DIGITAL TRANSFORMATION IN THE MANAUS INDUSTRIAL HUB (PIM): DEVELOPMENT AND IMPLEMENTATION OF AN ELECTRONIC KANBAN SYSTEM USING ARTIFICIAL INTELLIGENCE FOR PRODUCTION OPTIMIZATION AND SEQUENCING IN A PIM TAPE COMPANY

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SUMMARY

This article presents the development and implementation of an electronic kanban system with Artificial Intelligence (AI) in a company in the Manaus Industrial Estate (PIM). The research, based on the principles of Industry 4.0, aimed to optimize the sequencing of production orders and promote greater operational efficiency, process integration and cost reduction. Using an applied and exploratory approach, quantitative and qualitative methods were used to identify bottlenecks and develop technological solutions in line with the company's needs. The results show significant improvements, including a 67% reduction in order entry time, a 22% increase in overall equipment efficiency (OEE) and an 18% drop in non-conformities detected during final inspection. This study highlights the transformative potential of digitalization and automation for PIM companies, contributing to industrial modernization and serving as a replicable model for other contexts.

Key words

Industry 4.0; Electronic Kanban; Artificial Intelligence; Automation; Manaus Industrial Estate.

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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 of digital technologies and industrial processes. With the integration of tools such as Artificial Intelligence (AI), the Internet of Things (IoT), Big Data, cloud computing and cyber-physical systems, Industry 4.0 profoundly transforms production, management and distribution. These innovations provide greater efficiency, flexibility, mass customization and decision-making based on real-time data, essential characteristics for competitiveness in increasingly dynamic and global markets (Kagermann, Wahlster & Helbig, 2013; Hermann, Pentek & Otto, 2016).

In Brazil, the Manaus Industrial Complex (PIM) stands out as one of the largest and most important industrial complexes in the country, housing companies in 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, in order to maintain its competitiveness and face the challenges of a globalized market, the PIM needs to modernize and adopt Industry 4.0 enabling technologies. This modernization is essential to overcome production bottlenecks, reduce waste and promote more sustainable and efficient management (Marconi & Machado, 2020).

Among the technologies of Industry 4.0, electronic Kanban with AI has emerged as a powerful solution for improving production processes. Kanban, initially conceived as a visual tool for controlling flows 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 on the progress of production processes (Lingitz et al., 2018; Morais, Almeida & Santos, 2021).

This article describes the development and implementation of an electronic Kanban system with AI at **EMPRESA XXX**, a PIM company that was facing challenges related to operational efficiency, data integration and end product quality. Adopting this solution made it possible to improve resource allocation, reduce operational errors, increase process traceability and promote greater transparency for managers. As a result, **EMPRESA XXX** not only modernized its production line, but also aligned itself with the demands of a market that values digital transformation and sustainability.

Study Objectives The main objective of this work is to demonstrate how the implementation of an electronic Kanban system with AI can have a positive impact on the production processes of a PIM company. Specifically, the aim is to:

1. Evaluate the system's impact on operational efficiency, such as increasing OEE and reducing idle times;
2. Identify the benefits generated by real-time data integration and its influence on management decision-making;
3. Present a replicable model for other PIM companies facing similar challenges.

Structure of the article In order to achieve the proposed objectives, the article is structured in seven sections. After this introduction, the **Theoretical Framework** section presents the foundations of Industry 4.0, the evolution of Kanban systems and the context of PIM. The **Methodology section** details the stages used to develop and implement the system. **The Results and Discussions** present the impacts observed on production efficiency and quality. 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, is emerging 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 industry by integrating advanced technologies into production processes. The proposal involves transforming factories into intelligent, connected and autonomous environments, based on the integration of cyber-physical systems, the Internet of Things (IoT), Artificial Intelligence (AI) and Big Data (Kagermann, Wahlster & Helbig, 2013).

The impacts expected from the adoption of Industry 4.0 go beyond production efficiency, encompassing environmental sustainability, increased safety at work and continuous innovation. In Brazil, implementing this concept is a challenge due to the technological gap that exists in many industries. However, localized initiatives, such as those developed at the Manaus Industrial Estate (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 into the Toyota Production System as a simple visual tool designed to improve workflow, reduce waste and promote efficiency. Originally based on the "pull system" concept, the Kanban operates as a method for signalling the need to replenish materials, synchronizing production stages with actual demand (Ohno, 1988).

With the advance 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 combined with Artificial Intelligence, Electronic Kanban systems become even more effective, making it possible:

- **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 monitor 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 faults.

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 scenarios, such as PIM, these systems help to overcome traditional bottlenecks and improve competitiveness (Lingitz et al., 2018; Morais, Almeida & Santos, 2021).

The Manaus Industrial Estate: Relevance and Challenges

Created in 1967, the Manaus Industrial Estate (PIM) was conceived as an economic development strategy for the Amazon region, offering tax incentives and attracting investment in various sectors. Today, the PIM is home to more than 500 industries and is 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 lack of advanced technologies in many companies.
- **Workforce training**: The lack of qualified 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 intelligent networks. They allow data to be collected, analyzed and communicated in real time, enabling automated and optimized decisions. The adoption of these systems has transformed production processes in various sectors, generating significant improvements in areas such as:

- **Quality Control**: Early detection of faults and standardization of processes reduces rework and increases customer satisfaction.
- Predictive **Maintenance**: Real-time data analysis makes it possible to predict equipment failures before they cause outages.
- **Visual Management**: Interactive dashboards offer complete visibility of production status, improving coordination between sectors (Lee, Bagheri & Kao, 2015).

In PIM, the integration of cyber-physical systems is key to modernizing processes and making 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.

Integrating Sustainability and Digitalization

Industry 4.0 not only promotes efficiency, but also offers tools for sustainability. Digital systems enable better management of resources, minimizing waste and optimizing energy use. In the PIM, where environmental responsibility is a critical issue, adopting digital technologies can help companies meet environmental regulations and align with the demands of conscious consumers.

METHODOLOGY

Methodological Approach

This study adopted an applied, exploratory and descriptive approach, 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 **COMPANY XXX**, located in the Manaus Industrial Estate (PIM). In addition, the exploratory nature made it possible to identify opportunities for the application of Industry 4.0 enabling technologies, while the detailed description of the process helped to record and analyze the impacts of the actions taken.

The methodology followed the main stages of requirements gathering, system development, technological integration, data collection and validation. Each stage was designed to ensure that the electronic kanban system with Artificial Intelligence (AI) met the objectives of efficiency, traceability and integration.

Requirements gathering

The requirements survey was the initial and essential stage in understanding 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. **Documentary Analysis**: Operational reports and production histories were analyzed to map out the main problems, such as failures in order sequencing and a high rate of rework.
3. **Direct observation**: Workflows were monitored on site to identify opportunities for improvement and understand the limitations of legacy systems.

The data collected revealed critical problems such as:

- Excessive dependence on manual processes for recording and monitoring production orders;
- Lack of integration between management systems and the shop floor;

- High levels of non-conformities in quality control.

System development

Based on the requirements gathered, an electronic Kanban system was designed consisting of integrated modules that address each stage of the production flow. Development followed agile methodologies, using the Scrum framework for constant reviews and frequent validation with stakeholders.

The main modules include:

1. **Order** Entry: Digitization of the order entry process, integrating information from customers and sales representatives.
2. **Production sequencing with AI**: Predictive algorithms have been developed to optimally allocate production orders, taking into account 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 reports in real time.
4. **Visual Management**: Interactive dashboards have been designed to offer real-time visibility on the progress of production orders.

Technological integration

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

Data Collection and Analysis

Data was collected before and after the system was implemented, using the following tools and methods:

1. **Operational Indicators**: Metrics such as overall equipment efficiency (OEE), cycle times, rework rates and non-conformities were monitored.
2. **User feedback**: Qualitative and quantitative surveys with operators and managers evaluated usability and the perception of process improvements.
3. **Real-time monitoring**: Integrated dashboards made it possible to track system performance and identify opportunities for adjustment.

System validation

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

- **Adherence to requirements**: The system met the demands identified in the requirements gathering phase.
- **Impact on Operations**: Comparison of results before and after implementation, highlighting improvements in efficiency and cost savings.
- **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 made and the limitations faced.

Limitations

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

RESULTS AND DISCUSSION

This chapter presents the results obtained from the implementation of the Electronic Kanban system at Company X, located in the Manaus Industrial Estate (PIM), and the discussions that derive from the interpretation of this data. The results are presented systematically, using graphs, tables and charts, followed by a critical analysis that relates them to the theoretical framework discussed in the Theoretical Framework. The aim is to demonstrate how the application of Industry 4.0 tools has contributed to optimizing the production process, reducing costs and improving operational efficiency.

Results of Automating the Order Entry Process

The order entry module was one of the main innovations implemented. Before digitalization, the process was manual, involving filling in spreadsheets and verbal communication between sales representatives and the production team. After automation, the following results were observed:

- **Reduction in Order Registration Time:** The average time for registration was reduced from 15 minutes to 5 minutes per order, representing a 67% decrease.
- **Reduction in 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 can now be viewed in real time, resulting in a 30% reduction in manual queries made by sales representatives.

Table 1: Comparison of the Order Entry Process

Indicator	**Before Automation**	**After Automation**	**Variation (%)**
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), who highlights the importance of automation to reduce redundancies and increase reliability in information processing.

Impacts on Production Order Sequencing

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

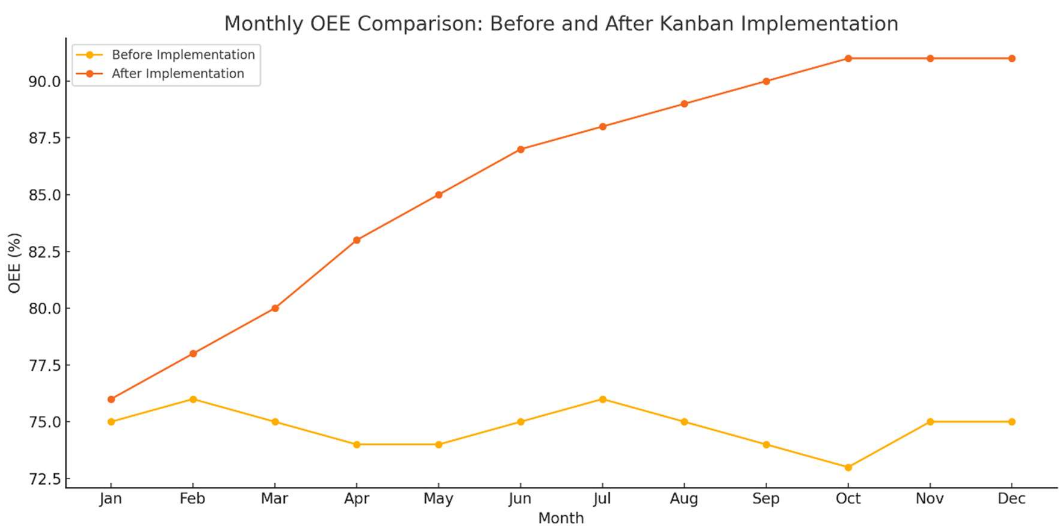
- **Improvement in Overall Equipment Efficiency (OEE):** Average efficiency increased from 75% to 91%, due to the intelligent allocation of machines and a reduction in idle times.
- **Reduction in rework:** The integration of the system reduced rework by 20%, mainly by avoiding the allocation of machines that were unavailable or defective.

- **Response Time to Changes:** In the event of interruptions, such as a lack of supplies, the system recalculated the sequencing in less than 2 minutes, minimizing delays.

Graph 01 shows 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), who emphasize how integrated systems can improve productivity and reliability on the shop floor.

Graph 1: Evolution of Overall Equipment Efficiency



Integrating Electronic Kanban with Visual Management

The electronic Kanban module centralized control of the production flow, replacing the physical and manual system used previously. 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, guaranteeing production continuity.
- **Detailed Production History:** The system generated digital records of all POs, facilitating audits and post-production analysis.

Table 2: Comparison of Indicators Before and After Electronic Kanban

Indicator	Before the system	After the system	Variation (%)
Setup times	30 min	20 min	-33%
POs 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.

Results in Quality Control and Traceability

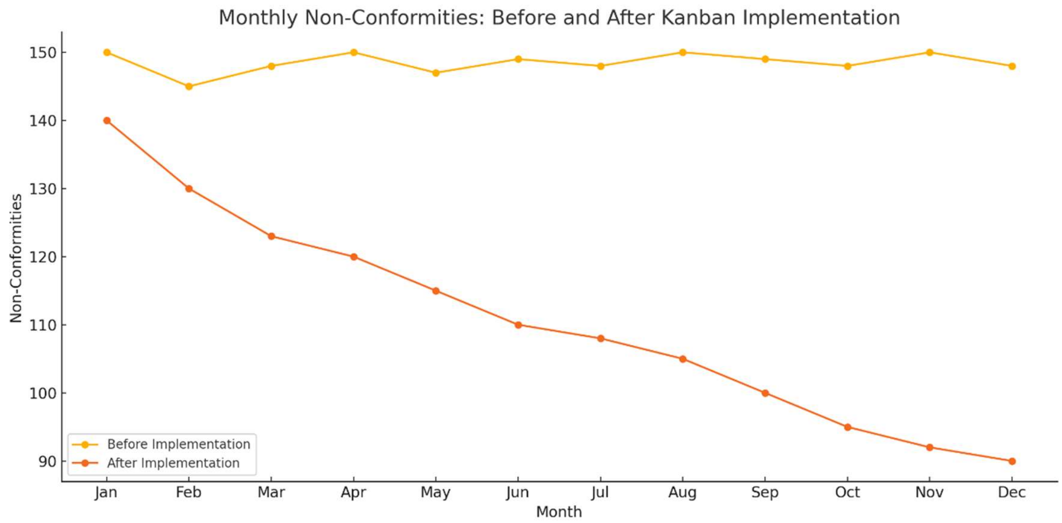
Digitizing the quality control process was one of the project's most important milestones. Before implementation, inspections were recorded manually, making traceability difficult and increasing response times. After digitization, the main advances were:

- **Reduction in Inspection Time:** The average time to complete an inspection fell from 10 minutes to 5 minutes, representing an efficiency gain of 50%.
- **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 illustrates 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.

Graph 2: Reduction in the Number of Non-Conformities



Discussions: Alignment with Industry 4.0 and PIM

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

- **Level 3 (Visibility):** The integration of data in real time has allowed the centralization of information and greater control over production processes.
- **Attributes of Levels 4 and 5 (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 Estate (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 **COMPANY XXX**, located in the Manaus Industrial Estate (PIM), demonstrated how digitization 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 reduction in non-conformities.

Main Contributions

1. **Operational Efficiency**: The increase in OEE from 75% to 91% demonstrates how the intelligent allocation of resources, 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 in waste and rework has promoted practices that are more in line with sustainability, a critical factor in the global and regulatory context.

Implications for the PIM Context

The results position the experience of **COMPANY XXX** as a replicable model for other industries in the PIM. In addition to increasing competitiveness, the application of Industry 4.0 enabling technologies contributes to regional modernization, boosting the PIM's role as a pole of excellence in advanced manufacturing.

Challenges and limitations

Despite the progress, the project faced some limitations:

- **Integration with ERP**: Partial system integration limited the full scope of automation.
- **Dependence 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 highlight the need for continued investment in technological infrastructure, professional qualifications and the integration of legacy systems in order 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. **Expansion of the Model**: Application of the system in companies from different PIM sectors to evaluate its effectiveness in different contexts.
2. **Digital Twins**: Development of simulation models to predict scenarios and improve production planning.
3. **Total integration with ERP**: Explore solutions to eliminate barriers between cyber-physical systems and corporate platforms.
4. **Advanced Data Analysis**: Use of 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 for technological transformation and competitiveness for the Manaus Industrial Estate. The experience of **EMPRESA XXX** shows that the combination of digitalization, automation and data analysis not only solves operational challenges, but also creates new opportunities for sustainability and 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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