scenario (DA SILVA, 2019).

For companies to take full advantage of the potential of Industry 4.0, Schwab (2016) and Zheng et al. (2018) highlight the need for significant investments in technological infrastructure and in the development of workforce skills, preparing employees to manage complex systems and voluminous data. The transition to this new industrial era transcends the technological aspect, also requiring a cultural transformation in organizations, where the promotion of a culture of continuous innovation is essential (Roblek et al., 2016). Monostori (2014) argues that the modernization induced by Industry 4.0 redefines production processes and demands a review of management practices to maintain competitiveness in a globalized market.

The Manaus Industrial Pole (PIM), highlighted as one of the most important industrial centers in Brazil, is central to the production of electronics, including cell phones, computers and batteries. It plays a crucial role in the development of the Amazon region, diversifying the local economy and promoting job creation, which is vital to combat socioeconomic inequalities in the North region (Pereira & Simões, 2016; Monteiro & Lima, 2017). In addition to serving the domestic market, Silva & Souza (2019) highlight that the hub contributes significantly to foreign trade, strengthening its economic importance in the national and international scenario. The Manaus Free Trade Zone's tax incentive policy further boosts social development and urbanization, reinforcing the role of the PIM as a pillar of sustainable regional development (Souza & Silva, 2018; Almeida & Santos, 2017).

To maintain its competitiveness in an increasingly technological market, PIM has incorporated industrial automation and cyber-physical systems, essential for Industry 4.0. Lima & Pereira (2020) and Fonseca & Ferreira (2021) observe that these technologies allow for more precise control of production and greater efficiency in the use of resources, adapting the industrial environment to market demands. With investments in digitalization, PIM companies seek not only to increase productivity, but also to reduce operating costs and increase the sustainability of operations. Santos & Oliveira (2021) state that the adoption of these technologies is crucial for PIM to continue to be a reference in Brazilian and global industry.

The increasing demand for mobile devices, such as smartphones and tablets, has driven the need for lithium batteries, which are known for their energy efficiency and durability. Renowned companies, such as Samsung, require high-quality batteries, which encourages the search for reliable suppliers, such as those located in PIM (Silva & Rocha, 2018; Ribeiro & Santos, 2020). Costa & Silva (2020) note that in order to meet international performance and safety standards, it is essential that PIM maintains a high level of quality control and adopts advanced technologies.

The challenges faced by PIM include not only low productivity due to the lack of automation in various stages of production, but also the ergonomic risks associated with manual processes. Souza & Rocha (2020) and Ramos & Silva (2019) discuss how automation proves to be an effective solution to these problems, improving quality control and reducing the need for human intervention in critical steps. Modernization with automation and cyber-physical systems ensures that PIM maintains its competitiveness and relevance in a demanding global market, transforming the battery manufacturing process and enabling more efficient and faster production, which is essential to meet the growing demands of the global market.

MATERIALS AND METHODS

A new advanced automation system was implemented in the battery production line at the Manaus Industrial Pole (PIM) to transform the production process that was previously carried out manually. Previously, 28 workstations presented challenges such as variability in product quality and low operational efficiency. To achieve significant improvements in consistency, safety, and productivity, the project proposed the introduction of an automated system that utilizes modern technologies, including sensors, robotics, and control systems. This new system consisted of 12 automated stations, strategically distributed in the critical stages of the production line. The objective was to optimize process performance, reducing failures and increasing operational efficiency, ensuring a more standardized and reliable production.

MATERIALS

The Manaus Industrial Pole (PIM) implemented an advanced automation system in the battery production line, replacing and complementing the manual steps previously distributed in 28 workstations with a more efficient process composed of 12 automated stations. The technologies used in this new system ensure greater precision, consistency and safety in production, in addition to allowing real-time monitoring and reduction of human errors.

The automated system integrates several cutting-edge technologies, including cyber-physical systems, which continuously monitor and adjust operating parameters through sensors, actuators, and controllers. Advanced robotics are used to perform repetitive and critical tasks, such as tape application and laser welding, significantly improving production speed and accuracy. Artificial vision sensors are responsible for quality inspection during assembly, automatically detecting any defect or misalignment. Programmable Logic Controllers (PLCs) coordinate operations, optimizing the production flow and integrating all automated stations.

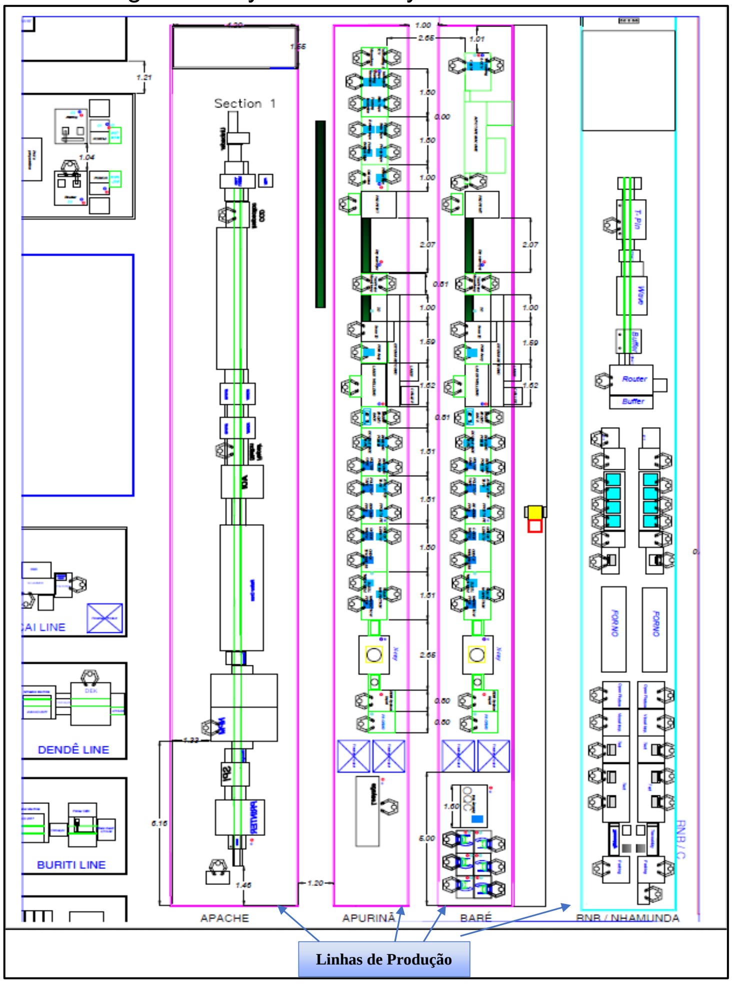
The implementation of this automation system represents a significant transformation in the battery assembly process at PIM, previously carried out predominantly manually in three main sections: Apache, Apurinã and Baré, ranging from the reception of materials to the final quality tests. Automating these steps aims to overcome the challenges of variability and inefficiency, ensuring a uniform and high-quality final product.

METHODS

Before automation, the production process at the Manaus Industrial Complex was carefully mapped to identify points of variability and ergonomic challenges in the 28 manual workstations, distributed in three sections: Apache, Apurinã and Baré. This mapping revealed critical dependencies of human operators on repetitive tasks and vulnerabilities in critical operations such as welding and inspection, which compromise production quality and efficiency. In addition, the constant manipulation of components and the execution of repetitive tasks increased ergonomic risks, affecting the health and productivity of workers.

Figure 1 illustrates the current layout of the production line, detailing the workflow and location of key critical points, clearly showing the areas that suffer the most from variability and repetitive effort, underscoring the need for automation.

Figure 1: Layout of Battery Production Lines



Source: Author.

The modernization of the production line was accomplished through the introduction of advanced technologies such as cyber-physical systems, advanced robotics, artificial vision sensors, and programmable logic controllers (PLCs). These technologies have not only replaced manual activities with automated processes at 12 specialized stations, but have also enabled accurate monitoring and adjustment of operations in real-time, increasing process consistency and reducing the risk of human error.

The development of the automation system was supported by software tools such as Easy Build and Cold Sys, which offered flexibility in PLC programming and efficient integration of control systems, making it easier to manage automated operations. These platforms helped maintain business continuity and minimize unexpected outages.

To assess the impact of automation, data collection was structured in three phases: before automation, during implementation, and after operations were stabilized. This approach helped monitor adjustments in real-time and evaluate the effectiveness of improvements through performance indicators, such as cycle time and bounce rate, accessible directly by the automated system.

Data analysis compared the results before and after the implementation of the technologies, using automatically generated graphs and tables to consolidate information on quality, productivity and safety. The detailed analysis allowed the identification of performance patterns and the correlation of operational variables with the observed results, optimizing the necessary adjustments to achieve continuous improvement.

RESULTS AND DISCUSSIONS

SUMMARY OF RESULTS OBTAINED

The implementation of automation in the battery production line has resulted in substantial improvements in the efficiency and quality of products. The technological innovations introduced have made it possible to increase the throughput rate to ≥99% and the production capacity to ≥1000 pieces per hour, while significantly reducing variability and production errors.

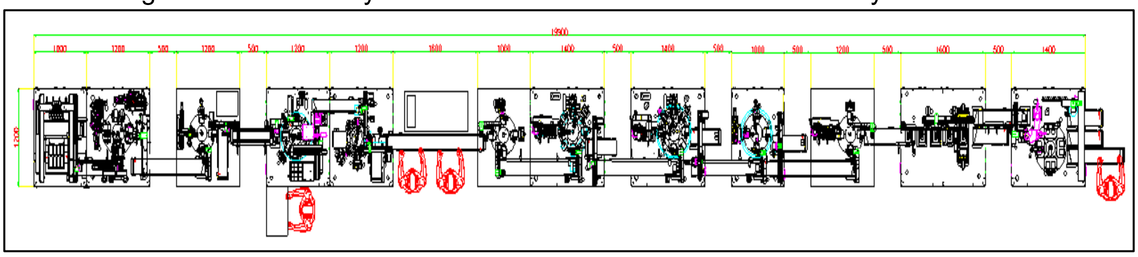
DISCUSSION ON TECHNOLOGICAL INNOVATIONS

The technologies implemented, such as automatic feeding machines, laser welding stations, and robots for applying tapes, have fundamentally transformed the production process. These technologies have not only automated repetitive and critical tasks, but have also integrated advanced controls to ensure the accuracy and consistency of operations, directly addressing the issues identified in the process mapping.

ILLUSTRATION OF LAYOUT AND STATIONS

The new layout of the automated stations is a visual representation of technological advancement on the production line. Each station is meticulously planned to maximize space efficiency and improve workflow, with configurations that facilitate integration and synchronization of operations.

Figure 2: General Layout of the 12 Automated Stations in Battery Production



Source: Author.

DESCRIPTION OF AUTOMATED STATIONS AND TECHNOLOGIES IMPLEMENTED

The 12 automated stations on the battery production line have been specifically designed to optimize various stages of the production process, operating in a synchronized manner to ensure efficiency, accuracy and consistency.

Each station incorporates advanced technologies that address different challenges identified in the previous manual process.

- Station 1: Automatic Cell Feeding Machine – Automates cell insertion, utilizing Cartesian manipulators and pneumatic suction cups for accuracy and reduced manual handling, essential for component integrity.
- Station 2: Application of Poron Tape – Automated robots apply tape consistently and accurately, reducing manual variability and improving grip, which is critical to the functionality of batteries.
- Station 3: CCD Scanning - Combines QR Code printing and data inspection, using CCD technology to ensure the correct identification of each cell and the quality of the subsequent process.
- Station 4: Laser Welding Station - Offers a high-precision welding process, directly contributing to the structural quality of the batteries and reducing assembly failures.
- Station 5: Laser Soldering and PCB Bending Inspection - Performs microscopic inspection and automated PCB bending, increasing accuracy and reducing manual effort, with immediate segregation of failed cells.
- Station 6: CLAD 90º Bending - Automates clad bending at a 90-degree angle, ensuring uniformity in the process and preventing damage to components.
- Stations 7, 8 and 9: Tape Application - Apply different types of tapes with precision and uniformity, essential for the mechanical integrity and protection of batteries.
- Station 10: 180º FPCB Adjustment - Performs FPCB adjustments, bending it 180 degrees with high precision, according to design specifications.
- Station 11: XYZ Measurement - Measures critical cell dimensions with a Cartesian robot, ensuring quality specifications are met.
- Station 12: Functional Testing - Subjects batteries to automated functional testing, segregating non-conforming ones to ensure that only quality products are distributed.

COMPUTATIONAL INTEGRATION AND CONTROL

The computational integration and control of the 12 automated stations on the battery production line were essential for the efficiency and synchronization of operations. Programmable Logic Controllers (PLCs) played a crucial role, coordinating all activities and ensuring accuracy at every step of the process. The system is designed to enable seamless communication and information sharing between stations, minimizing disruptions and maximizing operational efficiency.

Advanced system features include automatic segregation of non-conforming parts and data validation to ensure product compliance. The PLCs were configured to manage a variety of automated operations, such as moving robotic manipulators and monitoring critical parameters such as cycle time, reject rate, and equipment efficiency. This setting allows for automatic adjustments of operations to maintain optimal performance.

The control system provides detailed interfaces for setting operating modes and monitoring critical parameters, as shown in Figures 15 through 18. These interfaces allow precise adjustments in real time, ensuring the necessary flexibility to continuously optimize production operations.

Advanced machine vision sensors are integrated into the computer system, allowing real-time inspection and validation of components. These sensors help identify faults or misalignments before products move on to the next steps, with all information being shared between stations for necessary adjustments, maintaining consistency and product quality.

The real-time monitoring system collects and stores data in a centralized database, processed by specialized software for continuous analysis and adjustments. This integration not only optimizes the performance of the stations, but also lays a solid foundation for future innovations and responses to changes in demand, aligning with Industry 4.0 principles and promoting a continuous cycle of innovation and operational excellence.

EVALUATION OF COSTS AND BENEFITS

The evaluation of costs and benefits of implementing automation in the battery production line involves analyzing the investments made in comparison with the gains obtained in efficiency, quality and waste reduction.

Table 1: Evaluation of Costs and Benefits of Automation.

Indicator	Before Automation	After Automation
Initial Investment	N/A	Equipment acquisition, development of cyber-physical systems, advanced robotics and artificial vision sensors, operator training
Productivity Gains	Limited	Significant increase in production capacity
Reduced Bounce Rate	12%	3%
Reduction of Operating Costs	High reliance on manual labor	Significant reduction in operating costs with less dependence on manual labor and less incidence of leaves due to ergonomic problems
Cycle Time Reduction	5 minutes	3 minutes
Long-Term Benefits	N/A	Increased competitiveness, alignment with Industry 4.0, and opportunities for continuous innovation

Source: Author.

ERGONOMIC AND SAFETY BENEFITS

The implementation of automation in the battery production line has brought significant gains in safety and ergonomics, which can be directly related to the data presented in Chapter 3 and the performance indicators obtained. Prior to automation, manual labor on repetitive tasks such as taping and welding resulted in high reliance on human operators and an incidence of ergonomic issues such as repetitive strain injuries (RSIs) and sick leaves. With the introduction of the 12 automated stations, these problems have been significantly reduced.

The table below summarizes the main impacts of automation on safety and ergonomics, comparing the scenarios before and after implementation:

Table 2: Impacts of Automation on Safety and Ergonomics.

Aspect	Before Automation	After Automation
Reliance on Manual Labor	High dependence for repetitive and ergonomic tasks.	Robots and automatic manipulators perform critical tasks.
Incidence of Ergonomic Problems	Discharge, with frequent cases of RSI and leaves.	Significant reduction in problems related to RSI and health.
Work Posture	Operators exposed to static and uncomfortable positions.	Improved posture due to the shift to supervisory tasks.
Health Leaves	Frequent due to inadequate ergonomic conditions.	Reduction in leave rates.
Monitoring and Security	Reliance on manual inspections.	Real-time monitoring systems fix problems preemptively.
Operators' Quality of Life	Impacted by repetitive efforts and long hours.	Improved with a focus on supervision and reduction of physical effort.

Source: Author.

ALIGNMENT WITH INDUSTRY 4.0 AND CONTINUOUS IMPROVEMENTS

The automation implemented in the battery production line at the Manaus Industrial Pole is in line with the principles of Industry 4.0, using cyber-physical systems, intelligent sensors, and real-time connectivity. The use of these systems enables the continuous monitoring of indicators such as cycle time, reject rate, and operational efficiency (OEE), creating a solid foundation for a continuous cycle of improvements. The data collected is processed automatically, allowing for quick adjustments to operations and ensuring greater accuracy and consistency over time.

The following Table summarizes the main aspects of alignment with Industry 4.0 and the continuous improvement strategies adopted in the automated system:

Table 3: Alignment with Industry 4.0 and Continuous Improvement Strategies.

Aspect	Description	Benefits
Cyber-physical systems	Integration of sensors, actuators and control systems connected in real time.	Continuous monitoring and automatic adjustments for greater accuracy and consistency.
Monitored Indicators	Cycle time, rejection rate, and operational efficiency (OEE).	Solid basis for continuous cycles of improvements and optimizations in the production process.
Automated Data Processing	Automatic collection and analysis of operational data.	It allows for quick and accurate decisions, optimizing workflow and reducing waste.
Preparing for Expansions	System designed to incorporate new technologies, such as AI and machine learning.	Increases predictive capacity, improves real-time decisions, and reduces failures.
IoT connectivity	Integration with other areas of the factory and external systems.	It facilitates predictive maintenance, big data analysis, and greater connectivity with the production chain.
Competitive Benefits	Adoption of advanced Industry 4.0 strategies.	It consolidates its competitive position and promotes continuous evolution with global technological advances.

Source: Author.

CONCLUSION

This study demonstrated the significant impact of the implementation of Industry 4.0 technologies in the production line of lithium batteries in the Manaus Industrial Pole. The automation of the stations, integrated with cyber-physical systems, advanced robotics and artificial vision sensors, has resulted in remarkable improvements in terms of efficiency, quality and operational safety.

The results obtained reflect a considerable reduction in process variability and rejection rates, as well as a significant increase in operational efficiency, as evidenced by the increase in OEE to 95%. These improvements not only increase the competitiveness of production in the global context, but also promote a safer and more ergonomic work environment for operators, aligning with sustainability and corporate social responsibility guidelines.

The successful implementation of the 12 automated stations highlights the feasibility and benefits of applying Industry 4.0 concepts in complex industrial environments. However, the study also recognizes that the transition to full automation is an evolutionary process that requires continuous investments in technology, staff training, and infrastructure development.

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