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APPLICATION OF INDUSTRY 4.0 TECHNOLOGY IN IMPROVING PLASTIC INJECTION PROCESSES IN A COMPANY IN THE MANAUS INDUSTRIAL HUB

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ABSTRACT

Lead time optimization ensures compliance with deadlines established with customers, which in turn promotes customer satisfaction and loyalty. In addition, reducing this time provides more efficient resource management, with direct impacts on reducing operating costs. This study aimed to implement Industry 4.0 technologies to improve plastic injection processes in a company in the Manaus Industrial Park (PIM), reducing manufacturing costs, accelerating the lead time for building devices, and optimizing the time for developing new products. The methodology collected data on the new production processes and assessed the impact of the technology on reducing manufacturing costs and improving lead time, through mapping the current process flow, analyzing production loss reports, and production performance data. The results show a significant reduction in lead time, that is, the time required to create these devices, which was reduced from 35 (thirty-five) to 9 (nine) days. 3D printing has also made it possible to create more complex and precise devices, with less material waste, contributing directly to cost reduction and increased product quality.

Keywords: Automation. 3D printing. Improvement. Industry 4.0.

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INTRODUCTION

In the highly competitive scenario of modern industry, operational efficiency has become an imperative need for companies that wish to remain relevant and profitable (Serfontein, J., et al, 2013). The development of production devices, a crucial area for many sectors, faces significant challenges related to lead time. High lead time not only compromises delivery deadlines agreed with customers but also affects the supply chain, increasing costs and reducing business agility (Chen, Chih-Jou., 2019). Investigating the root causes of delays is essential to develop practical solutions for each stage of the production process, taking into account everything from the purchase of inputs to the manufacture and testing of devices on the production line, where each phase will be thoroughly analyzed to identify opportunities for improvement. Through a systematic and integrated approach, it is expected to achieve a substantial reduction in cycle times and, consequently, increase the competitiveness of the companies involved. Historically, development and production time has always been a critical factor in the success of manufacturing companies. From the early days of the Industrial Revolution, when production efficiency began to gain prominence, to the present day, where agility and flexibility are paramount, lead time has been an essential performance measure (Şen & İrge, 2020). However, with the increasing complexity of production devices and the demand for differentiated customization, lead time has become an even greater challenge. This research aims to address this contemporary challenge by exploring methods to reduce the development time of production devices. The analysis will cover the entire production chain, from material acquisition to final testing, with a special focus on practices that can be implemented to minimize delays and meet deadlines established with customers. The intention is to provide a historical perspective that contextualizes the importance of production efficiency and proposes innovative solutions to current problems.

The success of a production company is intrinsically linked to its ability to deliver high-quality products within the established deadlines (Tortorella, L. et al. 2021). However, many companies face significant challenges due to the high lead time in the development of production devices. This problem not only compromises customer satisfaction but can also result in lost revenue and increased operating costs. Using a combination of data analysis, project management techniques, and lean manufacturing methodologies, we hope to develop a set of best practices that can be adopted by companies to optimize their processes and more effectively meet customer demands.

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Lead time in the development of production devices is a crucial metric that directly affects the performance and competitiveness of companies (Henao, R.; Sarache, W.; Gómez, I., 2019). A high lead time can result in product delivery delays, customer dissatisfaction, and increased costs, which compromises the long-term viability of organizations (Mutua, M. 2015). This analytical research aims to investigate in detail the causes of high lead time, using a systematic approach that includes the analysis of device purchasing, manufacturing, and testing processes. The main barriers and bottlenecks at each stage will be examined, and solutions will be proposed based on best practices addressed in the company, technological advances, and innovations in process management. The ultimate goal is to implement Industry 4.0 technologies to improve plastic injection processes in a company in the PIM.

LITERATURE REVIEW

PRODUCTION MANAGEMENT

Production is the process of creating goods or services from the combination of different resources, such as raw materials, labor, capital, and technology, and has accompanied man since his origin.

Production management is an area of management that focuses on the efficient and effective management of an organization's production processes and operations, where it will ensure that goods and services are produced economically, with quality, and within the established deadlines, being an important factor for the success of any organization (Paiva et al., 2009). Production management has its roots in the Industrial Revolution when mechanization and mass production began to transform the way goods were produced. Pioneers such as Frederick Taylor and Henry Ford introduced scientific management and assembly line techniques, respectively, that revolutionized industrial production. Over time, the discipline evolved to incorporate more sophisticated approaches such as lean manufacturing, total quality management (TQM), and so on. and just-in-time (JIT) production (Jamba, 2024).

JUST-IN-TIME (JIT) PRODUCTION

JIT Production is based on several fundamental principles that aim to optimize production and reduce waste, eliminate waste, lean production, continuous process flow, quality at source, and continuous improvement using Kaizen tools. (Carvalho, 2016).

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The implementation of JIT uses several tools and techniques to achieve its objectives:

• Kanban: A signaling system that controls the flow of materials and products in the production process, ensuring that items are produced and delivered only when needed.

• SMED (Single-Minute Exchange of Die): Techniques to reduce machine setup time, allowing greater flexibility and smaller production batches.

• TPM (Total Productive Maintenance): An approach to ensure that machines and equipment are always in good working order, minimizing interruptions in production.

• Heijunka (Production Leveling): Technique to level the workload and avoid peaks and valleys in production, promoting a continuous and stable flow.

JIT Production has been widely adopted in several industries, including automotive, electronics, and consumer goods manufacturing. The practice offers several significant benefits such as reducing inventories by reducing storage costs and tied up capital, eliminating waste and creating a continuous production flow, and increasing operational efficiency. Emphasis on quality at the source and continuous improvement results in higher quality products and lower defect rates. The ability to produce based on actual demand allows greater flexibility to respond quickly to changes in the market. (Ribeiro, 2017).

INDUSTRY 4.0

Known as the Fourth Industrial Revolution, it is a new phase in the organization and control of the value chain throughout the product life cycle. This phase is characterized by the digitalization and integration of all elements of the value chain through the Internet of Things (IoT), Big Data and Analytics, Artificial Intelligence (AI), and other advanced technologies. The digitalization and integration of value chains create significant opportunities for the optimization of production processes and innovation in business models.

Schwab (2016) states that "Industry 4.0 is characterized by the digitalization and integration of value chains, products, and services, resulting in a fusion of physical, digital, and biological worlds" did not emerge in isolation, but is the result of a series of technological and organizational evolutions that date back to the First Industrial Revolution. The First Industrial Revolution, which occurred at the end of the 18th century, was marked by the mechanization of production through the use of water and steam. The Second Industrial Revolution, in the late 19th and early 20th centuries, introduced electricity and mass production, while the Third Industrial Revolution, from the 1970s onwards, brought automation and digitalization with the introduction of computers and information technologies. Kagermann, Wahlster, & Helbig (2013) state that "each industrial revolution has brought significant changes to society and the economy, and Industry 4.0 is no exception, promoting automation and data exchange in manufacturing technologies". The Fourth Industrial Revolution continues this trajectory but with a much greater focus on interconnection, artificial intelligence, and total automation of production processes, driven by a series of advanced technologies that together transform industrial processes. Among the main technologies, the following stand out:

Internet of Things (IoT)

IoT allows the interconnection of devices and systems, facilitating communication between machines and optimizing production processes. Lee, Bagheri, & Kao (2015) point out that "IoT plays a crucial role in Industry 4.0, enabling real-time data collection and analysis for informed decision-making".

Artificial Intelligence (AI) and Machine Learning

AI and Machine Learning are essential components in Industry 4.0, providing advanced analysis and automation capabilities. "AI is revolutionizing manufacturing by enabling failure prediction, predictive maintenance, and process optimization" (Russell & Norvig, 2016).

Big Data and Analytics

The ability to collect and analyze large volumes of data is critical in Industry 4.0. "Big Data enables companies to identify patterns and trends, improving efficiency and decision-making" (Manyika et al., 2011).

Advanced Robotics

Advanced robots are increasingly being used for complex and repetitive tasks, improving accuracy and efficiency. "Robotics in Industry 4.0 is characterized by collaboration between humans and robots, creating a safer and more efficient work environment" (Bauer, Hämmerle, & Schlund, 2015).

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Cloud Computing

Cloud computing allows companies to cite the storage and processing of data on a large scale, facilitating the access and analysis of information in real time. "Cloud computing is a crucial enabling technology in Industry 4.0, allowing scalability and resource flexibility" (Armbrust et al., 2010).

Additive Manufacturing (3D Printing)

3D printing is transforming manufacturing by enabling the production of complex parts quickly and cost-effectively. "Additive manufacturing is revolutionizing production, reducing waste, and enabling mass customization" (Gibson, Rosen, & Stucker, 2010).

Augmented and Virtual Reality

Augmented and virtual reality are being used for training, maintenance, and design, providing interactive and immersive visualization. Azuma (1997) notes that "these technologies are improving operational efficiency by providing real-time contextual information to workers." Industry 4.0 has profound impacts across multiple dimensions, including economic, social, and environmental. These impacts are felt across different sectors and scales, ranging from changes in the labor market to digital transformations in companies. The adoption of this revolution is increasing the productivity and efficiency of companies, resulting in significant economic benefits. “The digitalization and automation of production processes are creating new business opportunities and revenue models” (Pereira & Romero, 2017).

This revolution is transforming the labor market, creating demands for digital and technological skills. Lasi et al., (2014) state that “automation and AI are replacing repetitive and manual tasks while generating new opportunities for skilled workers”. Digital transformation is a central aspect of Industry 4.0, enabling companies to quickly adapt to market changes and improve their competitiveness. "Companies that adopt technologies of this model become more agile and innovative, able to respond quickly to customer demands." The adoption of Industry 4.0 is promoting more sustainable and energy-efficient practices. Rüßmann et al., (2015) note that "the integration of smart technologies allows the optimization of resource use, reducing waste and improving sustainability." Despite the numerous benefits, the implementation of Industry 4.0 faces significant challenges that need to be overcome to realize its full potential. The technological complexity of Industry 4.0

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represents a significant challenge for many companies. According to Müller, Buliga, & Voigt (2018) highlight that "the integration of heterogeneous systems and the need for interoperability are important technological barriers." With increasing digitalization and interconnection, concerns about cybersecurity increase. "Protection against cyberattacks and ensuring data security are critical challenges in Industry 4.0" (Müller, Buliga, & Voigt (2018). Small and medium-sized enterprises (SMEs) face unique challenges in implementing Industry 4.0 due to limited resources. “Lack of access to finance and the need for investment in technology are significant barriers for SMEs” (Mittal, Khan, & Romero, 2018).

The transition to Industry 4.0 requires a highly skilled workforce, which poses a significant challenge in terms of training and education. The development of technical and digital skills is essential to take full advantage of the opportunities offered by the digital economy and technological innovation. As the world becomes increasingly connected and dependent on technology, these skills become fundamental for competitiveness and adaptation in the labor market.

METHODOLOGY

RESEARCH AREA

The project was carried out in the plastic injection sector of a company located in the PIM, where data were collected on the production processes before and after the implementation of 3D printing technology.

Initially, the current process flow for the manufacture of jigs and templates was mapped, including the dependence on external suppliers, and data was collected on annual costs for new projects, considering the delay in the development of new products, production time, and the quality of the devices produced. This data served as a basis for comparison to analyze the impacts of implementing 3D printing. The company was monitored during the transition process to internal production of devices using 3D printing. Data were collected on the new production processes, including the development time of the devices, production costs, and the quality of the printed products, where the analysis included the assessment of the impact of the technology on reducing manufacturing costs and improving lead time. (Figure 1).

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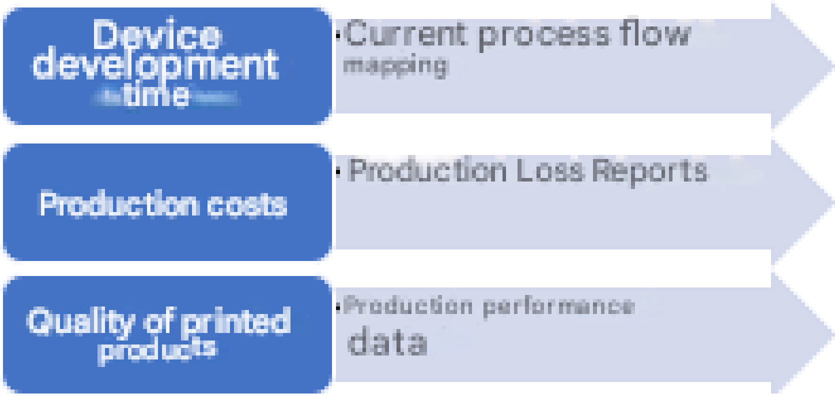
Figure 1 Collection methods



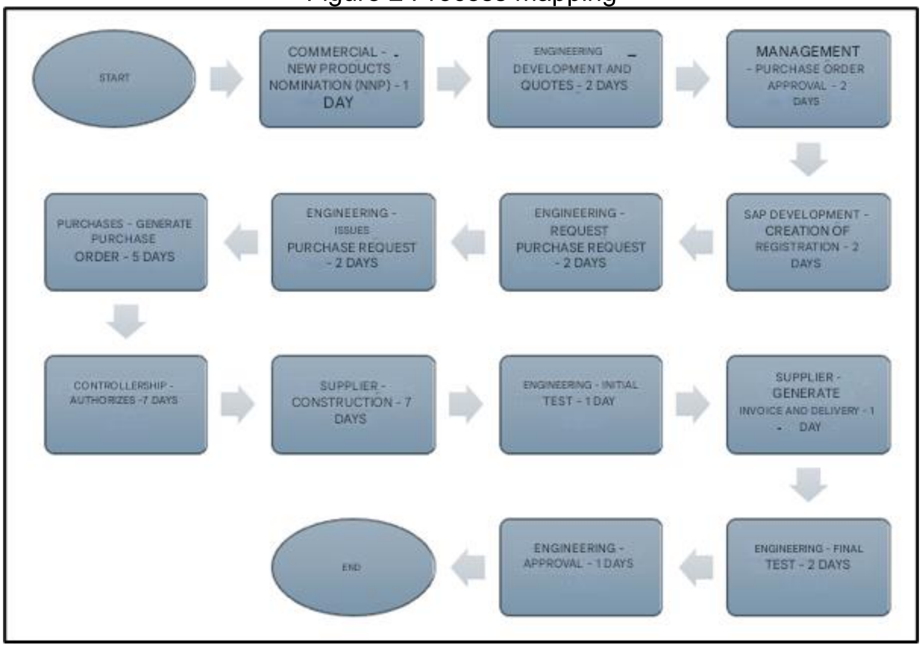
Source: Authors.

RESULTS AND DISCUSSION

MAPPING THE MAIN DEFICIENCIES IN CURRENT PLASTIC INJECTION PROCESSES

The mapping, as shown in Figure 2, consists of everything from the preparation of the device design to the approval of the final device by the engineering team. This process, when mapping to find the deficiencies was carried out, had a period of 35 (thirty-five) days distributed in 13 (thirteen) stages.

Figure 2 Process mapping



Source Authors.

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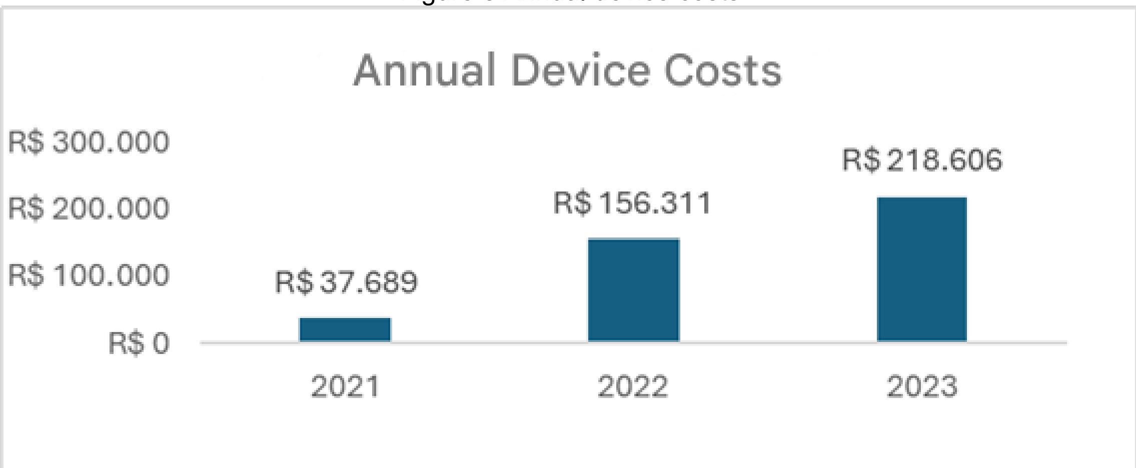
REDUCE MANUFACTURING COSTS BY ELIMINATING DEPENDENCE ON EXTERNAL SUPPLIERS

According to Figure 3, it can be seen that in 2021, the demand for production using devices (Jigs) in the process was relatively low, this scenario reflected a limited use of this resource. However, in 2022, the situation underwent a significant change, with a considerable increase in the use of Jigs, which led to an improvement in the company's processes and productivity. This growth, although it contributed to an increase in production, also brought with it an increase in operating costs.

In 2023, the company received new processes, including more pad printing and assembly, which generated a substantial increase in production costs. These processes, although they added value to the operation and allowed the diversification of production capacities, also resulted in a higher cost compared to previous years. The increase in costs is related to the complexity of the new processes and the need for greater investment in technology.

Figure 3 Annual device costs



Source: Authors, (2024).

In the traditional manufacturing scenario, production processes often involve the use of machining processes, in addition to the cost of materials and the high production time of 240 hours, as shown in Figure 5, which includes steps such as design, preparation, molding, and finishing by the supplier. With 3D printing, these costs can be drastically reduced. 3D printing allows the direct manufacture of the part from a digital model, without the need for additional molds or tools, eliminating preparation costs and considerably reducing material waste. Production time is significantly reduced to 6 hours, as shown in Figure 5, since 3D printing can create a part in hours, while traditional methods can take

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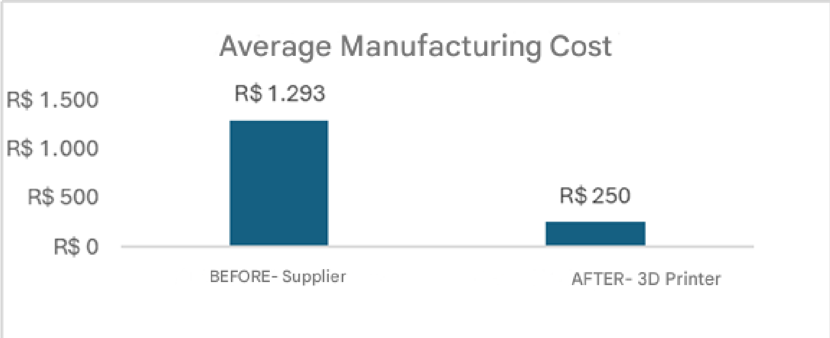
days, especially for small production runs or prototypes. A recent survey conducted by Gartner (2023) highlights that 3D printing has the potential to reduce manufacturing costs by up to 25% for companies that adopt the technology for mass production, especially in sectors with high customization and low runs.

Figure 4 Average manufacturing costs

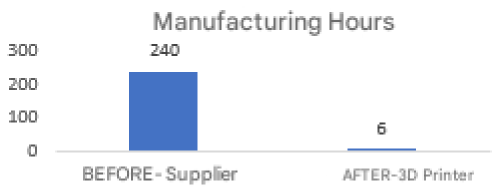


Source: Authors, (2024).

ACCELERATE DEVICE BUILDING LEAD TIME, IMPROVING AGILITY IN DEPLOYING NEW PROJECTS

The implementation of strategies such as process automation and the integration of advanced technologies, such as 3D printing, has enabled a significant reduction in device development time. Before the adoption of these improvements, the average lead time for device construction was 240 hours. After the implementation of the changes, this time was reduced to just 6 hours. This improvement not only accelerates the launch of new products for customers but also strengthens the company's competitiveness in the market, allowing a more agile response to consumer demands and innovation requirements. (Kuczynski et al., 2023).

Figure 5 Manufacturing hours



Source: Authors, (2024).

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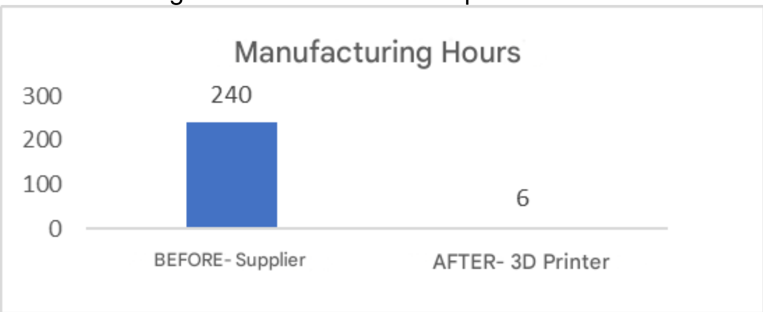
This process, when mapping after implementation, had a deadline reduced from 35 (thirty-five) to 9 (nine) days distributed in 9 (nine) stages, a 74% reduction in the time to manufacture the part itself, which eliminated the need for purchases by suppliers.

Figure 6 Flowchart after implementation



Source: Authors, (2024).

3D Printing Process Steps

The 3D printing process was divided into a few main steps:

• Creating the 3D Model: The first step consisted of creating or obtaining a digital 3D model of the object to be printed using 3D modeling software.

• Slicing the Model: The 3D model was converted into thin layers (slices) using slicing software, which generated the G-code that the printer used to determine how the object would be printed layer by layer.

• Preparing the Printer: Before starting printing, it was necessary to check that the printer was set up correctly, with the filament inserted and the printing bed leveled.

• Loading the G-Code into the Printer: The G-Code generated by the slicing software was loaded into the printer, usually via SD card, USB, or direct connection to the computer.

• Printing Start: The printer begins to heat the necessary components (such as the extruder nozzle and heated bed) and then begins printing layer by layer, according to the G-code instructions.

• Printing Monitoring: During the printing process, the monitoring process was important to ensure that the material was deposited correctly and that the model was being printed without flaws.

• Finishing and Removing the Object: After printing is finished, the object must be carefully removed from the printing platform.

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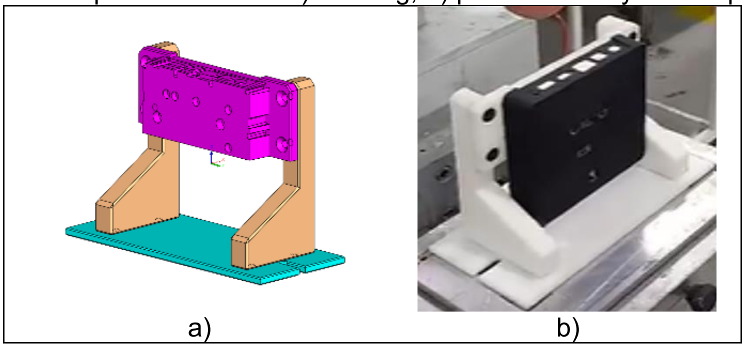
Implementing the Improvement

These steps are quite common and apply to several 3D printers. Figure 7 shows the modeling of a "Jig" type device used to assemble the Top Cover. This device has the function of facilitating the positioning and fixing of the part during the pad printing process. Figure 7 shows the designed part, which was 3D printed, allowing a more detailed and accurate visualization of the design.

Figure 7 Modeling of the Top Cover device. a) drawing; b) part created by the 3D printer, implemented.



Source: Authors, (2024).

The evolution of production demands in recent years has driven a constant search for the optimization of industrial processes. In this scenario, 3D printing stands out as a transformative technology, bringing significant advances in terms of both cost and efficiency. The ability to produce parts on demand and with high customization makes 3D printing an essential tool for reducing waste and improving process agility. In industries, 3D printing allows the manufacture of rapid prototypes, which accelerates the development of new products. In addition, it enables the creation of complex components that would be difficult or impossible to produce using traditional methods. This flexibility in design results in a significant reduction in raw material costs and reduces the need for expensive tools and tooling equipment.

Another crucial benefit of 3D printing is the reduction in production times. The possibility of producing parts directly from digital models eliminates the need for additional steps, such as adjustments to tooling machinery. This not only speeds up product delivery but also allows for better use of human and material resources.

Therefore, 3D printing not only improves operational efficiency but also offers practical and innovative solutions to the challenges of modern industry, effectively balancing costs and product quality. This technological advancement is an important step towards meeting the growing demand for faster and more customized production.

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Figure 8 Future situation of the process with the Kings 3D Printer with its characteristics

Source: KINGS 800PRO industrial 3D printer, based on SLA (Stereolithography Apparatus) technology, (2024).

Table 1: Materials and Characteristics

Material	Characteristics
Standard Resin	- Smooth surface finish. - Brittle.
High-Detail Resin	- Higher dimensional accuracy. - Higher price.
Transparent Resin	- Transparent material. - Requires post-processing.
Castable Resin	- Used to create mold parts. - Low ash percentage after burning.
Tough or Durable Resin	- Mechanical properties similar to ABS. - Low thermal resistance.
High-Temperature Resin	- Heat resistance. - Used for injection molding and tooling.
Dental Resin	- Biocompatible. - High abrasion resistance.
Flexible Resin	- Rubber-like material. - Dimensional accuracy.

Source: Industrial 3D printer KINGS 800PRO, based on SLA (Stereolithography Apparatus) technology (2024).

Figure 8 shows an industrial 3D printer, the KINGS 800PRO, based on SLA (Stereolithography Apparatus) technology. The content is organized into three main sections: equipment, materials, and their characteristics. At the bottom of the figure, the following benefits are highlighted: **Printing Quality; Speed and Efficiency; Precision and Consistency; and Variety of Materials.**

Figure 8 demonstrates that the KINGS 800PRO 3D printer offers high versatility, being capable of using a wide range of resins with specific characteristics that cater to various industrial and technical applications (Table 1).

Figure 9 presents the results of a comparative analysis before and after implementing a 3D printer, emphasizing cost reduction, manufacturing time savings, and economic feasibility. Below is the detailed description:

Comparative Chart:

1. **Before Implementation (Supplier A):**
   - Manufacturing Time: 240 hours

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- Unit Manufacturing Cost: R$ 1,293.00

2. **After Implementation (KINGS 3D):**
   - Manufacturing Time: 6 hours (**97% reduction**)
   - Unit Manufacturing Cost: R$ 250.00 (**81% reduction**)

The comparison shows a significant reduction in manufacturing time and costs with the use of the KINGS 3D printer.

Identified Problems:

- **Location:** 3D Printer
- **Problems:**
  1. High device manufacturing hours
  2. Long lead time for procurement flow
  3. High supplier costs
  4. High rate of defective devices

Actions Taken:

a) **75% reduction** in the development of new NNP devices
b) **90% reduction** in manufacturing time
c) **80% reduction** in manufacturing cost per device

Payback (Return on Investment):

The Payback section presents:

- **Average Device Cost:** R$ 1,293.00 before → R$ 250.00 after
- **Number of Devices:** 50 units
- **Total Cost (before):** R$ 64,650.00
- **Total Cost (with 3D printer):** R$ 12,500.00
- **Total Savings:** R$ 52,150.00
- **Simple Payback:** 15.1 months

The implementation of the KINGS 3D printer has brought significant advantages to the process:

1. **Drastic reduction in manufacturing time** (from 240h to 6h)
2. **Significant reduction in unit costs** (from R$ 1,293.00 to R$ 250.00)
3. **Savings of R$ 52,150.00** in 50 devices
4. **Confirmed economic feasibility** with a payback period of **15.1 months**

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This action has resulted in greater operational efficiency, cost reduction, and improved agility in the production process.

Figure 9 Before and after comparisons of process results

1. 1-year savings estimate profit of R$ 156,145.00.
2. 5-year savings estimate profit of R$ 782,250.00.

Source: Authors, (2024).

CONCLUSION

Specifically Jigs, and how this technology has positively impacted the development process, the main advantage highlighted is the significant reduction in lead time, that is, the time required to create these devices, which was reduced from 35 (thirty-five) to 9 (nine) days, distributed in 9 (nine) stages in the manufacturing time, which provided greater agility in responding to customer demands. 3D printing has made it possible to accelerate the stages of creating and adjusting devices, which were previously time-consuming and dependent on traditional methods, such as manual machining. In addition, the adoption of printing technology has increased operational efficiency. Replacing traditional methods with more modern Industry 4.0 solutions has reduced production costs, improving the company's competitiveness in the market.

3D printing has also made it possible to create more complex and precise devices, with less material waste, contributing directly to cost reduction and an increase in product quality. Integrating 3D printing into jig development and production not only optimizes time and costs but also offers benefits in terms of flexibility and customization, making companies more adaptable to specific customer needs. The adoption of 3D printing brings

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about a significant transformation in the production process, providing continuous improvement in delivery times, cost reduction, and product quality, in addition to boosting the company's competitiveness in the market.

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