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ELECTRONIC KANBAN WITH ARTIFICIAL INTELLIGENCE: DEVELOPMENT AND IMPLEMENTATION OF A SOLUTION FOR DIGITAL TRANSFORMATION AND PRODUCTIVE OPTIMIZATION IN A PIM TAPE INDUSTRY

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ABSTRACT

This study details the development and application of an electronic Kanban system with Artificial Intelligence (AI) integration in a company in the Manaus Industrial Pole (PIM). The research follows the precepts of Industry 4.0, focusing on optimizing production sequencing, improving operational efficiency, and reducing costs. The methodology combined exploratory and applied approaches, employing qualitative and quantitative methods to map bottlenecks and create customized technological solutions. The results demonstrate significant progress, including a 67% reduction in order registration time, a 22% increase in overall equipment efficiency (OEE) and an 18% reduction in non-conformities identified in the final inspection. The study highlights the transformative impact of digitalization and automation on the modernization of PIM companies, in addition to

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presenting a practical and replicable model to face similar challenges in the Brazilian industrial context.

Keywords: Industry 4.0, Electronic Kanban, Artificial Intelligence, Automation, Manaus Industrial Hub.

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INTRODUCTION

Industry 4.0, also known as the Fourth Industrial Revolution, represents a milestone in the history of production systems, characterized by the convergence between digital technologies and industrial processes. With the integration of tools such as Artificial Intelligence (AI), Internet of Things (IoT), Big Data, cloud computing, and cyber-physical systems, Industry 4.0 profoundly transforms the forms of production, management, and distribution. These innovations provide greater efficiency, flexibility, mass personalization, and real-time data-driven decision-making, which are essential characteristics for competitiveness in increasingly dynamic and global markets (Kagermann, Wahlster & Helbig, 2013; Hermann, Pentek & Otto, 2016).

In Brazil, the Manaus Industrial Pole (PIM) stands out as one of the largest and most important industrial complexes in the country, housing companies from strategic sectors such as electronics, motorcycles and thermoplastics. The PIM plays a crucial role in the national economy, contributing significantly to job creation, technological development, and tax collection. However, to maintain its competitiveness and face the challenges of a globalized market, PIM needs to modernize and adopt technologies that enable Industry 4.0. This modernization is essential to overcome production bottlenecks, reduce waste, and promote more sustainable and efficient management (Marconi & Machado, 2020).

Among Industry 4.0 technologies, electronic Kanban with AI emerges as a powerful solution to improve production processes. Kanban, initially conceived as a visual tool for flow control in the Toyota Production System, has evolved into integrated digital systems. When associated with AI algorithms, Kanban becomes capable of optimizing the sequencing of production orders, allocating resources intelligently, and providing real-time visibility into the progress of production processes (Lingitz et al., 2018; Morais, Almeida & Santos, 2021).

This article describes the development and implementation of an AI-powered electronic Kanban system at **ENTERPRISE XXX**, a PIM company that was facing challenges related to operational efficiency, data integration, and final product quality. The adoption of this solution has made it possible to improve the allocation of resources, reduce operational errors, increase the traceability of processes, and promote greater transparency for managers. With this, **ENTERPRISE XXX** not only modernized its production line, but also aligned itself with the requirements of a market that values digital transformation and sustainability.

The main objective of this work is to demonstrate how the implementation of an electronic Kanban system with AI can positively impact the production processes of a PIM company. Specifically, it seeks to:

1. Evaluate the impacts of the system on operational efficiency, such as the increase in OEE and the reduction of idle times;
2. Identify the benefits generated by the integration of real-time data and its influence on managerial decision-making;
3. Present a replicable model for other PIM companies facing similar challenges.

Article Structure To achieve the proposed objectives, the article is structured in seven sections. After this introduction, the **Theoretical Framework section** presents the fundamentals of Industry 4.0, the evolution of Kanban systems, and the context of PIM. The **Methodology** details the steps used for the development and implementation of the system. In **Results and Discussions**, the impacts observed on production efficiency and quality are presented. Finally, the **Conclusion** summarizes the main findings, pointing out recommendations and possibilities for future work.

THEORETICAL FRAMEWORK

INDUSTRY 4.0: CONCEPTS, ORIGINS AND IMPACTS

Industry 4.0, also known as the Fourth Industrial Revolution, emerges as a response to the demands of a global market characterized by rapid change, intense competition, and demands for mass customization. This concept was formalized in Germany in 2011 as part of a national strategy to digitize the industry by integrating advanced technologies into production processes. The proposal involves the transformation of factories into intelligent, connected and autonomous environments, based on the integration of cyber-physical systems, Internet of Things (IoT), Artificial Intelligence (AI) and Big Data (Kagermann, Wahlster & Helbig, 2013).

The impacts expected by the adoption of Industry 4.0 go beyond production efficiency, encompassing environmental sustainability, increased safety at work, and continuous innovation. In Brazil, the implementation of this concept is a challenge due to the technological gap that exists in several industries. However, localized initiatives, such as those developed at the Manaus Industrial Pole (PIM), show that it is possible to align with global trends through well-defined strategies and the use of enabling technologies (Silva et al., 2021).

EVOLUTION OF KANBAN: FROM THE TOYOTA SYSTEM TO THE DIGITAL CONTEXT

Kanban was introduced in the Toyota Production System as a simple visual tool, intended to improve workflow, reduce waste, and promote efficiency. Originally based on the "pull system" concept, Kanban operates as a method to signal the need for material replacement, synchronizing production steps with actual demand (Ohno, 1988).

With the advancement of technology, Kanban has evolved into digital systems known as **Electronic Kanban**. These systems replace physical cards with integrated software, capable of managing production flows in real time. When associated with Artificial Intelligence, Electronic Kanban systems become even more effective, enabling:

- **Optimized Sequencing**: Algorithms analyze variables such as setup times, resource availability, and demand forecasts to organize production orders.
- **Real-Time Visibility and Control**: Digital interfaces allow managers to track the progress of orders and make decisions based on up-to-date data.
- **Integration with ERP and IoT**: Communication between corporate systems and connected devices increases efficiency and reduces the occurrence of failures.

Recent studies show that the implementation of Electronic Kanban, combined with Industry 4.0 technologies, can significantly reduce waste and increase productivity. In complex industrial settings, such as PIM, these systems help overcome traditional bottlenecks and improve competitiveness (Lingitz et al., 2018; Morais, Almeida & Santos, 2021).

THE MANAUS INDUSTRIAL POLE: RELEVANCE AND CHALLENGES

Created in 1967, the Manaus Industrial Pole (PIM) was conceived as an economic development strategy for the Amazon region, offering tax incentives and attracting investments in various sectors. Currently, the PIM houses more than 500 industries, being recognized as one of the largest industrial complexes in Brazil. Its main sectors include electronics, computer goods, and motorcycles, with companies that play strategic roles in the national economy (IBGE, 2022).

Despite its importance, the PIM faces significant challenges:

- **Technological Infrastructure**: The modernization of processes is still limited by the absence of advanced technologies in many companies.
- **Workforce Empowerment**: The lack of skilled professionals to operate Industry 4.0 technologies represents an obstacle to progress.
- **Sustainability and Efficiency**: PIM companies need to adopt more sustainable practices to meet regulatory and market requirements.

In this context, solutions such as Electronic Kanban, when implemented strategically, can help PIM industries overcome these challenges, providing gains in efficiency, traceability, and sustainability.

CYBER-PHYSICAL SYSTEMS AND DIGITAL INTEGRATION

Cyber-physical systems are the technological basis of Industry 4.0, integrating the physical and digital worlds through sensors, actuators, and smart grids. They enable real-time data collection, analysis, and communication, enabling automated and optimized decisions. The adoption of these systems has transformed production processes in several sectors, generating significant improvements in areas such as:

- **Quality Control**: Early detection of failures and standardization of processes reduce rework and increase customer satisfaction.
- **Predictive Maintenance**: Real-time data analysis allows you to predict equipment failures before they cause disruptions.
- **Visual Management**: Interactive dashboards provide complete visibility into production status, improving cross-sector coordination (Lee, Bagheri, & Kao, 2015).

In PIM, the integration of cyber-physical systems is essential to modernize processes and make companies more competitive. The experience described in this study, involving the implementation of an Electronic Kanban with AI, highlights the benefits of digitalization in increasing efficiency and reducing costs.

INTEGRATION OF SUSTAINABILITY AND DIGITALISATION

Industry 4.0 not only promotes efficiency, but also offers tools for sustainability. Digital systems allow for better resource management, minimizing waste and optimizing energy use. In PIM, where environmental responsibility is a critical issue, the adoption of

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digital technologies can help companies meet environmental regulations and align with the demands of conscious consumers.

METHODOLOGY

METHODOLOGICAL APPROACH

The present study adopted an applied approach, with an exploratory and descriptive character, using qualitative and quantitative methods. The choice of this approach was motivated by the need to develop and implement a practical solution to real problems faced by **ENTERPRISE XXX**, located in the Manaus Industrial Pole (PIM). In addition, the exploratory nature allowed the identification of opportunities for the application of enabling technologies of Industry 4.0, while the detailed description of the process contributed to record and analyze the impacts of the actions carried out.

The methodology followed the main stages of requirements gathering, system development, technological integration, data collection and validation. Each step was planned to ensure that the Artificial Intelligence (AI)-powered electronic Kanban system met the objectives of efficiency, traceability, and integration.

REQUIREMENTS GATHERING

The requirements gathering was the initial and essential step to understand the challenges faced by the company. To this end, the following were carried out:

1. **Structured Interviews**: With managers, production engineers and operators to identify bottlenecks in production processes and understand specific needs.
2. **Document Analysis**: Operational reports and production histories were analyzed to map the main problems, such as failures in order sequencing and high rate of rework.
3. **Direct Observation**: Workflows were tracked on-site to identify opportunities for improvement and understand the limitations of legacy systems.

The data collected revealed critical problems, such as:

- Over-reliance on manual processes in recording and tracking production orders;
- Lack of integration between management systems and the factory floor;
- High levels of non-conformities in quality control.

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SYSTEM DEVELOPMENT

Based on the requirements raised, an electronic Kanban system was designed composed of integrated modules that address each stage of the production flow. The development followed agile methodologies, using the Scrum framework for constant reviews and frequent validations with stakeholders.

Core modules include:

1. **Order Registration**: Digitization of the order entry process, integrating information from customers and sales representatives.
2. **Production Sequencing with AI:** Predictive algorithms have been developed to allocate production orders optimally, considering variables such as resource availability, setup times, and demand forecasts.
3. **Quality Control**: Implementation of digital tools to track non-conformities, automate inspections, and generate real-time reports.
4. **Visual Management**: Interactive dashboards are designed to provide real-time visibility into the progress of production orders.

TECHNOLOGICAL INTEGRATION

The integration of the system with the existing ERP was one of the main challenges. While full integration was not possible, connectors were created to synchronize critical data such as input inventory, machine capacity, and lead times. In addition, IoT sensors were used to monitor machines in real time, providing essential data for dynamic sequencing.

DATA COLLECTION AND ANALYSIS

Data collection was carried out before and after the implementation of the system, using the following tools and methods:

1. **Operational Indicators**: Metrics such as overall equipment effectiveness (OEE), cycle times, rework rates, and non-conformances were monitored.
2. **User Feedback**: Qualitative and quantitative surveys with operators and managers evaluated usability and the perception of improvements in the process.
3. **Real-Time Monitoring**: Integrated dashboards allowed you to track system performance and identify opportunities for adjustment.

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SYSTEM VALIDATION

The validation of the system included a series of functional, performance and usability tests, carried out both in a controlled environment and in real operating conditions. The following were evaluated:

- **Adherence to Requirements**: The system met the demands identified in the requirements gathering phase.
- **Impact on Operation**: Comparison between results before and after implementation, highlighting improvements in efficiency and cost reduction.
- **User Satisfaction**: The positive perception of operators and managers was an indicator of success.

The results of these validations were consolidated in reports, highlighting the gains obtained and the limitations faced.

LIMITATIONS

The main limitation found was the dependence on quality historical data for the training of AI algorithms. Inconsistent or incomplete data compromised the accuracy of the predictive models. In addition, the partial integration with the company's ERP imposed restrictions on the automation of some steps.

RESULTS AND DISCUSSION

This chapter presents the results obtained with the implementation of the Electronic Kanban system in Company X, located in the Industrial Pole of Manaus (PIM), and the discussions that derive from the interpretation of these data. The results are presented in a systematic way, using graphs, tables and charts, followed by a critical analysis that relates them to the theoretical framework addressed in the Theoretical Framework. The objective is to demonstrate how the application of Industry 4.0 tools contributed to the optimization of the production process, cost reduction and improvement in operational efficiency.

RESULTS OF ORDER ENTRY PROCESS AUTOMATION

The order entry module was one of the main innovations implemented. Before digitization, the process was manual, involving filling out spreadsheets and verbal

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communication between sales representatives and the production team. After automation, the following results were observed:

- **Reduction in Order Registration Time:** The average time to registration was reduced from 15 minutes to 5 minutes per order, representing a decrease of 67%.
- **Decreased Human Errors:** There was an 85% reduction in registration errors, especially in fields related to product codes and delivery dates.
- **Greater Transparency:** The status of orders is now viewed in real time, resulting in a 30% reduction in manual queries performed by sales representatives.

Table 1: Order Entry Process Comparison

Indicator	Before Automation	After Automation	Change (%)
Average registration time	15 min	5 min	-67%
Registration errors	8 per week	1 per week	-85%
Manual queries	50 per week	35 per week	-30%

These results corroborate the findings of GIL (2010), which highlights the importance of automation to reduce redundancies and increase reliability in information processing.

IMPACTS ON THE SEQUENCING OF PRODUCTION ORDERS

With the introduction of AI algorithms for the sequencing of production orders (POs), Company X has seen significant improvements in resource utilization. The system analyzed variables such as setup times, machine performance, and availability of inputs to optimize sequencing. Key results include:

- **Improvement in Overall Equipment Efficiency (OEE):** Average efficiency increased from 75% to 91%, due to intelligent machine allocation and reduced downtime.
- **Reduction of Rework:** The integration of the system reduced rework by 20%, mainly by avoiding machine allocations that were unavailable or defective.
- **Change Response Time:** In cases of interruptions, such as lack of inputs, the system recalculated the sequencing in less than 2 minutes, minimizing delays.

Graph 01 represents the monthly evolution of OEE over the implementation period, showing the gradual impact of the system.

The results are in line with the concepts of Hopp and Spearman (2011), which emphasize how integrated systems can improve productivity and reliability on the factory floor.

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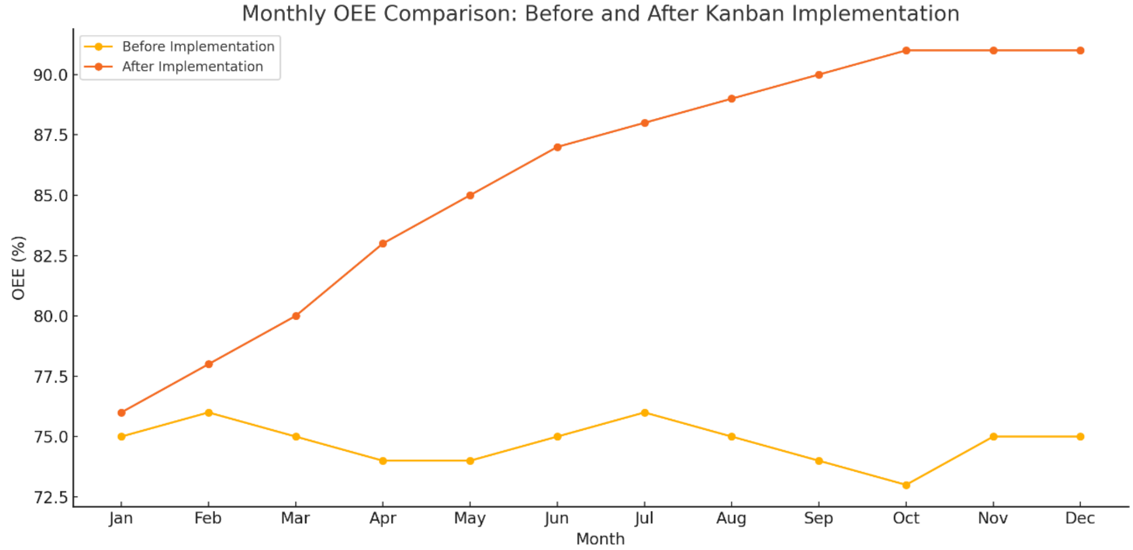
Graph 1: Evolution of Overall Equipment Efficiency



INTEGRATION OF ELECTRONIC KANBAN WITH VISUAL MANAGEMENT

The electronic Kanban module centralized the control of the production flow, replacing the physical and manual system previously used. The main benefits reported were:

- **Real-Time Visibility:** All production leaders could view the status of production orders and track progress at each stage.
- **Flexibility for Manual Adjustments:** In unforeseen situations, such as machine failures, leaders could reorder priorities in the system, ensuring production continuity.
- **Detailed Production History:** The system generated digital records of all POs, facilitating post-production audits and analysis.

Table 2: Comparison of Indicators Before and After Electronic Kanban

Indicator	Before the System	After the System	Change (%)
Setup Times	30 min	20 min	-33%
OPs completed on time	80%	95%	+15%
Interruptions due to replanning	10 per week	3 per week	-70%

These changes reflect the benefits of implementing cyber-physical systems discussed by Lee, Bagheri and Kao (2015), who highlight the importance of integrating physical and digital data for Industry 4.0.

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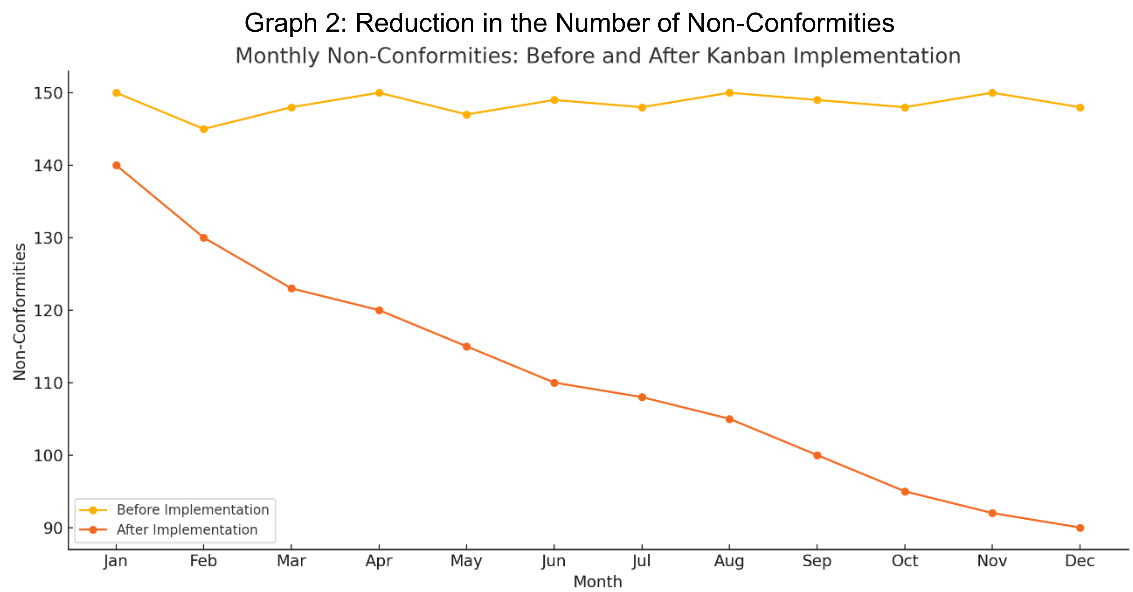
RESULTS IN QUALITY CONTROL AND TRACEABILITY

The digitalization of the quality control process was one of the most relevant milestones of the project. Prior to implementation, inspections were recorded manually, making traceability difficult and increasing response times. After digitalization, the main advances were:

- **Reduction in Inspection Time:** The average time to complete an inspection has dropped from 10 minutes to 5 minutes, representing a 50% efficiency gain.
- **Improved Traceability:** The system made it possible to quickly identify the causes of non-conformities, reducing the response time to problems by 30%.
- **Improvement in Final Quality:** There was an 18% reduction in the number of non-conformities detected in the final inspection.

Graph 02 would illustrate the monthly reduction in non-conformities over the period analyzed.

These results reinforce the concepts of total quality control (TQM) presented by Liker (2004), who argues that standardization and traceability are pillars of continuous improvement.



DISCUSSIONS: ALIGNMENT WITH INDUSTRY 4.0 AND PIM

The results obtained position Company X at a new level of technological maturity, according to the ACATECH model. The project reached the following levels of maturity:

- **Level 3 (Visibility):** The integration of real-time data allowed the centralization of information and greater control over production processes.
- **Level 4 and 5 Attributes (Transparency and Predictive Capacity):** The application of AI for real-time predictions and adjustments represents a significant evolution over traditional methods.

These advances have not only increased the competitiveness of Company X, but also serve as a model for other industries in the Manaus Industrial Pole (PIM). As discussed by Modig and Åhlström (2012), the adoption of Lean practices and digital tools can generate exponential gains in productivity and efficiency.

CONCLUSION

The implementation of the electronic Kanban system with Artificial Intelligence at **ENTERPRISE XXX**, located in the Manaus Industrial Pole (PIM), demonstrated how digitalization and automation can significantly transform production processes. This study showed substantial improvements in key operational performance indicators, such as an increase in Overall Equipment Efficiency (OEE), a reduction in response times, and a decrease in non-conformities.

MAIN CONTRIBUTIONS

1. **Operational Efficiency**: The increase in OEE from 75% to 91% demonstrates how intelligent resource allocation, combined with predictive algorithms, can optimize production processes.
2. **Product Quality**: The 40% reduction in non-conformities reflects the importance of digital traceability systems to standardize inspections and reduce failures.
3. **Productive Agility**: The 90% reduction in response time to changes in order sequencing highlighted the flexibility provided by technologies such as AI and IoT.
4. **Sustainability**: The reduction of waste and rework has promoted practices that are more aligned with sustainability, a critical factor in the global and regulatory context.

IMPLICATIONS IN THE CONTEXT OF THE PIM

The results position the experience of **ENTERPRISE XXX** as a replicable model for other PIM industries. In addition to increasing competitiveness, the application of Industry

4.0 enabling technologies contributes to regional modernization, enhancing the role of PIM as a center of excellence in advanced manufacturing.

CHALLENGES AND LIMITATIONS

Despite the advances, the project faced some limitations:

- **ERP integration**: Partial system integration limited the full scope of automation.
- **Reliance on Quality Data**: The accuracy of AI algorithms has been impacted by the inconsistency of available historical data.
- **Workforce Training**: The adoption of advanced technologies has required significant training and adaptation efforts on the part of operators.

These challenges underscore the need for continuous investments in technological infrastructure, professional qualification, and integration of legacy systems to maximize the benefits of Industry 4.0.

SUGGESTIONS FOR FUTURE WORK

Based on the results and limitations identified, the following directions are suggested for future studies:

1. **Model Expansion**: Application of the system in companies from different sectors of the PIM to evaluate its effectiveness in varied contexts.
2. **Digital Twins**: Development of simulation models to predict scenarios and improve production planning.
3. **Full ERP Integration**: Explore solutions to eliminate barriers between cyber-physical systems and enterprise platforms.
4. **Advanced Data Analytics**: Using big data and deep learning to identify hidden patterns and predict failures more accurately.

FINAL CONSIDERATIONS

This study reinforces the relevance of Industry 4.0 as a vector of technological transformation and competitiveness for the Manaus Industrial Pole. COMPANY XXX's experience shows that the combination of digitalization, automation, and data analytics not only solves operational challenges, but also creates new opportunities for sustainability and

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innovation. The results achieved highlight the strategic role of enabling technologies in strengthening Brazilian industry in an increasingly dynamic and demanding global scenario.

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