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THE IMPACTS OF INDUSTRY 4.0 ENABLING TECHNOLOGIES ON OPERATIONAL STRATEGY

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ABSTRACT

Purpose: Adapting to technological advances is a pertinent challenge for operations in the Manaus Industrial Park. This study aims to address the following research question: how do Industry 4.0 (I4.0) enabling technologies impact the quality and flexibility strategy in the Manaus Industrial Park?

Originality / Value: This study developed a systematic and structured way to understand the benefits of I4.0 technologies in quality strategies and flexibility of manufacturing production lines. Manaus Industrial Park plays an essential role in the development of innovations in the Amazon region, and companies must be competitive in this new context of digitization of manufacturing.

Methods: This study used a qualitative and descriptive approach. Data were collected through semi-structured interviews with industrial managers from 12 companies that operate in the Manaus Industrial Park.

Results: The results of this work point to a frequent use of computer systems to integrate machines in operations, such as the use of M2M technology and cyber-physical systems. The companies researched in the Manaus Industrial Park are adopting essential technologies to create the infrastructure for the I4.0 implantation. This is the first step to making smart factories in the future.

Conclusions: Industry 4.0 enabling technologies affect operations' quality and flexibility strategy, promoting cost savings by optimizing production processes.

Keywords: Smart manufacturing. Operations strategy. Technology adoption. Industry 4.0.

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1. INTRODUCTION

In recent years, industries have been concerned about digitizing operations with Industry 4.0 (I4.0) technologies. The adoption of these technologies can confer a competitive advantage to organizations, enabling them to gather and examine a plethora of data in real-time to promote strategic improvements in operations, such as boosting the productivity of production lines (Chen et al., 2021; Chiarini et al., 2020; Sony et al., 2021).

I4.0 is operationalized through enabling technologies that facilitate establishing an interlinked environment of intelligent devices and systems responsible for digitizing processes vertically or horizontally (Chen et al., 2021; Tortorella et al., 2019). The Internet of Things (IoT), Cloud Computing, Big Data, Simulation, Autonomous Robot, Additive Manufacturing, and Machine Learning are examples of I4.0 enabling technologies (Asokan et al., 2022; Fatorachian and Kazemi, 2018; Ghobakhloo, 2018).

The application of Industry 4.0 technologies in operations can increase the efficiency and enhance the quality of production processes (Cagliano et al., 2019; Chiarini et al., 2020; Sony et al., 2021), improve the flexibility of production lines (Calabrese et al., 2020; Fatorachian & Kazemi, 2018; Tortorella et al., 2019), optimize the consumption of internal resources (Ancarani et al., 2020; Moktadir et al., 2018), help in the process of internationalization of companies (Pereira & Cardoso, 2023), and facilitate the application of lean production strategies (Chiarini et al., 2020; Tortorella et al., 2019). However, the adoption of these technologies brings some challenges, such as high demand for more qualified professionals, high initial investments for technological infrastructure, privacy, and data security, lack of public policies encouraging the financing of new technologies, and other barriers (Cagliano et al., 2019; Ghobakhloo, 2018; Horváth & Szabó, 2019).

Manufacturers need to understand better how I4.0 impacts their strategic objectives to reduce risks during the implementation phase and enhance the efficiency of their organizations (Raj et al., 2020; Sony et al., 2021). Adapting to these technological advances is a relevant challenge for operations in the Manaus Industrial Park. The companies in this industrial park are promoting numerous modifications in their production processes and incorporating advanced technologies to enhance the digitization of their operations. This study aims to answer the following research question: how do Industry 4.0 enabling technologies impact companies' quality and flexibility strategy in the Manaus Industrial Park?

Our intended contributions are twofold: theoretically, we propose a systematic and structured way to understand the impacts of I4.0 technologies on operation strategy. As managerial implications, this article seeks manufacturing professionals to better understand how to use each I4.0 technology in their operations, to improve quality and flexibility on their production lines.

The choice of Industry 4.0 as the subject of this study, with its enabling technologies and their impacts on operations strategies, is due to two reasons. First, the disruptive changes caused by enabling technologies that will impact strategic decisions in operations; second, the Manaus Industrial Park's importance for innovation in the Amazon region due to its influence on the State's GDP and the generation of numerous direct and indirect jobs. Besides that, the existence of Manaus Industrial Park, historically dependent upon tax incentives, has been an important public policy aiming to keep the rainforest in Amazonas state – more than 90% of the natural forest has been preserved in the state. Pará state, in comparison, has only 75% (Secretaria do Meio Ambiente do Amazonas, 2023). This could be explained by the income and jobs generated by Manaus Industrial Park. Therefore, increasing the competitiveness of this Industrial Park could benefit the protection of the Amazon Rainforest.

2. THEORETICAL BACKGROUND

2.1 Manaus industrial park

In five decades, SUFRAMA, which is an autonomous entity that is responsible for managing the Manaus Free Trade Zone (ZFM), has implemented three industrial parks there: commercial, industrial, and agricultural. SUFRAMA promotes the exteriorization of development in the Amazonian state, identifying business opportunities and attracting investments to the region. SUFRAMA and ZFM have an essential role in the future of innovation in the Amazon region.

The Manaus Industrial Park has around 500 high-technology industries, generating approximately one hundred thousand direct jobs and more than half a million indirect jobs. In 2021, the park employed 100,005 permanent, outsourced, and temporary workers (SUFRAMA, 2021). Cell phones, televisions, computers, air conditioning, and microwaves are products manufactured in the park that stand out in the electronics sector (SUFRAMA, 2018).

The Manaus Industrial Park is primarily responsible for the development of the Amazon region and represents more than 90% of the gross domestic product of the Amazonas state (SUFRAMA, 2018). The electronics segment, which will be the object of this research, is the most crucial sector from an economic point of view for the industrial park, as it represents almost 48% of the park's revenue and employs the most significant number of people (SUFRAMA, 2021).

Electronics sector companies in this industrial park invest in innovation to create different strategies for operations, as is the recent case of adopting new technologies that are pillars of I4.0. The Ministry of Economy recently created a methodology to be adopted in investments in R&D focused on Industry 4.0 and created the "Industry 4.0" seal that will be applied to companies installed in the Manaus Industrial Park (Ministry of Economy, 2018). Therefore, there is a movement to encourage the development of innovation in the Manaus Industrial Park, and I4.0 has a vital role in the future development of the Amazon region.

2.2 Industry 4.0 (i4.0) and enabling technologies

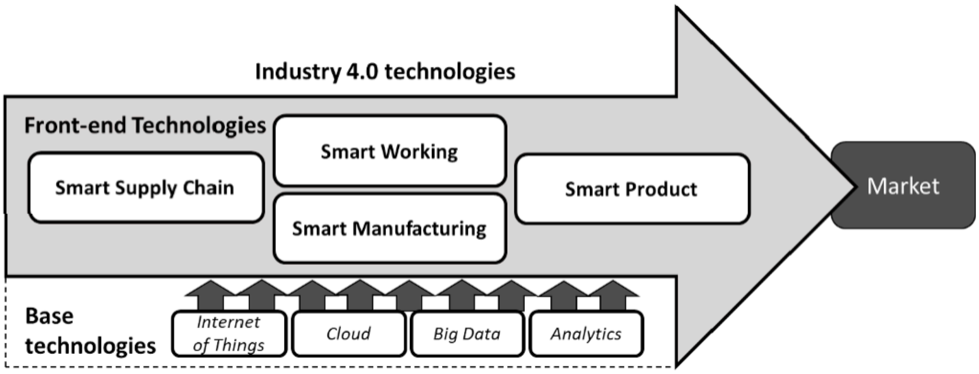
Industry 4.0 represents a new phase of industrial progress that facilitates the integration of production processes with digital innovations to streamline communication and data collection (Dalenogare et al., 2018; Xu et al., 2018). Integrating innovative technologies into production lines creates intelligent factories that can self-manage their production processes with the help of continuous data analysis (Kamble et al., 2018). In this work, I4.0 is defined as the adoption of intelligent technologies in manufacturing to collect and analyze data autonomously, allowing interaction with other areas of companies, suppliers, and consumers (Buer et al., 2018).

I4.0 enabling technologies enable the integration of vertical and horizontal production processes within industries, connecting production lines with other company departments, suppliers, and consumers (Buer et al., 2018; de Sousa Jabbour et al., 2018). Cyber-physical systems, Machine-to-Machine (M2M) communication, and Internet of Things (IoT) are essential I4.0 enabling technologies to create a digital infrastructure that allows the integration and communication of other technologies (Fatorachian & Kazemi, 2018; Zangiacomi et al., 2020). Klingenberg et al. (2019) performed a systematic literature review of 119 scientific articles and identified 111 technologies related to I4.0, the top five are cyber-physical systems, IoT, big data, data analysis tools, and cloud computing. There is still no consensus among authors about the set of technologies that make up I4.0, however, the Internet of Things (IoT), cloud computing, big data, and data analysis tools are essential for I4.0 adoption as they allow interoperability across different types of equipment (Frank et al., 2019).

The Internet of Things (IoT) is a network of interconnected machines, sensors, systems, and products that collect and transmit data, allowing the tracking and monitoring of various integrated devices (de Sousa Jabbour et al., 2018; Fatorachian & Kazemi, 2018). Real-time data collection and analysis in industries allow better control and planning of production processes, so IoT can improve operational aspects in manufacturing, such as predictive maintenance, optimization of energy and resource consumption, and product quality control (Ghobakhloo, 2018; Moktadir et al., 2018). Cloud computing allows the storage of large volumes of data on servers located anywhere in the world, and users can remotely access this information according to their demand (Xu et al., 2018). The use of IoT is financially feasible due to the opportunity to perform these operations through the cloud, otherwise, the investment required to store and analyze this large volume of data on proprietary servers would make this technology impractical (Klingenberg et al., 2019). The application of cloud computing in industries helps to store real-time data collected from industrial equipment and enables the connection of manufacturers with other departments or organizations regardless of their geographical location (Ghobakhloo, 2018).

Big data technology enables organizations to gather and analyze large volumes and varieties of data to generate knowledge and value for the company (Ghobakhloo, 2018). The extraction and analysis of data are performed through systems based on IoT, which enables interconnectivity between devices, sensors, and equipment responsible for gathering this information (Singh & Bhanot, 2020). To generate relevant knowledge for companies, it is necessary to identify patterns that allow predicting what may happen and which actions should be taken to improve operational results (Ghobakhloo, 2018). Integration and interpretation of big data information are performed by data analysis tools, which are essential techniques for identifying, organizing, and storing relevant knowledge for organizations (Klingenberg et al., 2019). Machine learning and Artificial Intelligence techniques can be used to analyze the collected data and assist in pattern prediction for better operational planning and increased efficiency (Singh & Bhanot, 2020). Figure 1 summarizes the theoretical framework of Industry 4.0 technologies proposed by Frank et al. (2019), though it is possible to understand that these four base technologies allow the implementation of other technologies and make some manufacturing processes smart.

Figure 1 - Theoretical framework of Industry 4.0 technologies



Source: Frank et al. (2019)

Industry 4.0 provides numerous benefits to manufacturing, but its implementation poses challenges and uncertainties that may impede technology adoption (Horváth & Szabó, 2019). These barriers pertain to technical, social, and scientific aspects, which organizations must grasp to succeed in adopting Industry 4.0 (Kamble et al., 2018; Xu et al., 2018). Reis & Camargo Júnior (2021) identified through a systematic review of the literature a total of 9 barriers to the I4.0 adoption, which are: government and regulations; organizational resistance; new employee skills; loss of jobs; data security and privacy; lack of infrastructure; high investments; uncertainties concerning financial results; standardization. According to Raj et al. (2020), these barriers appear to vary according to the level of development of countries; they identified 15 barriers to the I4.0 adoption in the scientific literature and interviewed experts in the industrial field to validate them. The results show that in developing countries, the biggest challenge for implementing this set of technologies is the lack of regulations and standards, whereas in developed countries, the main barrier is the low level of maturity of the technologies that integrate this new industrial revolution. To successfully digitize their operations, companies must identify these barriers beforehand (Kamble et al., 2018; Moktadir et al, 2018).

In summary, several technologies can be used to implement I4.0 in operations, but some technologies are essential to start the manufacturing digitalization process. The enabling technologies most related to I4.0 are cyber-physical systems, M2M, IoT, big data and data analytics, cloud computing, artificial intelligence, robotics, intelligent sensors, and additive manufacturing (Agostini & Filippini, 2019; Frank et al., 2019; Xu et al., 2018). In addition, the adoption of these new technologies has the potential to bring operational benefits to manufacturers, but it also brings challenges and barriers that need to be better understood before the digitalization of production chains.

2.3 Operations strategy in i4.0

The use of I4.0 enabling technologies in production lines brings strategic benefits to companies, increasing the efficiency of production processes and generating a competitive advantage for manufacturers (Fatorachian & Kazemi, 2018). Understanding the benefits of I4.0 better is essential to broaden the understanding of the adoption process of enabling technologies in organizations (Horváth & Szabó, 2019). Companies need significant investments to digitize their factories, so it is necessary to describe better the operational and strategic gains arising from I4.0 (Ghobakhloo, 2018).

There are several strategic benefits related to I4.0 adoption in production lines, such as increased quality and flexibility, optimization of resource consumption, predictive maintenance, and manufacturing of customized and intelligent products (Reis & Camargo Júnior, 2021). The increase in quality and flexibility of manufacturing processes with I4.0 enabling technologies makes operations more productive and efficient (Fatorachian & Kazemi, 2018).

2.3.1 Quality

Quality was defined by Slack, Chambers, and Johnston (2009) as consistent conformity to clients' expectations. It implies the necessity of meeting certain pre-defined specifications with uniformity. The use of IoT, cloud computing, and big data in operations increases the quality of manufacturing processes, allowing real-time quality control through constant monitoring of information from production line machines (Ancarani et al., 2020; Sony et al., 2021). The constant collection of data through smart devices and the analysis of this information with predictive techniques allows IoT to monitor the quality of production processes along the production chain, and quality managers can more efficiently identify problems in production lines (Chiarini et al., 2020; Dalmarco et al., 2019). The analyzed information makes it possible to previously identify the machine maintenance needs and schedule predictive maintenance to ensure the quality of operations processes (Kamble et al., 2018).

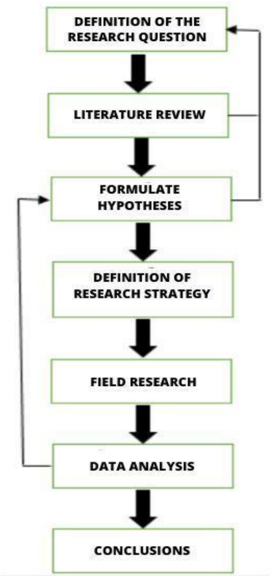
2.3.2 Flexibility

Flexibility in the context of manufacturing is the ability of a production line to do different things for different customers (Pine et al., 1993). I4.0 technologies allow the reconfiguration of production processes, physically or digitally, by collecting real-time information analyzed by intelligent systems and other technologies such as IoT, big data, or artificial intelligence (Ancarani et al., 2020; Fatorachian & Kazemi, 2018). I4.0 enabling technologies make production lines more flexible through data analysis that helps plan and schedule production processes more efficiently (Cagliano et al., 2019; Kamble et al., 2018). Calabrese et al. (2020) performed a systematic literature review and interviewed managers from 39 companies to identify benefits related to adopting I4.0. Flexibility was considered the most crucial benefit for operations. Increasing production line flexibility is essential to increase the company’s competitiveness (Tortorella et al., 2019). Technologies such as 3D printers and autonomous robots can help increase flexibility in operations as they optimize production processes and increase the speed of prototyping (Ghobakhloo, 2018).

3. MATERIAL AND METHODS

The study uses a qualitative and descriptive approach, having an applied nature. Applied research aims to collect data and analyze them to provide important information so managers can make more assertive decisions regarding the strategy of their companies (Marcondes et al., 2017). Figure 2 illustrates the planning of this research and below the main phases will be better described.

Figure 2 – Research stages



3.1 Definition of research question and propositions

This study defined the following research question: how do Industry 4.0 enabling technologies impact the quality and flexibility strategy of companies in the Manaus Industrial Park? The literature review allowed the elaboration of the following propositions:

Proposition 1: The use of Industry 4.0 enabling technologies impacts the quality of production processes.

Proposition 2: The use of Industry 4.0 enabling technologies impacts the flexibility of production processes

3.2 Definition of the research strategy

This work uses a qualitative approach and collected data through semi-structured interviews with industrial managers. Choosing this method of data collection allows for obtaining qualitative information about the phenomenon studied (Seidman, 2006), which in this work is the adoption of base technologies that allow the implementation of I4.0 to improve strategic aspects in organizations. An interview script was created and presented in Appendix 1, which guided the conversation with the interviewee; the creation of this script is important to facilitate the conduct of the interview and allow the interviewer to be able to capture hidden attitudes and feelings about a topic (Malhotra, 2006). This study selected respondents from organizations that operate in the Manaus Industrial Park. Interviews were conducted with managers of twelve companies that are part of the industrial park, all belonging to the electronics market. The interviews were conducted by an interviewer who has solid managerial experience in operations and production activities in companies in the electronics chain.

3.3 Data collection

Interviews were conducted with production or industrial managers of 12 companies during the months of September to December 2019. Data were collected through an interview script (Appendix 1) consisting of open and closed questions. All interviews were recorded and transcribed for later analysis (Seidman, 2006).

3.4 Data analysis

The content analysis of the interviews was performed and the data were reduced to be presented in the next session in a summarized form (Seidman, 2006). Content analysis is the objective and systematized description of the content collected in the interviews (Malhotra, 2006), the results will be divided by company and the information presented was collected through the interviews with managers. The interviews were analyzed to understand how technologies improved production processes' quality and flexibility.

4. RESULTS AND DISCUSSION

First, the interviews will be discussed individually, summarizing their content, and presenting it separately by company. The companies will be presented classified from 1 to 12 to keep them anonymous and were divided into five groups according to the area in the electronics sector, which are: robotics, plastic injection, suppliers of SMT machines/process, suppliers of boards printed circuit board (PCI) and final product assemblers. Subsequently, a comparative table of the cases will be presented with the following information: area of activity in the electronics sector, the enabling technologies adopted, and their impacts on the quality strategy and flexibility of operations. Table 1 shows the summary of the interviews.

Table 1 – Summary of the interviews

Company	Interviewee	Interviewee's time in the company	Area	Products
Company 1	Technical manager	10 years	Robotics	Robots, parts, and pieces for robots for the electronics and automotive industry
Company 2	Manufacturing manager	1 year	Plastic injection	Plastic parts for the Manaus Industrial Park, components, and parts for the electronics sector
Company 3	Engineering manager	2 years	Plastic injection	Operates in the plastic segment for the electronics, home appliances, and automobile industries
Company 4	Production manager	1 year	Plastic injection	Cabinets and screens for the company's own televisions
Company 5	Technical coordinator	14 years	SMT machine/process suppliers	SMT machines
Company 6	Production manager	6 years	PCI vendors	Printed circuit boards, AOC branded monitors and Philips televisions
Company 7	Production manager	8 years	PCI vendors	Boards for the electronics and automotive industry
Company 8	Engineering manager	20 years	PCI vendors	Motherboards for several customers, HD for the company Western Digital
Company 9	Engineering manager	10 years	final product assembly	Audio, video, telecommunications, electronic security (monitoring) and white goods appliances
Company 10	Production manager	5 years	final product assembly	Televisions, miscellaneous audio products, air conditioning, microwave ovens
Company 11	Production manager	6 years	final product assembly	Philips TV and AOC brand monitors
Company 12	Engineering manager	9 years	final product assembly	Cell phone batteries (LG, Motorola), notebook adapters and LED lamps

4.1 Company 1

Pioneer company in the development of robots for several industrial segments, of Japanese origin, present for more than 20 years in the Manaus Industrial Park and has approximately 35 employees. The company supplies plastic injection and automotive companies, such as Honda and Yamaha. The company is investing in modernizing technologies to make robots more autonomous. Robots improve productivity and reduce operating costs by 5 to 15%, increasing the safety of machine operators. One of the most important enabling technologies for I4.0 in the industrial park is autonomous robots, which is why other companies in the chain (i.e., plastic injection and final product assemblers) present technological solutions related to I4.0, given the specificity of the technologies embedded in these robots and the need to integrate them with other machines and computational systems.

4.2 Company 2

Brazilian company, which operates in the Manaus Industrial Park for 26 years and has approximately 850 employees. The company has used robots in its operational processes for years, however, this technology is not integrated with other areas or communicates autonomously with other devices, as the company has not adopted the Internet of Things. In all injection machines, robots are programmed to remove parts from the injection molding machines; The use of this technology affects performance, increasing productivity and improving quality and costs. All production is controlled by a computer program called "Injet." This system captures information from the machines monitored by the production and planning areas, allowing for better management control. The Injet system interconnects, using sensors, all the injection machines in the plants and other branches of the company, capturing production information, set-up time and machine downtime, generating management reports, optimizing the production process, and reducing costs. The company has 120 Star Seiki robots and 05 Dalmachio robots. The use of robots in the production process generates better productivity (increase varies from 5 to 20%) and quality (reduction in the rejection rate from 10 to 20%).

4.3 Company 3

Brazilian company that operates in the Manaus Industrial Park for 37 years and has approximately 750 employees. The company uses robots in injection machines to remove and cut the injection channel. It also uses the "Injet" machine management system for production control and planning. The company has 55 injection machines operated by 25 robots from the Negri Boss brand and 30 from the Wittmann Battenfeld brand. As a result of I4.0, the company is forming partnerships with national technology suppliers in search of innovations for its industrial park. Machine automation increased quality levels (5 to 10%) and reduced costs (5 to 15%). Greater control over machine management thanks to the Injet system, which allows tracking events (e.g., maintenance downtime, unplanned downtime, set-up downtime) with the generation of indicators to facilitate decision-making. Increased safety for operators, molds, and the machine itself. The company has six injection machines in the plastic injection unit and plans to reach eight, working in three shifts. The company developed its own computerized production control system. This system captures various information related to the production process and allows better management of what was planned and done.

4.4 Company 4

Korean company that has been in the Manaus Industrial Park for 30 years and has approximately 50 employees. The removal of parts from the machine is done by robots, and the parts are positioned on conveyor belts that go directly to the assembly sector. The company is adept at lean production techniques and needs intermediate stock. The machines have an automated mold-fixing system, eliminating manual work. Using robots in injection molding machines reduces production costs by reducing labor. The use of robots also increases the level of quality, as the machine cycle remains constant. The company developed the machine's production control system, increasing production planning efficiency. The set-up time for changing the mold was reduced by 10 to 15% due to an automated system for fixing the molds and digitizing the machine settings, with sensors in all parameters.

4.5 Company 5

A Japanese company, which operates in the Manaus Industrial Park for 50 years and has approximately 20 employees. The company invests in solutions for Shop Floor/Warehouse Automation for ERP. It uses personal equipment with placement control and connection to other platforms. The Panasonic machine system analyzes data and assists in decision-making. Current equipment analyzes production processes throughout the day, checking for changes (e.g., changing components) and correcting them. The SMD equipment/machines work interconnected with M2M technology. The machine that applies the solder paste sends a message if the solder is deposited in an offset way. Costs are reduced, and quality is increased through Panasonic machine systems. The systems can identify a wrong allocation before assembly, and it was only possible to verify the error after the production process. The systems embedded in the machines make it possible to identify problems and perform predictive maintenance.

4.6 Company 6

Taiwanese company that has been in the Manaus Industrial Park for 22 years and has approximately 600 employees. The company sponsors lectures and courses for the technical and managerial staff about I4.0. Lectures are held in partnership with technical consulting companies and equipment suppliers (SMT machines). There is a development of machines with computational control in solder paste applications. The quality control of the solder paste application on the boards is automated. There is also automated control on component testing, which replaces the tests previously done by "test jigs." The improvement of tests by computational systems has demanded better qualifications of the operators and the body of technical programmers who control this equipment. Using computer systems and sensors in production makes the company obtain a higher product quality. There is a noticeable improvement in the productivity of the boards and a reduction in costs of around 5%.

4.7 Company 7

A Japanese company that operates in the Manaus Industrial Park for 50 years and has approximately 1200 employees. The company manufactures plates for its products and supplies plates to the automotive industry. The quality requirement of the automotive industry is very high due to the high risk to the car, and the plates cannot be accepted. With I4.0 enabling technologies, the company created internal systems. For example, before, the operator adjusted machine by machine; now, the operator controls several machines on several assembly lines. The current equipment requires a better qualification of the workforce. There is a significant reduction in labor costs since, through technologies, an operator can control machines from several production lines.

4.8 Company 8

Brazilian company, which operates in the Manaus Industrial Park for 25 years and has approximately 400 employees. The company had contact with I4.0 technologies through suppliers of SMT machines. The company uses M2M systems. The machines apply solder to the plates, and a computational system with sensors checks the alignment to see if the component is displaced. When doing this check, the system sends a correction message to the machine when the weld is out of standard. The inspection of the boards in the assembly is also done by a computational system called Automatic Optical Inspection (AOI). Due to the automation of its processes, the company constantly trains its employees. M2M technologies, in which the machines carry out inspections and inform the adjustments that must be made when there are deviations, improves quality by up to 25% in visual inspection.

4.9 Company 9

Brazilian company that has been in the Manaus Industrial Park for 35 years and has approximately 1200 employees. The company has been making technological advances in its operations over the past few years but has planned to adapt to new I4.0 technologies for the next five years. One of the systems that most evolved in the company was production planning. There was a noticeable improvement in the ERP production control system with the integration of processes. Another area that has evolved is IT: before, there were only three employees focused on maintenance, but today there are 17, who, in addition to maintenance, program and control all production equipment (SMT machines). The company's management highlights a perception of a lack of network infrastructure that should be provided by companies/governments. There is also a concern regarding professional qualifications, as new technologies require specific skills. With the help of technologies such as cyber-physical systems, the company continuously seeks to improve the quality of its processes. Product exchanges are made more flexible due to the automation of several processes, such as the inspection of plates, which was previously done visually, and is now done virtually.

4.10 Company 10

The company, in partnership with the Korean headquarters, develops its computer systems for managing and controlling production. The company has been in the industrial park for 25 years and has approximately 2000 employees. Significant investment in the qualification of the workforce through training at the unit in Brazil and sending employees to receive further training at the headquarters. Application in production lines of controls with intelligent sensors for fault detection in assembly and test operations. In the final product production processes, the company has been replacing manual labor with automated operations with the help of robots. Automation at various stages of production improves productivity and reduces quality issues.

4.11 Company 11

A Dutch company that has been in the Manaus Industrial Park for 48 years and has approximately 600 employees. The company has a software architecture using RAMI 4.0

principles and concepts. The company uses equipment with the Internet of Things and stores data in the cloud. The company develops technological projects aimed at the safety and health of employees, as well as managing operational risks. Other projects are focused on qualifying the workforce to operate I4.0 enabling technologies. The company is applying Artificial Intelligence, with the support of Big Data, to detect patterns in its production lines. One of the company's motivations to evolve technologically towards Industry 4.0 is to reach maturity with the ACATECH system. Through the R&D, Engineering, and Production area, the company has been implementing several technologies that seek results in quality, flexibility, and cost reduction.

4.12 Company 12

Korean company that has been in the Manaus Industrial Park for 30 years and has approximately 400 employees. The company develops its program aimed at I4.0. The program consists of an automated mapping of improvements in production processes. The company has already implemented several improvements in reorganizing its production line, applying intelligent production systems that allow complete control of production processes and tracking resources from entry into the production line to packaging. The company also has a computational system to control the welding process, which is carried out by Fuji and DEK machines. The machines have an integrated control with adjustment of solder paste application and chip positioning. With the company's program, which is divided into ten stages, it has been transforming its processes with technologies aimed at Industry 4.0. The company is already noticing a significant improvement in product rejection rates and quality (around 2 to 5%).

4.13 Impact of technology adoption on operations strategies

Table 2 allows us to compare the companies according to the following information: adopted technology, affected strategy, and the impact of technology on the quality and flexibility of production processes.

Table 2 - Summary of the impact of technology adoption on operations strategies

Company	Area	Adopted technology	Affected strategy	Impact on operation
1	Robotics	M2M, autonomous robot	Quality	Waste reduction
			Flexibility	Speed of changes (set-up)
2	Plastic injection	M2M, autonomous robot, cyber-physical systems	Quality	Downtime and waste reduction
			Flexibility	Speed of change (set-up) and resource planning
3	Plastic injection	M2M, autonomous robot, cyber-physical systems	Quality	Downtime and waste reduction
4	Plastic injection	M2M, autonomous robot, cyber-physical systems	Quality	Waste reduction
			Flexibility	Speed of change (set-up) and lean production
5	SMT machine/process suppliers	M2M, integrated sensors, cyber-physical systems	Quality	Wrong assembly identification
			Flexibility	Speed of change (set-up)
6	PCI vendors	M2M	Quality	Wrong assembly identification and waste reduction
7	PCI vendors	M2M, cyber-physical systems	Quality	Control of several machines in the production lines and waste reduction
8	PCI vendors	M2M, cyber-physical systems	Quality	Wrong assembly identification
9	Final product assembly	Cyber-physical systems	Quality	Control of several machines of the production lines and inspection of the boards made by sensors
			Flexibility	Speed of change (set-up) and resource planning
10	Final product assembly	Cyber-physical systems, autonomous robot	Quality	Control of several machines in the production lines and waste reduction
11	Final product assembly	Big Data, cloud computing, IoT, M2M, cyber-physical systems	Quality	Control of several machines in the production lines and waste reduction
			Flexibility	Speed of change (set-up)
12	Final product assembly	M2M	Quality	Control of several machines of the production lines and reduction of waste

Machine-to-Machine (M2M) enabling technology was used by 10 of the 12 companies surveyed. This technology uses sensors or gauges on production lines to identify specific events. These events can be, for example, an increase in temperature or the level of inventory. Based on the analysis of these collections, the company can transform data into information to improve its production process. Cyber-physical systems were another technology adopted by most of the companies studied. The software can communicate with sensors and monitor virtual and physical spaces to obtain accurate environmental information (Fatorachian & Kazemi, 2018). Both technologies help digitize operational processes and are essential for adopting other I4.0 technologies (Frank et al., 2019). However, only company 11 adopted more elaborate enabling technologies, such as IoT and big data, which can potentially digitize the entire production process. In this way, the companies surveyed are preparing the digital infrastructure, using cyber-physical and M2M systems, to adopt more improved technologies that accelerate the digital transformation of production lines.

In the quality strategy, I4.0 enabling technologies helped companies minimize production lines' downtime and reduce wasted resources throughout manufacturing. The constant collection of information in operations improved the quality control of production processes and facilitated the identification of assembly problems in advance, in line with the results of other works (Ancarani et al., 2020; Chiarini et al., 2020; Dalmarco et al., 2019; Sony et al., 2021). The control of several machines on the production lines keeps the machines operating longer, and the information collected and analyzed allows for scheduling predictive maintenance to avoid machinery wear (Kamble et al., 2018). In summary, the interviews show that most companies have adopted technologies to control and optimize internal processes, allowing the identification of quality problems in the production line. Company 9 was the only one that used technologies directly in the quality control of its products, this company adopted a digital inspection of the products produced, increasing the efficiency of quality control.

I4.0 enabling technologies have impacted companies' flexibility strategy as they allow for the incredible speed of changes in production lines. The reconfiguration of production processes is done through data analysis by intelligent technologies and increases the efficiency of operations (Fatorachian & Kazemi, 2018; Tortorella et al., 2019). Autonomous robots increase the flexibility of production lines, and 5 out of 12 companies use this technology (Ghobakhloo, 2018). IoT and big data are essential technologies to increase the flexibility of production chains (Ancarani et al., 2020; Fatorachian & Kazemi, 2018), however, only one company adopted these technologies on the production line. The results of the interviews show that most companies are starting to create the infrastructure to adopt more improved I4.0 technologies, which is why most of the interviewees highlighted the creation of cyber-physical and M2M environments in organizations. In this sense, the high investments in the application of more improved technologies, such as the IoT, and the lack of adequate infrastructure are important barriers to the adoption of I4.0 in manufacturing (Raj et al., 2020; Reis & Camargo Júnior, 2021)

5. CONCLUSION

This research described how Industry 4.0 technologies impact the quality and flexibility strategy of companies in the Manaus Industrial Park. Twelve company managers were interviewed to understand which technologies were adopted and their impact on quality strategies and flexibility of production processes.

The interview results show that the electronics companies in Manaus Industrial Park use I4.0-enabling technologies in different operational processes. These technologies affect the quality and flexibility of production lines, reducing costs and generating a competitive advantage for operations. Most of the interviewed companies adopted enabling technologies, such as M2M and cyber-physical systems, essential for creating the digital infrastructure that will allow more improved technologies to digitize productive processes. Only one company has adopted IoT and big data. It seems that digital transformation from factories to I4.0 is still in the initial phase in the companies of Manaus Industrial Park.

I4.0 technologies impact operations quality and flexibility strategies. The constant collection and analysis of data make it possible to improve the quality of operational processes, increase quality control on the production line, identify problems in product assembly in advance, and carry out digital inspections of items that are more efficient than visual inspections. In addition, it is possible to predict machine downtime and anticipate maintenance based on the predictive analysis of information collected along the production line.

Regarding the operations' flexibility strategy, the enabling technologies allow optimizing the speed of changes in production lines for the manufacture of other parts, reduce costs in the manufacture of more customized goods, and help in planning and optimizing the resources used in the production processes. The cost reduction comes from more efficient production processes and the reduction in the use of labor due to the digitization of some processes. In this sense, it is essential to highlight that implementing new technologies can generate the loss of jobs, especially in repetitive tasks that can be easily automated (Kamble et al., 2018). There are other challenges related to the adoption of I4.0, especially in developing countries, such as the lack of adequate infrastructure, the need for more qualified professionals, and the high investments involved in the digitization process of manufacturers (Raj et al., 2020; Reis & Camargo Junior, 2021)

The main theoretical contribution of the work is to develop a systematic and structured way to understand the benefits of I4.0 technologies in quality strategies and flexibility of manufacturing production lines. The mapped impacts can encourage the implementation of I4.0 technologies in other manufacturers. A greater understanding of the benefits related to the digitization of production chains can help overcome challenges inherent to the I4.0 adoption process.

In this context, due to the significant impact on the regional economy of the Manaus Industrial Park, companies must start planning the implementation of these new technologies to increase their competitive advantage and develop innovative solutions for further development of the region in the future. As managerial implications, this work identifies impacts on the quality of the production line and flexibility strategies that can help to manufacture professionals to better understand how to use each technology in their operations.

This work has limitations due to the impossibility of generalizing its results since the companies surveyed, despite belonging to the same sector, have different sizes, products, and origins. However, this limitation does not prevent the results of additional evidence from originating new hypotheses and future research in similar or even different sectors to verify the validity of the results in other scenarios.

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APPENDIX

Appendix 1: Interview script:

This interview script is the instrument of field research on Industry 4.0 and is part of a doctoral thesis investigation in the line of research in Production and operations research. The doctorate is being carried out by the Faculty of Economics, Administration, and Accounting (FEA) of the University of São Paulo (USP) in partnership with the University of the State of Amazonas (UEA). It aims to investigate the impacts of technologies that enable Industry 4.0 in the operational strategies of companies in the electronics sector in the Industrial Park of Manaus. The results obtained will be used only for academic purposes. We emphasize that the data will be kept confidential. There are no right or wrong answers. Therefore, we ask that you respond spontaneously and sincerely to all questions.

Your participation is essential to the success of this research.

Thank you for your collaboration.

1) **Interviewee data**

Name:

Function:

Department:

Education:

Profession:

Time working in the company:

2) **Company's Socio-Economic Data**

Company Name:
Origin:
Time at the Polo de Manaus:
Number of Employees:
Products Manufactured by the Company:

3) In the corporate world, the topic "Industry 4.0" has been talked about, a term that represents the advancement of industrial companies through various technologies with significant interconnectivity. As a manager at your company, are you aware of the Industry 4.0 topic? How did you find out about it?

4) Does your company use some enabling technologies related to Industry 4.0 in its operational activities? Could you give us examples:

( ) Internet of Things (IoT)
( ) Big Data
( ) Cloud computing
( ) Autonomous robot
( ) Augmented reality
( ) Simulation
( ) Cyber-physical systems
( ) Machine to Machine (M2M)
( ) Additive manufacturing
( ) Others

Comments on the technologies in the company's activities:

5) In your company, does the use of enabling technologies related to Industry 4.0 reflect impacts on operations/production activities, such as impacts on Quality, Process Flexibility or Costs?

6) Are there impacts related to Industry 4.0 concerning other operational aspects in your organization? For example, absenteeism, safety, workforce qualification, or other aspects?

7) Regarding technologies related to Industry 4.0, does your organization observe opportunities for future improvements in operations/production activities related to quality improvements, flexibility, cost reduction, or other aspects?