




APPLICATION OF CONTINUOUS IMPROVEMENT IN THE OPTIMIZATION OF CUTTING, SEPARATION, AND FINISHING MACHINE PROCESSES IN THE ELECTRONICS INDUSTRY

APLICAÇÃO DA MELHORIA CONTÍNUA NA OTIMIZAÇÃO DE PROCESSOS DE MÁQUINAS DE CORTE, SEPARAÇÃO E ACABAMENTO NA INDÚSTRIA ELETRÔNICA

APLICACIÓN DE LA MEJORA CONTINUA EN LA OPTIMIZACIÓN DE PROCESOS DE MÁQUINAS DE CORTE, SEPARACIÓN Y ACABADO EN LA INDUSTRIA ELECTRÓNICA

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ABSTRACT

The optimization of production processes in the electronics industry, from the perspective of continuous improvement and digital transformation, constitutes a strategic challenge for increasing organizational competitiveness. This study investigates the integrated application of Lean methodologies, such as PDCA, Kaizen, and 5S, combined with the use of advanced technologies, focusing on the operation of Elite Routers in an industrial environment. The objective is to analyze the impacts of standardization, automation, and digitalization of operational activities on efficiency, quality, and process traceability. The research adopts a case study methodological approach, based on the collection and analysis of operational data, systematic observation, and comparison of performance indicators before and after the implementation of improvements. The interventions involved restructuring the production flow, eliminating waste, integrating monitoring systems, and strengthening operational training. The results demonstrate substantial gains, including reduced cycle time, mitigation of rework, increased productivity, and enhanced process reliability, as well as significant advances in traceability and operational control. It is concluded that the convergence between established continuous improvement practices and the principles of Industry 4.0 enhances systemic efficiency and promotes sustainable competitive advantages in the context of electronic manufacturing.

Keywords: Continuous Improvement. Router. Manufacturing Processes. Industry 4.0.

RESUMO

A otimização dos processos produtivos na indústria eletrônica, sob a perspectiva da melhoria contínua e da transformação digital, constitui um desafio estratégico para o aumento da competitividade organizacional. Este estudo investiga a aplicação integrada de metodologias Lean, como PDCA, Kaizen e 5S, combinadas ao uso de tecnologias avançadas, com foco

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na operação de Routers Elite em ambiente industrial. O objetivo é analisar os impactos da padronização, automação e digitalização das atividades operacionais sobre a eficiência, a qualidade e a rastreabilidade dos processos. A pesquisa adota uma abordagem metodológica de estudo de caso, baseada na coleta e análise de dados operacionais, observação sistemática e comparação de indicadores de desempenho antes e depois da implementação das melhorias. As intervenções envolveram a reestruturação do fluxo de produção, a eliminação de desperdícios, a integração de sistemas de monitoramento e o fortalecimento do treinamento operacional. Os resultados demonstram ganhos substanciais, incluindo redução do tempo de ciclo, mitigação de retrabalho, aumento da produtividade e maior confiabilidade dos processos, bem como avanços significativos em rastreabilidade e controle operacional. Conclui-se que a convergência entre práticas consolidadas de melhoria contínua e os princípios da Indústria 4.0 potencializa a eficiência sistêmica e promove vantagens competitivas sustentáveis no contexto da manufatura eletrônica.

Palavras-chave: Melhoria Contínua. Router. Processos de Manufatura. Indústria 4.0.

RESUMEN

La optimización de los procesos productivos en la industria electrónica, desde la perspectiva de la mejora continua y la transformación digital, constituye un desafío estratégico para aumentar la competitividad organizacional. Este estudio investiga la aplicación integrada de metodologías Lean, como PDCA, Kaizen y 5S, combinadas con el uso de tecnologías avanzadas, con foco en la operación de Routers Elite en un entorno industrial. El objetivo es analizar los impactos de la estandarización, automatización y digitalización de las actividades operativas sobre la eficiencia, la calidad y la trazabilidad de los procesos. La investigación adopta un enfoque metodológico de estudio de caso, basado en la recopilación y el análisis de datos operativos, la observación sistemática y la comparación de indicadores de desempeño antes y después de la implementación de mejoras. Las intervenciones implicaron la reestructuración del flujo de producción, la eliminación de desperdicios, la integración de sistemas de monitoreo y el fortalecimiento de la capacitación operativa. Los resultados demuestran ganancias sustanciales, incluyendo la reducción del tiempo de ciclo, la mitigación del retrabajo, el aumento de la productividad y una mayor confiabilidad de los procesos, así como avances significativos en trazabilidad y control operativo. Se concluye que la convergencia entre prácticas consolidadas de mejora continua y los principios de la Industria 4.0 potencia la eficiencia sistémica y promueve ventajas competitivas sostenibles en el contexto de la manufatura electrónica.

Palabras clave: Mejora Continua. Router. Procesos de Manufatura. Industria 4.0.



1 INTRODUCTION

The growing competitiveness of the electronics industry, combined with the demand for higher quality, productivity, and cost reduction, has driven the adoption of continuous improvement practices as a fundamental strategy for organizational sustainability. In this context, methodologies such as Lean Manufacturing have been widely employed to eliminate waste, optimize production flows, and increase operational efficiency, contributing to the enhancement of industrial processes and the creation of customer value (Womack & Jones, 2003).

The application of lean principles in the manufacturing industry, especially in processes involving machining and precision cutting operations, such as those performed by CNC Router machines, has shown significant results in terms of production performance and product quality. According to Ohno (1997), the systematic elimination of waste enables continuous process improvement, while Liker (2005) emphasizes the importance of standardization and team involvement for consolidating an organizational culture oriented toward operational excellence.

In the specific scenario of the electronics industry, the use of Elite Routers in the processing of printed circuit boards (PCBs) represents a critical stage of the production process, as it directly impacts the final product quality, productivity, and operating costs. However, challenges such as rework, process variability, high setup times, and lack of digital integration are still frequent, highlighting the need for systematic application of continuous improvement tools combined with digital transformation technologies (Slack; Brandon-Jones; Johnston, 2018).

Given this context, the following research problem emerges: how can the integrated application of continuous improvement practices contribute to the optimization of production processes that use Elite Router machines in the electronics industry? Investigating this problem becomes relevant not only from an academic perspective but also from a practical standpoint, since its results can help reduce waste, increase productivity, and improve product quality, while promoting gains in operational efficiency and organizational competitiveness.

This study aims to analyze the impacts of applying continuous improvement methodologies, such as PDCA, Kaizen, and 5S, associated with process digitalization, in optimizing operations performed by Elite Routers. Specifically, it seeks to identify waste in the production process, propose improvements based on Lean principles, and evaluate the results obtained in terms of operational performance, quality, and process reliability.



The justification for conducting this research is based on the growing need for integration between traditional continuous improvement practices and emerging Industry 4.0 technologies, especially in the context of manufacturing engineering. The adoption of these approaches allows not only the optimization of production processes but also increased traceability, improved decision-making, and greater adaptability to dynamic market demands.

Thus, this study contributes to advancing knowledge in the field of Mechanical Engineering, with an emphasis on manufacturing processes and CNC machining, by demonstrating the integrated applicability of continuous improvement practices and digital technologies in optimizing production processes in the electronics industry, promoting sustainable gains in efficiency, quality, and competitiveness.

2 THEORETICAL FRAMEWORK

2.1 CONTINUOUS IMPROVEMENT AND LEAN MANUFACTURING

Continuous improvement constitutes one of the fundamental pillars of quality management, being widely used to promote process optimization and the systematic elimination of waste. In the industrial context, the concept of continuous improvement is strongly associated with Lean Manufacturing practices, whose main objective is to maximize customer value through the efficient use of resources and the reduction of activities that do not add value to the production process (Womack & Jones, 2003).

According to Ohno (1997), creator of the Toyota Production System, waste can be classified into different categories, including overproduction, waiting, unnecessary transportation, excessive processing, inventory, movement, and rework. There is consensus in the literature that identifying and eliminating these wastes represents an essential path to increasing operational efficiency and organizational competitiveness.

Furthermore, tools such as PDCA, Kaizen, and 5S are widely applied to structure continuous improvement initiatives. According to Liker (2005), the adoption of these practices contributes to the development of an organizational culture oriented toward excellence, promoting team engagement and process standardization. However, despite the broad recognition of the benefits of Lean Manufacturing, a contradiction between theory and practice is observed, as many organizations face difficulties in the sustained implementation of these methodologies, especially regarding cultural change and continuous employee engagement, which characterizes a relevant gap in applied studies.



2.2 MANUFACTURING PROCESSES AND CNC MACHINING

Manufacturing processes play a central role in Mechanical Engineering, being responsible for transforming raw materials into products with high precision and quality. Among these processes, CNC machining (Computer Numerical Control) stands out for its ability to perform complex operations with high repeatability and dimensional control.

CNC Router machines, especially in applications aimed at the electronics industry, are widely used in the cutting and separation of printed circuit boards (PCBs), requiring a high level of precision, operational parameter control, and equipment reliability. According to Groover (2016), the use of CNC technologies allows greater production flexibility, reduced variability, and improved quality of final products, representing a consensus in the literature regarding their operational benefits.

However, even with the advancement of these technologies, challenges such as high setup times, rework, and operational failures are still observed in industrial practice. This situation highlights a gap between the technological potential of CNC machines and their effective use in production environments, indicating the need for integration with continuous improvement methodologies to maximize results.

2.3 DIGITAL TRANSFORMATION AND INDUSTRY 4.0 IN MANUFACTURING

Industry 4.0 has promoted a profound transformation in production systems through the incorporation of digital technologies such as the Internet of Things (IoT), cyber-physical systems, big data, and advanced automation. These technologies enable greater connectivity, traceability, and real-time analysis capabilities, contributing to decision-making and the optimization of industrial processes (Slack; Brandon-Jones; Johnston, 2018).

In the manufacturing context, digital transformation allows the integration of equipment, systems, and data, promoting greater transparency in processes and facilitating the identification of improvement opportunities. According to Kagermann, Wahlster, and Helbig (2013), industrial digitalization represents a milestone in the evolution of production systems, enabling the creation of smart and highly efficient factories, a point of consensus among various studies in the field.

On the other hand, a relevant contradiction is observed regarding the adoption of these technologies, since despite their high innovation potential, many organizations still face limitations in terms of implementation costs, technical training, and integration of legacy systems. This reality demonstrates that digital transformation does not occur uniformly, highlighting gaps in its practical application, especially in more traditional industrial environments. The application of these concepts in processes using CNC Router machines



enables continuous monitoring of operational parameters, automation of previously manual activities, and reduction of human errors, directly contributing to improved quality and productivity.

2.4 INTEGRATION BETWEEN LEAN MANUFACTURING AND INDUSTRY 4.0

The integration between Lean Manufacturing principles and Industry 4.0 technologies has been consolidated as a strategic approach to optimizing production systems. While Lean focuses on waste elimination and continuous improvement, Industry 4.0 provides the technological resources necessary to enhance efficiency and analytical capacity in processes.

According to Sanders, Elangerswaran, and Wulfsberg (2016), the convergence between Lean and digital technologies enhances the creation of more agile, intelligent, and adaptable production systems, allowing variability reduction, productivity increase, and product quality improvement, which represents a growing consensus in the literature.

However, despite the widely discussed benefits, gaps still exist regarding the integrated implementation of these approaches, especially concerning the compatibility between Lean organizational culture and the complexity of digital technologies. This difficulty highlights a contradiction between the conceptual advancement of Lean 4.0 integration and its practical application in real industrial environments.

In this context, the digitalization of operational processes, associated with the application of structured continuous improvement methodologies, enables significant gains in operational performance, especially in industrial environments that demand high precision and control, such as those using Elite Router equipment.

2.5 SYNTHESIS OF THE THEORETICAL FRAMEWORK

The literature analysis shows that continuous improvement, combined with Lean Manufacturing practices and Industry 4.0 technologies, plays a fundamental role in optimizing production processes. In the context of Mechanical Engineering, especially in CNC machining processes, the integration of these approaches allows not only waste reduction but also increased efficiency, quality, and industrial competitiveness. However, it is observed that gaps still exist regarding the practical application of these approaches in an integrated manner in specific environments, such as operations performed by CNC Router machines in the electronics industry. Thus, this study seeks to contribute to the advancement of knowledge by proposing and analyzing the joint application of these methodologies in a real industrial context.

3 METHODOLOGY

This research is characterized as an applied case study, with both quantitative and qualitative approaches, conducted in a company from the electro-electronic sector located in the Industrial Pole of Manaus. The study focuses on the analysis and optimization of production processes that use Elite Router machines in the processing of printed circuit boards (PCBs), based on the application of continuous improvement methodologies and digital transformation tools.

Regarding its objectives, the research is classified as descriptive and explanatory, since it seeks to identify, analyze, and understand the factors that impact the performance of production processes, as well as to propose and evaluate solutions for improving operational efficiency and product quality.

The scope of the research comprises production processes related to the cutting and separation stage of PCBs using CNC Router equipment. Sampling was intentionally defined, considering a specific production line in which recurring problems were identified, such as rework, process variability, high setup times, and low integration of operational data.

Data collection was carried out using multiple techniques to ensure greater reliability and consistency of the information obtained. The following methods were employed: (I) direct observation of the production process, (II) analysis of historical data from the company's internal systems, (III) collection of performance indicators such as cycle time, rework rate, productivity, and operational efficiency, and (IV) value stream mapping (VSM), including a cross-functional approach, to identify waste and bottlenecks across areas involved in the process.

As a methodological procedure, the structured application of the PDCA cycle (Plan, Do, Check, Act) was adopted to guide improvements. In the planning phase (Plan), the main opportunities for improvement were identified through analysis of the current state of the process. In the execution phase (Do), corrective actions and improvements were implemented, including activity standardization, reduction of setup times, and digitalization of operational controls. In the verification phase (Check), the results obtained were analyzed based on previously defined indicators. Finally, in the action phase (Act), improvements were consolidated and new operational standards were established.

Additionally, Lean tools such as Kaizen and 5S were employed to promote workplace organization, waste elimination, and team engagement in the pursuit of continuous improvement. Process digitalization was carried out through the implementation of monitoring and control systems, aiming to increase traceability, reduce manual activities, and improve information integration.

The collected data were tabulated and analyzed through comparative analysis before and after the implementation of improvements, using key performance indicators (KPIs). This approach allowed for a quantitative evaluation of the impacts of the interventions, as well as validation of the effectiveness of the proposed solutions.

Thus, the adopted methodology enables not only a detailed understanding of the studied process but also the replication of practices in other industrial contexts, contributing to the dissemination of applicable solutions for process improvement in the electronics industry, particularly within Mechanical Engineering and advanced manufacturing.

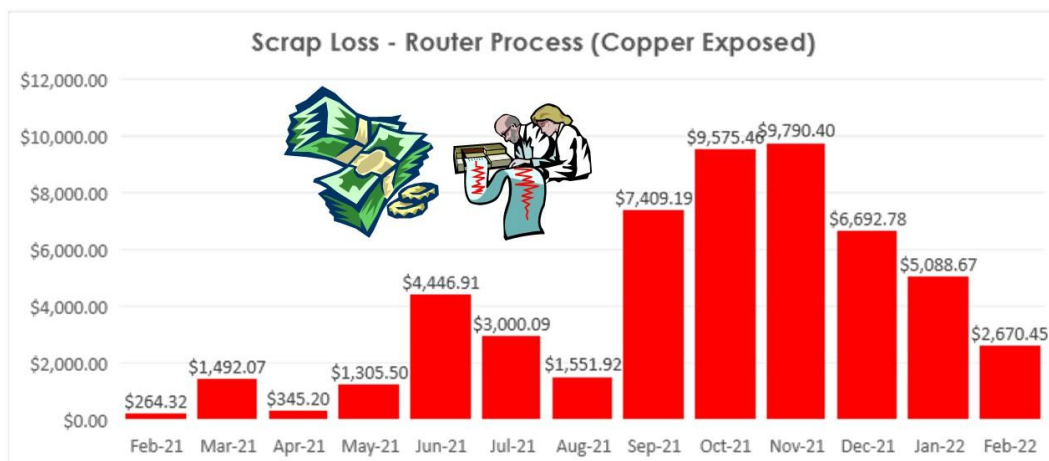
4 RESULTS AND DISCUSSION (DATA ANALYSIS)

4.1 INITIAL PROCESS SITUATION ANALYSIS

The initial analysis of the production process revealed significant losses associated with the operation of Router machines in the cutting and separation of printed circuit boards (PCBs). Based on the data collected, an average monthly loss of approximately US\$ 4,125.61 was identified, highlighting a direct impact on operational costs and process efficiency.

Figure 1

Monthly Losses in the Router Process (US\$)

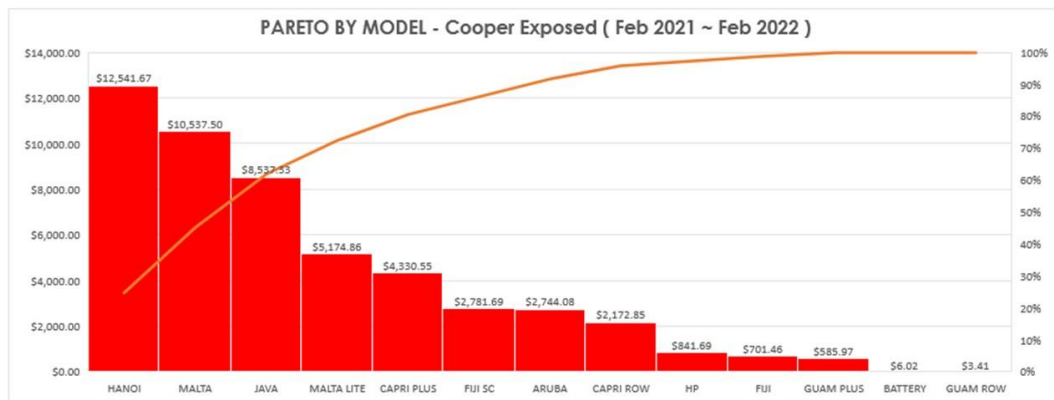


Source: prepared by the author based on research data (2021).

The analysis through the Pareto chart made it possible to identify the main contributors to the losses, with the Hanoi models (25%), Malta (21%), and Java (17%) standing out. Together, these account for the largest share of the observed waste. These results are consistent with the Pareto principle, widely applied in Lean approaches, in which a small portion of causes is responsible for the majority of problems.

Figure 2

Pareto Analysis of Losses by Model



Source: prepared by the author based on research data (2022).

Additionally, recurring failures were identified related to:

- a) Inadequate transportation of boards (generating scrap).
- b) Problems with table return after cutting.
- c) Variability in operational parameters.

These factors indicate the presence of typical wastes described by Ohno (1997), such as rework, unnecessary movement, and process failures, reinforcing the need for structured application of continuous improvement practices.

4.2 IDENTIFICATION OF PROBLEMS AND IMPLEMENTATION OF IMPROVEMENTS (KAIZEN)

Based on the initial diagnosis, improvement actions were carried out using the Kaizen approach, focusing on eliminating the main causes of losses identified. The methodology emphasized small, continuous changes aimed at reducing waste and stabilizing processes.

4.2.1 Safety and Operational Control

A critical problem was identified related to the return of the side tables after cutting, which represented an operational risk and the possibility of process failures. This issue not only compromised the safety of operators but also increased the likelihood of equipment malfunction and production interruptions.

Figure 3

Initial Condition with Failures in Table Return

Problem
Prevent the return of the tables on the right and left side after cutting, in order to guarantee the protection of the operator during handling and interaction with the equipment.

Source: collection of the surveyed company.

As a corrective action, a detection system with a light curtain (NR12) was implemented, capable of identifying the operators presence and blocking the machine's automatic movement under unsafe conditions.

Figure 4

Implementation of NR12 Safety System



Source: collection of the surveyed company.

The comparison between conditions before and after implementation shows a significant improvement in operational safety and process reliability, reducing the risks of accidents and failures.

4.2.2 Reduction of Scrap in Transportation

Another relevant problem was associated with the displacement of boards during transportation, causing failures in the robot's pick-up and consequently generating scrap.

Figure 5

Board Misalignment (Before Kaizen)

Action Taken
Installation of NR12, with the light curtain system for detecting operator interaction with the equipment, triggering the safety relay where the table return command is cut, triggering their alarms. It also has indication lights (safe and not safe).

Source: collection of the surveyed company.

To mitigate this condition, guides (pins) were implemented on the transport pallets, ensuring the correct positioning of the boards.

Figure 6

Implementation of Guides (After Kaizen)



Source: collection of the surveyed company.

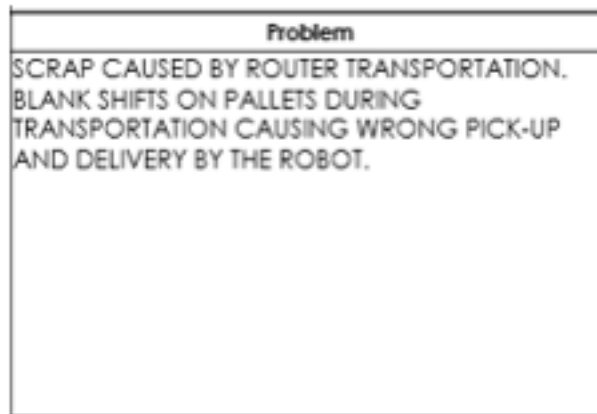
After the improvement, the improper displacement of blanks was eliminated, resulting in greater process stability and a significant reduction in losses due to positioning errors.

4.2.3 Automation of the Production Process

It was identified that part of the routing process was carried out manually, contributing to variability and an increase in cycle time.

Figure 7

Manual Process



Source: collection of the surveyed company.

As an improvement, automated routing was implemented, reducing the dependence on human intervention.

Figure 8

Automated Process



Source: collection of the surveyed company.

The comparison between the previous and the improved state shows clear gains in:

- a) Process standardization
- b) Reduction of operational errors
- c) Increase in productivity

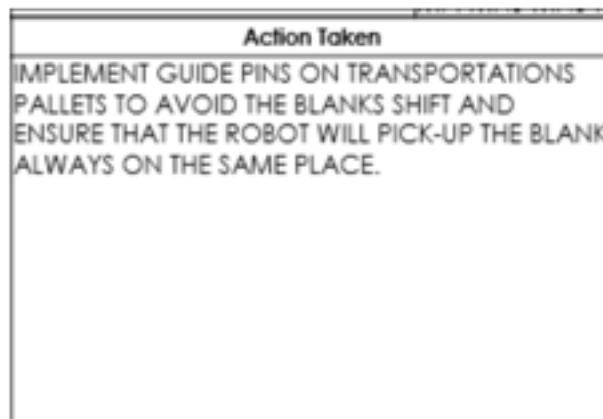
This result is aligned with the principles of Industry 4.0, which advocate for greater integration and automation of production systems. By reducing human dependency and variability, the process not only became more efficient but also more reliable, reinforcing the transition toward smart manufacturing environments.

4.2.4 Statistical Process Control (SPC)

The analysis of the data revealed high defect rates associated with variations in the Router machines' process. This finding highlighted the need for stricter monitoring and control of process parameters to ensure consistency and reduce variability.

Figure 9

Process Before SPC



Source: collection of the surveyed company.

As a corrective action, Statistical Process Control (SPC) was implemented, focusing on the monitoring of critical variables such as mechanical clearances, alignment, and operational parameters.

In addition, complementary actions were carried out, including:

- a) Cause analysis (screw, linear guide, table)
- b) Retrofit on machines with greater variability
- c) Adjustment of the capability plan (CPK)
- d) Implementation of Automated Optical Inspection (AOI)

Figure 10

Process After SPC



Source: collection of the surveyed company.

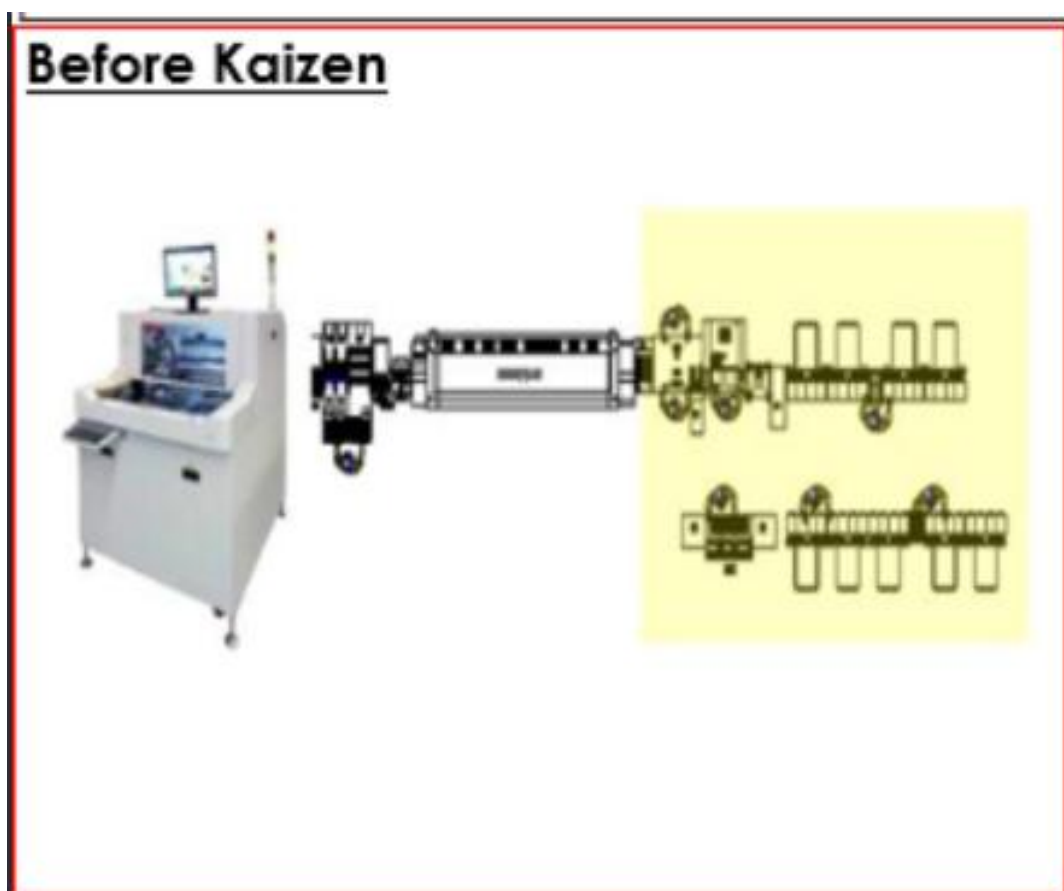
The results demonstrated a significant improvement in process stability, with reduced variability and increased operational capability.

4.3 COMPARISON BETWEEN EQUIPMENT (AUROTEK ROUTER VS ELITE ROUTER)

Comparative analysis between the equipment revealed significant differences in terms of performance and technological capability. The Router Elite machine presents advantages related to positioning accuracy (± 0.01 mm), a wider operating range, and greater mechanical stability when compared to conventional equipment.

Figure 11

Comparison Between Equipment



Source: prepared by the author based on the technical specifications of the equipment.

These characteristics directly contribute to improving the quality of the machining process and reducing variability, reinforcing the importance of appropriate technological choices for increasing production efficiency.

4.4 EVALUATION OF THE RESULTS OBTAINED

The implementation of improvement actions resulted in significant impacts on the performance of the production process, notably:

- a) Reduction of scrap losses
- b) Decrease in process variability
- c) Increase in productivity
- d) Improvement in operational safety
- e) Greater control and traceability of processes

The comparative analysis before and after the improvements highlights the effectiveness of the integrated application of Lean tools and digital technologies, corroborating the studies of Womack & Jones (2003) and Slack; Brandon-Jones; Johnston (2018), which emphasize the importance of waste elimination and technological integration for optimizing production systems.

Furthermore, the results obtained demonstrate that the combination of continuous improvement and automation contributes to the creation of more robust and efficient processes, reducing the dependence on manual interventions and increasing operational reliability.

4.5 DISCUSSION OF RESULTS

The results obtained in this study show that the structured application of continuous improvement practices, combined with the use of Industry 4.0 technologies, represents an effective strategy for optimizing processes in the electronics industry. The reduction of waste, especially those related to scrap and variability, confirms the relevance of Lean principles in improving operational performance.

Additionally, the implementation of automation and monitoring solutions reinforces the importance of digital transformation in Manufacturing Engineering, enabling greater process control and better data-driven decision-making.

5 FINAL CONSIDERATIONS

It is concluded that the structured application of continuous improvement practices, combined with the use of automation and digitalization technologies, significantly optimizes production processes in Router machines used in the electronics industry. The results demonstrate that the overall objective of the study has been achieved, by showing that the integration of Lean methodologies and Industry 4.0 tools directly contributes to waste reduction, improved operational efficiency, and increased process reliability.

The identification and elimination of failures related to board transport, table return, and manual activities enabled reductions in scrap losses, decreased variability, and increased productivity. The implementation of solutions such as light curtains, pallet guidance, routing



automation, and statistical process control resulted in standardized operations and strengthened control over critical variables.

It was also observed that the use of technologically advanced equipment, such as the Elite Router, enhanced the results obtained due to its higher precision, stability, and ability to integrate with digital systems, thereby contributing to improved product quality and production system performance.

From a theoretical perspective, the study reinforces the relevance of integrating Manufacturing Engineering, Lean Manufacturing, and digital transformation as an effective approach for optimizing industrial processes. From a practical standpoint, it demonstrates the applicability of the improvements implemented in real industrial environments, with measurable gains in operational performance, safety, and process control.

As a limitation, it is recognized that the research was conducted in a specific environment, which may restrict the generalization of results to other production contexts. Future studies are recommended to expand the application of the methodology across different production lines and incorporate new digital technologies to deepen the analysis of Industry 4.0's impact on manufacturing processes.

Thus, it is concluded that the integrated adoption of continuous improvement practices and advanced technologies is a determining factor for increasing competitiveness and operational sustainability in the electronics industry.

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