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Integrative Technologies in Traceability Systems: Advancing Industry 5.0 in a Brazilian company

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ABSTRACT

This study aims to investigate how the implementation of an automated traceability system facilitates the transition from Industry 4.0 (I4.0) to Industry 5.0 (I5.0) in a medium-sized Brazilian company. A qualitative single case study approach was employed, involving the application and development of the traceability system through barcode reading on stainless steel capacitor tanks, the RAST 4.0 system. The analysis focuses on the contribution of the RAST 4.0 system, which incorporates I4.0 technologies, to production efficiency and product quality, while also fostering more sustainable and human-centered industrial practices. Focus groups, documentary analysis and direct observations were utilized to collect data, thereby enabling a deeper understanding of the system's implementation. The system provided improved control through real-time information, enabling informed decisions for continuous improvement and management of non-conformities in production. In addition, it was possible to achieve the three pillars of I5.0 and propose a conceptual model. The results of this study may encourage other companies looking to adapt to I5.0 to invest in similar systems to improve their processes, resulting in a more humane, productive, and sustainable work environment.

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1. Introduction

The fast growth of technology in recent years has significantly improved society's quality of life and driven companies' evolution [1]. With increased market competition and globalization, companies face growing challenges that demand improved performance [2], [3]. The ability of organizations to adapt their products and processes to meet the demands of the market is essential for their survival. This context has driven the emergence of Industry 4.0 (I4.0), first introduced in Germany in 2011 as part of an effort to create a new paradigm in the country's economic policy focused on high-tech strategies [4]-[6]. In 2021, a report was published that addressed a new concept, Industry 5.0 (I5.0) [7], which shifts the principles of I4.0 toward directing industrial research and innovation to a human-centered and environmentally conscious future [8]. The authors stress that I5.0 is not

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merely a chronological extension of I4.0, but rather a concept that supplements its key features. Figure 1 illustrates the evolution of Industries 1.0 - 5.0.

In this way, I4.0 is the starting point for developing I5.0. I4.0 introduces the idea of smart manufacturing by offering digital solutions based on a set of technologies that merge the physical, digital and biological worlds. This results in a significant and exponential impact on the entire production chain [10]. As a consequence, companies will be challenged to cope with technological advances, work with significant volumes of data and share large amounts of information [11], [12]. Furthermore, I5.0 proposes to complement automation with a more human-centric approach, with the objective of developing industrial practices that promote sustainability, resilience and human-centredness [8], [13], [14]. As observed by Cazeri et al. [15] and Kopeinig et al. [16], there are still few studies that address the implementation of I4.0 technologies and aspects as sustainability, corporate social responsibility, and other related concepts. These concepts are associated with the pillars of I5.0.

The transition to this industrial phase in emerging countries such as Brazil still faces significant challenges. Infrastructural limitations, resistance to the adoption of new technologies, high implementation costs, and a shortage of skilled labor represent some of the key barriers hindering the implementation of advanced traceability systems. Brunheroto et al. [17] have identified that the level of implementation of 4.0 technologies in Brazil, mainly in Small and Medium-Sized Enterprises (SMEs), is still lower than in countries such as Germany. Fewer than half of Brazilian industries utilize digital technologies, with a lack of knowledge identified as a significant contributing factor [18]. This information is consistent with the findings of Benitez et al. [19], which identified several barriers to the implementation of I4.0 and, consequently, I5.0. These include the level of knowledge of managers and the ability to provide the appropriate technologies. These gaps suggest a potential avenue for further investigation into the broader and strategic applications of traceability in the context of I5.0. This context demands more than just efficiency; it calls for a fully integrated approach that prioritizes sustainability and human-centered practices.

In this sense, this study explores how an automated traceability system (RAST 4.0 system) implemented in a medium-sized Brazilian company can facilitate the transition from I4.0 to I5.0, within a specific organizational and socio-industrial context. The company operates in the electricity sector and experienced traceability problems in its production, which consequently influenced the quality of its products. To address these issues, an automated traceability system was implemented, integrating various technologies. Beyond the empirical case narrative, this study makes a theoretical contribution to the development of I5.0 by proposing the concept of integrated sustainable traceability. In this perspective, traceability should be considered not only as a technical tool for quality control and operational efficiency but also as a facilitator for the adoption of more sustainable and human-centered industrial practices. Thus, the case study serves as an analytical basis to advance the understanding of how I5.0 principles can be operationalized in emerging economy contexts. The primary challenges and research questions (*RQs*) addressed in this article are as follows:

RQ1. What benefits might be gained by the implementation of I4.0 technology in a medium-sized Brazilian company?

RQ2. What are the key pillars of I5.0 that can be achieved through the implementation of traceability?

To address these questions, a case study was conducted to analyze the impact of implementing a traceability system in the stainless-steel capacitor tank production chain.

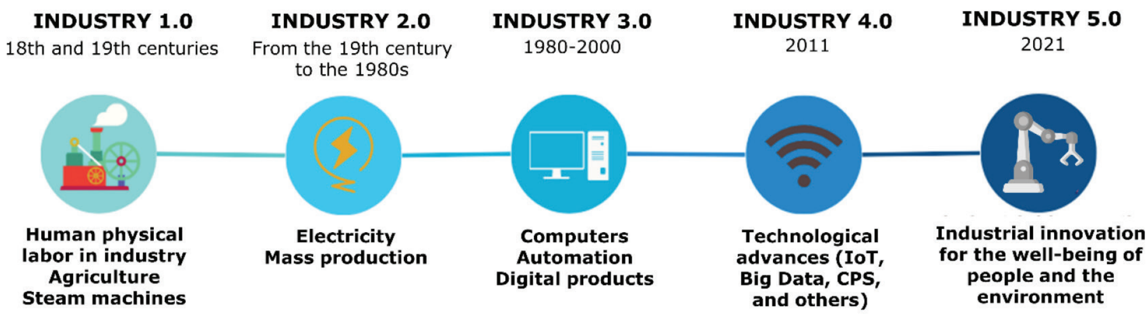

Figure 1. Evolution of Industries 1.0 - 5.0. *Source: Adapted from Maddikunta et al. [9].*

2. Literature review

The I4.0 concept is founded upon nine technological pillars [5], [20], including big data, cloud computing, Internet of Things, augmented reality, additive manufacturing (3D printing), cybersecurity, horizontal and vertical integration, simulation, and autonomous robots. I4.0 focuses on the connectivity of Cyber-Physical Systems (CPSs), while I5.0 connects to the applications of I4.0 and focuses mainly on mass customization, establishing a relationship between collaborative robots (cobots) [9]. In general, the focus of I4.0 is on the use of technology and automation of processes, while I5.0 presents a human-machine interaction approach, bringing machines closer to everyday human life [13], [21], [22]. For Maddikunta et al. [9], this is not an evolution, but the next industrial revolution in which humans and robots work together.

Thus, I5.0 is predicated upon three fundamental values: human-centeredness, sustainability, and resilience [8], [13], [14]. I5.0 acknowledges the potential of industry to achieve social goals that extend beyond employment and growth, to become a resilient generator of prosperity [4], [23]. This requires sustainable production that respects our planet's limits, reduces waste generation, and creates a pollution-free environment [9], [24]. It must also be centered on the well-being of industry workers at the heart of the production process [4], [25]. A collaborative approach is needed that combines worker training with the adoption of advanced technologies, thereby achieving a balance between technological efficiency and organizational sustainability [26].

According to Xu et al.[4], I5.0 is implemented based on the observation or assumption that I4.0 gives priority to digitization and AI-based technologies to improve production efficiency and flexibility, while less attention is paid to the principles of social justice and sustainability. In addition to increasing employment opportunities, I5.0 enhances productivity, efficiency, and sustainability, thus lowering the occurrence of workplace accidents and reducing production cycles [22]. Maddikunta et al. [9] posit that, compared to I4.0, I5.0 creates more highly skilled jobs as a result of intellectual professionals working alongside machines. In addition, Nahavandi [22] argues that advanced technologies are necessary to address the challenges linked with the elimination of human workers from various processes. In a scenario marked by global crises such as the COVID-19 pandemic, conflicts, climate change, and environmental impacts, I5.0 emerges as a necessary response, promoting more resilient and sustainable alternatives for both industry and everyday life [27].

Among these technological applications, traceability stands out as a tool for real-time process control and decision-making. Tortorella et al. [28] described traceability as a process that adheres to specific requirements for the transfer of inputs (materials, resources, and equipment) between locations to perform activities to achieve certain results. Its plays an important role in the reliable and comprehensive tracking of products or constituent parts throughout the production chain. To achieve this, it integrates a range of advanced technologies to collect and share data in real-time, including the Internet of Things (IoT), smart sensors, interconnected systems, and other technologies. In addition to identifying the origin of a raw material or a component [29] or the location of products, it provides detailed information on their history, environmental conditions, and production stages.

According to Bougdira et al. [11], traceability systems should not only enable traceability but also ensure product quality and safety. Dragičević et al. [30], their implementation reduces production costs and enhances security for both suppliers and customers. The introduction of this technology throughout the process allows for the rapid identification and resolution of issues, thereby ensuring more effective control and preventing the occurrence of failures that could reach the end customer. The combination of quality and I4.0 technologies can enhance traceability and transparency throughout the supply chain, from the initial purchase and acquisition to the end customer [31], [32]. According to Nahavandi [22], the integration of a company's various devices, including suppliers, production lines, and customers, is known as the Internet of Things. The traceability system is situated within the context of the IoT, which employs a range of technologies, including barcodes, quick response codes (QR codes), Radio Frequency IDentification (RFID), and other automatic identification technology systems (Auto-ID systems), to track and monitor assets and processes in real time. According to Fraga-Lamas et al. [8], the deployment of IoT architectures within industrial contexts is contingent upon the utilization of Auto-ID technologies, which collectively facilitate the location and identification of a multitude of objects.

The implementation of a traceability system tailored to digital technologies can facilitate process control, enabling company managers to monitor operations remotely. When data is accessible and verifiable, this allows for more effective management and efficient use of information in the production process. According to Fortuna and Gaspar [1], the most commonly used automatic identification technologies in production and distribution chains for tracking items are barcodes and RFID. Auto-ID technologies play an important role due to their ability to provide automated recognition, positioning, and tracking of items, without the need for human intervention or in collaboration with industrial operators [8]. In addition to optimizing operational efficiency, they increase transparency, sustainability, and safety in production processes.

In the existing literature on supply chain traceability, numerous studies have developed solutions to guarantee quality, transparency and traceability in real time [1], [8], [11], [29], [33]-[38] (see Table 1). Notwithstanding these advancements, the extant literature still lacks approach that directly connects traceability systems with the fundamental pillars of I5.0. It was observed that the majority of these studies tend to focus more on technological innovations such as blockchain, the IoT and highly automated architectures, whereas, while the discussion on traceability based on mature and widely adopted such as QR codes, RFID, barcodes and other Auto-ID systems is less prevalent. Agrawal et al. [27] highlighted that the applications and real-life examples of I5.0 technologies in supply chain management remain scarce, reinforcing the need for further studies in this field.

Studies such as those by Fernández-Caramés et al. [35] and Fraga-Lamas et al. [8] proposed the utilization of advanced architectures based on drones, RFID, blockchain, and the IoT for real-time tracking and inventory management. However, these approaches are generally associated with high implementation costs, technical complexity, and elevated energy consumption, in addition to a strong dependence on advanced technological infrastructure, which limits their applicability in small and medium-sized enterprises and in emerging economies such as Brazil. In a similar vein, Araújo et al. [29] proposed a comprehensive architecture for the naval industry. However, they have acknowledged that their proposal remains at a conceptual level, leaving practical implementation and performance evaluation to future studies. Conversely, studies that employ more mature and accessible technologies, such as barcode systems, tend to prioritize operational improvements or initiatives grounded in Lean philosophy. Fortuna and Gaspar [1] demonstrated that barcode-based solutions are often preferred over RFID due to their approximately 50% lower cost and greater compatibility with existing ERP systems. Nevertheless, in these studies, traceability remains limited to the operational level, without integration into broader digital architectures such as CPSs, cloud computing and Big Data.

Thus, it is observed that few empirical studies demonstrate how mature and low-cost technologies can be integrated with I4.0 solutions to practically support the transition toward I5.0, particularly in the context of emerging economies. A clear dichotomy can be observed: on the one hand, there are highly sophisticated solutions that are often economically restrictive; on the other, there are accessible approaches that remain limited to isolated operational improvements. In this sense, the present study seeks to address this gap. In contrast to studies that depend on sophisticated and expensive infrastructures or remain at a conceptual level, this research proposes the RAST 4.0 system, which is based on the use of mature technologies, especially barcode system, integrated into a CPS architecture, cloud computing, and Big Data. This integration facilitates effective monitoring, traceability, and decision support. Moreover, this research presents an empirical case study conducted in a medium-sized company, thereby demonstrating the practical feasibility, scalability, and operational impacts of the proposed system. Consequently, this study makes a contribution from both methodological and applied standpoints. It demonstrates that the transition from I4.0 to I5.0 can be achieved through the intelligent integration of data and the valorization of the human factor. This transition can be accomplished without reliance on costly or difficult-to-maintain technologies.

3. Research method

This study employed a qualitative approach, which aligns with the empirical and descriptive nature of the case study [39], [40]. The single case study method is employed to investigate a contemporary phenomenon within a real context, mainly when the boundaries between the phenomenon and the context are not clearly defined [40], [41]. As Yin [41] asserted, this method is most effective for investigating the "how" and "why" of a set of contemporary events. The level of detail in a case study is achieved through comprehensive data collection, which involves the analysis of multiple sources of information, including documents, reports, observations, and interviews [39], [42]. The triangulation of data sources enhances the robustness and validity of the results [43]. As pre-

Table 1. Overview of traceability technologies

Author(s)	Application Sector	Technology Used	Study Contributions	Advantages	Limitations
Appelhanz et al. [33]	Manufacturing (Wood Furniture)	RFID, Ink Printing, and QR Code	Cost–benefit model for B2B and B2C traceability integrating product history.	Increased consumer trust; low cost of printed labels.	RFID is expensive; ink fading; risk of middleware failure.
Peng et al. [34]	Cold Chain (Pork Industry)	QR Code, GPRS, and Sensors	QR-based traceability method integrated with temperature monitoring.	High error correction capability (up to 30%); large data storage capacity.	Reprinting required if QR code is damaged; training costs.
Fernández-Caramés et al. [35]	Warehousing / Logistics	Drones (UAV), RFID, and Blockchain	Design and evaluation of drone-based systems for inventory automation and external auditing.	Fast data collection; improved data integrity and redundancy	Immature technology; low scalability and high energy consumption
Bougdira et al. [11]	Manufacturing (Canned Fish Industry)	Ontologies (Auto-ID systems), Cloud, and IoT	Intelligent traceability description (TaaS) and ontology-based modelling.	Integration of heterogeneous data; real-time monitoring and control.	High complexity in ontology modelling.
Fraga-Lamas et al. [8]	Naval Construction (Military)	UHF RFID	Methodology for selecting Auto-ID technologies aimed at Industry 5.0.	Identification of parts in high-density metallic environments without human intervention.	Sensitivity to electromagnetic interference; high infrastructure cost.
Fortuna & Gaspar [1]	Metallurgy (Luxury parts)	Barcode and ERP	Sequential model for adapting AIDC systems to manual production flows.	Low acquisition cost (approximately 50% lower than RFID); improved production performance (Lean/ Kaizen).	Labels may become unreadable; not fully automated (requires human intervention).
Araújo et al. [29]	Shipbuilding Industry	IoT and Blockchain (QR Code/RFID)	System architecture for process traceability in ship construction.	Decentralized, immutable, and transparent data for end users	Predominantly theoretical approach; lack of practical performance evaluation
Raja Santhi and Muthuswamy [36]	Manufacturing (Cutting Tools)	Blockchain (QR Code/RFID) and Smart Contracts	Comprehensive assessment of blockchain impact on supply chain transformation.	Secure and agile transactions; anti-counterfeiting and immutability.	Low throughput compared to traditional systems; high computational cost.
Wu et al. [38]	Agricultural E-commerce	QR Code, RFID, and Cloud Computing	Agricultural product monitoring system based on 2D codes in cloud environments.	Real-time record management and quality auditing for food safety.	Dependence on stable cloud infrastructure; need for specific RFID readers.
Voulgaridis et al. [37]	Manufacturing (Digital Circular Economy)	Digital Product Passports (DPP) and IoT	CE framework integrated with DPP for data generation and distribution to stakeholders.	Full lifecycle traceability; supports reuse and material recovery.	Technical requirements still unclear; complexity in identifying specific data.

viously stated, this study aims to investigate how the implementation of an automated traceability system facilitates the transition from I4.0 to I5.0 in a medium-sized Brazilian company. This investigation is based on an in-depth qualitative single-case study, thereby answering the research questions addressed in Section 1. Figure 2 depicts the stages of the case study method, as adapted from Yin [41] and Miguel [40].

In the initial phase of the study, a conceptual-theoretical framework was established to map the extant literature on the subject. The data collection involved a focus group consisting of the quality coordinator, the PPC planner, and some employees of the company. During these sessions, the researcher was free to direct the questions according to the participants' answers and the needs of the research. The evidence from the focus group was triangulated with documentary analysis and direct observation. Figure 3 illustrates the research protocol, which describes the instruments used for data collection.

The case study was then reported and analyzed based on the information gathered, resulting in final discussions and conclusions. It is important to acknowledge that, given the adoption of a qualitative

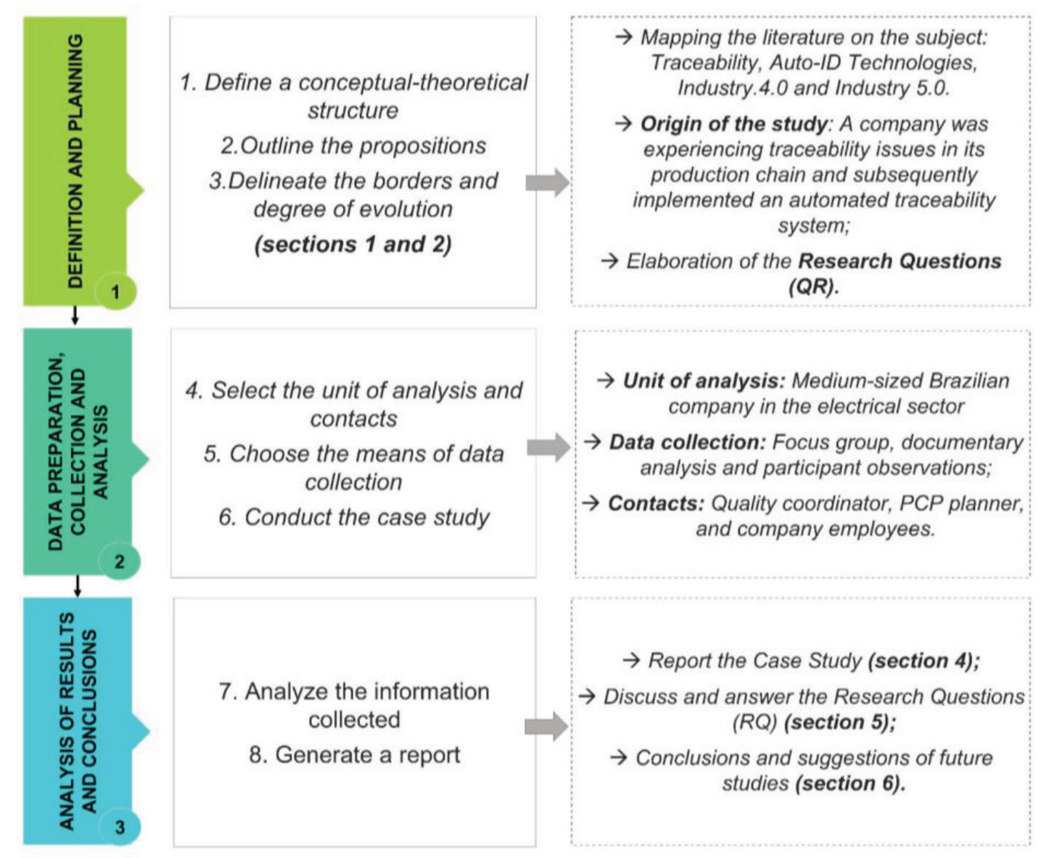

Figure 2. Stages of the Case Study. Source: Adapted from Yin [41] e Miguel [40].

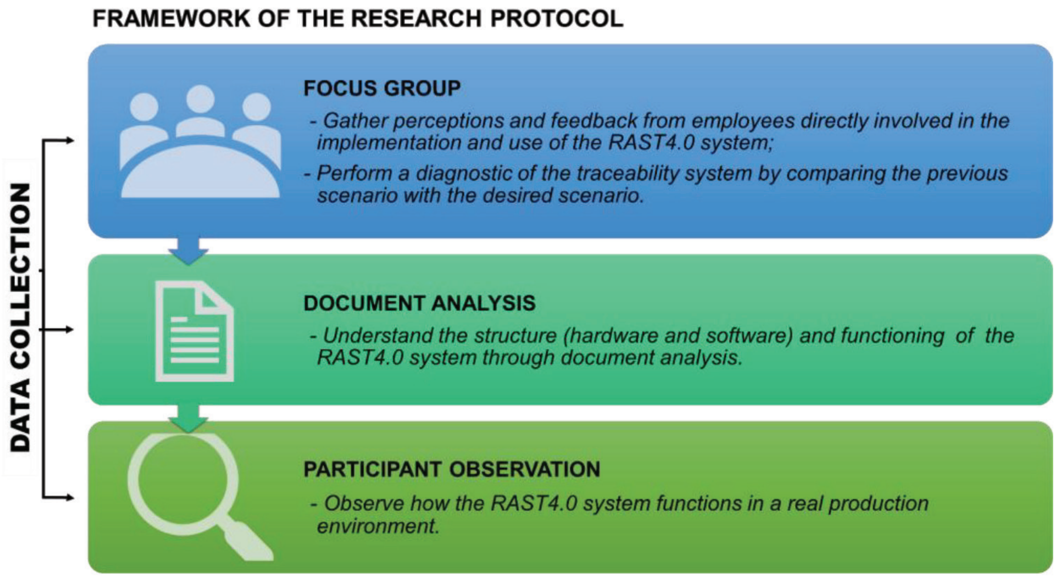

Figure 3. Framework of the Research Protocol. Source: Authors own work.

single-case research design in this study, the findings are inherently constrained in terms of statistical generalizability to other contexts [41], [42]. Nevertheless, the case study approach enables an in-depth examination of the phenomenon under investigation, contributing to theoretical development through analytical generalization. In addition, the triangulation of data sources strengthens the methodological rigor of the case study by reducing interpretative bias and enhancing the analytical validity of the findings. In this sense, the insights derived from the analysis may inform organizations operating in similar industrial and socio-organizational contexts, particularly those undergoing early transitions from I4.0 to I5.0.

4. Case study

The case in question pertains to a medium-sized Brazilian company, situated in the southern region of Minas Gerais, Brazil. The application was performed in one of the factories that produces power capacitor tanks, with robotic welding in 304 and 409 stainless steels. These products are of high value-added nature and are tailored to the energy sector industry.

The utilization of focus groups as a qualitative research technique was pivotal in comprehending the impact of the RAST 4.0 traceability system in the company and identifying the perceptions and challenges encountered by the principal individuals involved throughout the process. A focus group constitutes a small group of participants who engage in informal discussion on one or more predetermined themes under the guidance of a moderator. This approach enables participants to articulate their perceptions and share their experiences. During the discussions, participants engage in collective reflection and construct interpretations about a specified context or phenomenon [44]. Guest et al. [45] posited that the recommended modal size for focus groups, as evidenced in the literature, ranges between six and twelve participants. Accordingly, the focus group in this study consisted of seven participants, which is methodologically adequate. The participants were selected with the intention of ensuring their involvement in the process under analysis, thereby ensuring their familiarity with the operational routines and the system under study. As part of a qualitative case study, the focus group was composed of key actors involved in the process under investigation, rather than aiming to represent the entire company. The demographic details of the seven individuals involved are provided in Table 2.

The focus group aimed to comprehend employees' perceptions of the manual traceability system (previously scenario) and their expectations of the new automated system. It was revealed by employees that the manual monitoring that had been carried out at the capacitor factory was prone to failures. These failures were not monitored in real time. Instead, the information was reviewed subsequently, as it was first recorded on paper and then entered into a spreadsheet. The development of RAST 4.0 incorporated the following technologies: IoT, CPSs, Big Data, and cloud computing. In this study, integrative technologies are defined as the functional integration of these technologies into a unified system, thereby enabling automated data collection, processing, storage, and traceability throughout the process. Table 3 presents a comparative analysis of the pre-implementation scenario and the post-implementation (desired) scenario, as reported by the focus group participants. It is important to emphasize that the pre-implementation scenario does not represent an I4.0 configuration, but rather the operational conditions that prevailed prior to the adoption of the proposed system.

The document analysis was conducted with the objective of investigating the structure and functionality of the RAST4.0 system. To achieve this, docu-

Table 2. Demographic details of the focus group members

Participants	Position/Role	Area of Operations	Academic Background	Experience Time
P1	Quality Coordinator	Quality Management System	Master's in Industrial Engineering	20 years
P2	PPC planner	Production Planning and Control (PPC)	Business Administration	5 years
P3	Production Process Operator	Cutting	High School	5 years
P4	Production Process Operator	Folding	High School	8 years
P5	Robotic Welding Operator	Robotic Welding	High School	4 years
P6	Production Assistant	Pressurizing	Elementary School	5 years
P7	Quality Inspector	Inspection	Elementary School	8 years

Table 3. Diagnosis of the analyzed unit before and after system implementation

Pre-implementation scenario	Post-implementation (desired) scenario
Traceability performed manually	Traceability via automated system
Low level of reliability	High level of reliability
Information available on paper and in spreadsheets	Information available in the system
Difficulty for everyone involved in the process to access the information	Information easily accessible to all involved via the system
Offline information	Online information
Difficulty (delay) in the fault diagnosis process	Easy fault diagnosis
Lack of control of part(s) x employee	Control of parts x employee
Stipulated manufacturing time	Real manufacturing time
General indicators	Specific indicators with more reliable information

ments and materials related to the implementation of this system were analyzed, including reports, manuals, technical specifications, and diagrams delineating the hardware and software components. The RAST4.0 system comprises a hardware set (Figure 4) and a software (Figure 5).

The totem-mounted hardware was positioned adjacent to every production cell to facilitate process traceability. The RAST4.0 production control and tracking platform comprises two subsystems: the Main System and the Remote Panel. Both subsystems operate on the ASP.NET® platform (Microsoft, USA) with a web-based interface. SQL Server 2019® (Microsoft, USA) is the linked database for the platform. The main system is accessible via any web browser on the local network of the server. Its primary framework involves of the inspection and control of raw materials; control of production orders with a focus on the designation and separation of the manufacturing components of each tank in relation to a batch that has already been inspected and registered; and control of the production stages of each of the tanks produced (via printed barcodes). The remote panel is specifically designed for installation at each production point of power capacitor tanks. The device features a 7" touch screen and utilizes a Raspberry 3B+® micro-PC (Raspberry Pi, UK) for all processing and communication. Its primary function is to record the date, time, and user of each tank that has passed through a production station and store this information in a database. To accomplish this task, the operator employs a barcode reader to scan the serial number of the capacitor tank that is being handled at the end of the process.

Participant observation permits the researcher to observe processes directly on-site, not merely as a passive observer, but also by actively engaging in the company's activities [41]. It was observed that the RAST 4.0 platform was designed to manage the manufacturing of capacitor tanks, from the delivery of raw materials to after-sales support. All stages of this process are recorded and archived for real-time monitoring of current production and future tracking of each manufactured tank. The procedure begins by creating lots for tracking within the traceability system. To achieve this, raw materials are initially registered based on the supplier's and/or customer's invoice, which is the prevailing system in the company under study. Partners (customers and suppliers) are also registered in this system. All received materials are entered into the traceability system with the respective receipt data. After registering the invoice, it is necessary to input

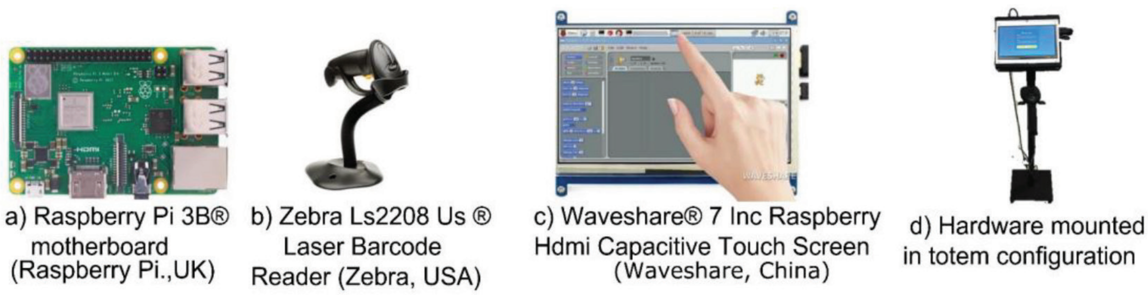

Figure 4. RAST 4.0 hardware. Source: Authors own work.

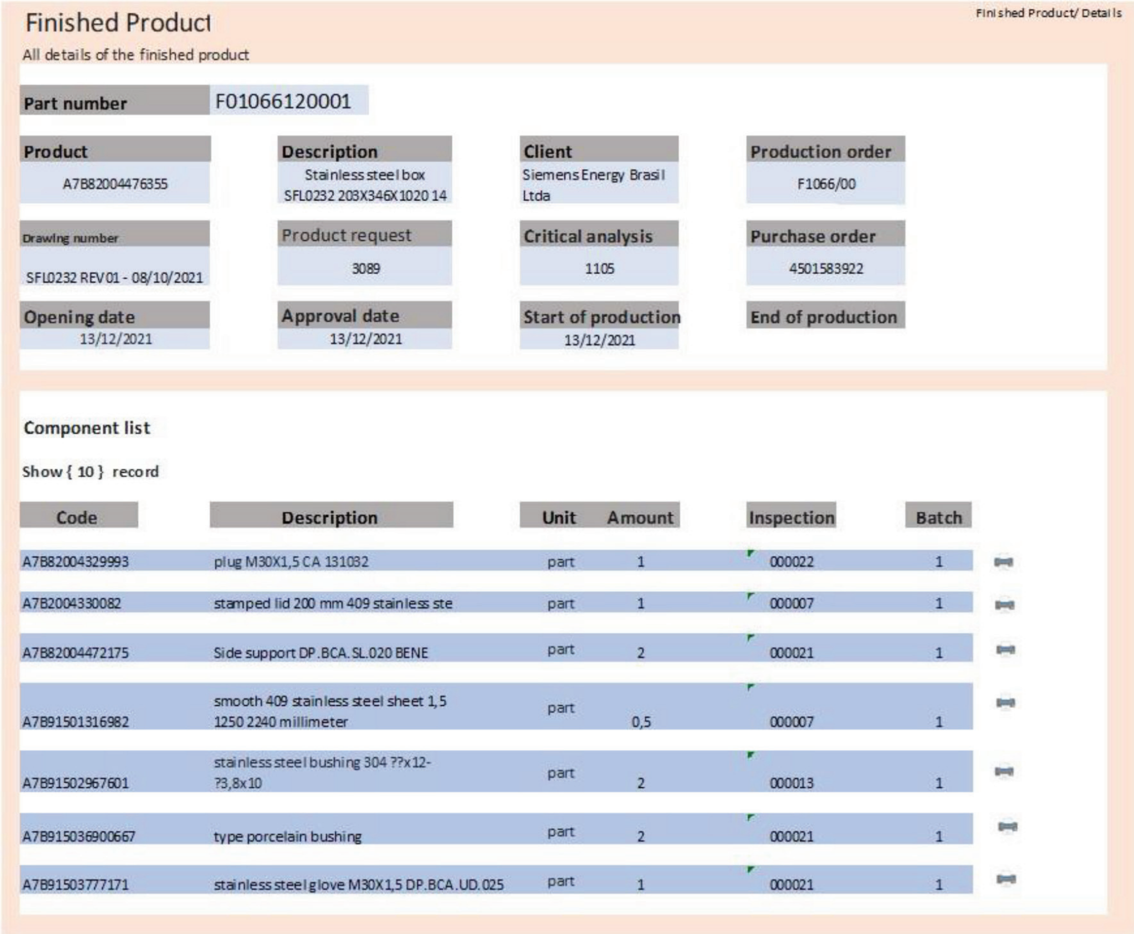

Figure 5. Deployed software screen. Source: Authors own work.

information about the items and quantities. This data is used to create batches separated by raw material. The first entry generates Batch 1, and when there is a new entry of the same material, its entry will generate Batch 2, and so forth. This information will be available in the tracking code generated for each finished product, including the date of receipt, quantity, batch, invoice, and other relevant details. The inventory can be accessed at any time and is consistently updated to account for the incoming and outgoing movements related to production orders.

In the production area, the traceability system records the final product requested by the customer through a purchase order, including the order information and bill of materials quantity, which lists the product components and raw materials. Following this registration, the production order is generated with the requested quantity of products, and a tracking code is created. Production commences in the factory at this point. The initial production step involves cutting either the AISI 304 or AISI 409. A tracking code is assigned to the blank at this step (Figure 6).

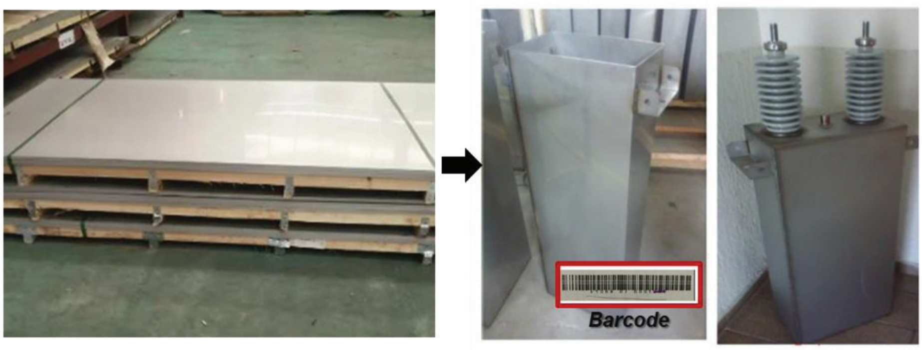

Figure 6. Capacitor tanks. Source: Authors own work.

Subsequently, each subsequent operation has a reader and a system that is fed simultaneously with the code of the operator carrying out the action and the exact date and time of execution. This real-time data can then be accessed by management. Within the operations area, the manager can access the system to review the serial number and find out which operator performed the action and when. The products undergo multiple inspections during the process and all information is entered into the system, creating a report that serves as internal control and is presented to the client. In case of customer complaints, the system allows tracking of internal faults in the product. Once the process is complete, the entire history of the product becomes visible, helping to identify and resolve potential faults faster.

5. Results and Discussions

The RAST 4.0 system took important steps to improve the traceability of capacitor tanks through the implementation of barcodes in a medium-sized Brazilian company, which allowed the desired scenario to be achieved (Table 3). While the system has been implemented in production, its impact extends to other links in the supply chain, benefiting suppliers, customers, management, and other company departments. As discussed in the study by Lafquih et al. [2], the traceability of a product requires the interconnection of all the processes involved. With RAST4.0, It becomes possible to trace the raw material or component of a product claimed by the customer, as well as the tests conducted on the shop floor and the individual responsible for the production stages. These operations ensure that the product is correctly identified, traced and located [11], [29], resulting in quality improvements, productivity gains and better customer service.

Although barcode technology is well established in industrial environments, RAST 4.0 system stands out due to its incorporation of existing barcode solutions into a digital architecture centered on I4.0 principles. This integration facilitates real-time traceability, process visibility, and data interoperability, thereby enhancing operational efficiency and decision-making capabilities within industrial contexts. In the Brazilian context, particularly in medium-sized companies, financial and technical constraints often impede the adoption of entirely novel digital systems. In this particular instance, the implementation of an incremental approach, grounded in existing technological frameworks, enabled the enterprise to enhance traceability and operational control without the necessity of disruptive investments. It is noteworthy that the RAST 4.0 system was developed as a customized tool to address the operational requirements of the company under scrutiny.

A comparison of the RAST 4.0 system with conventional barcode-based systems, as reported in the extant literature, demonstrates its superiority in terms of process integration and decision support. This is achieved by embedding traceability data into an I4.0-oriented digital architecture. The use of barcodes remains a promising solution due to their technological maturity, low implementation cost, and ease of reading using commonly available mobile devices. However, despite their economic advantages and effectiveness in facilitating traceability, barcodes are subject to certain limitations. They require direct line-of-sight and short reading distances, cannot support the simultaneous reading of multiple products, and may become unreadable in the event of physical damage. These limitations are also discussed in the studies by Fernández-Caramés et al. [35] and Guruswamy et al.[13].

When compared with RFID-based solutions, RAST 4.0 offers a more economically viable and easily deployable alternative. RFID tags are easy to use, eliminate the need for line-of-sight, enable the simultaneous reading of multiple items, and offer greater storage capacity and higher data transfer rates. However, they typically require higher investment, specialized infrastructure, and tag-related costs, as well as greater complexity in integrating with existing ERP systems [1], [13], [35]. In a similar vein, blockchain-based traceability systems enhance data immutability and transparency across supply chains [36]. However, these systems require advanced digital maturity, interoperability among multiple actors, and greater organizational coordination. Conversely, RAST 4.0 capitalizes on existing barcode infrastructure to ensure effective traceability and process visibility while requiring less implementation complexity. This renders it particularly well-suited for SME's grappling with financial and technical limitations.

With regard to integrative technologies, the system employs I4.0 tools, such as IoT and system integration, to receive the data collected at the entry of the raw material by a trained operator, validate the information to ensure its reliability, and make it available to interested parties. IoT makes it possible to integrate different company departments (production system, maintenance, inventory control, etc.) and thus improve the overall performance of the company. The combined use of IoT and system integration offer greater flexibility by allowing services to be customized to meet specific customer needs and adapt to changes in the production environment. They also contribute to higher quality by producing products within customer and process specifications, reducing the likelihood of defects.

Given that these integrated environments generate continuous data streams, cloud computing technology is employed to store and process the data collected by IoT devices and systems integration. Information is available in real time, thereby giving managers instant access from anywhere. This technology facilitates collaboration between different departments and stakeholders in the production chain, as everyone can access and share data quickly and efficiently. By tracking each stage of the production process and collecting a large amount of information about process time, professionals involved, materials, type of process, and other relevant information, the company can build a huge database, the big data. Subsequently, various big data analysis tools can be used to identify insights related to the process. According to a study by Guruswamy et al. [13], Big Data analysis can extract trends and useful information that can help understand system behavior and optimize system performance, as well as make predictions that lead to intelligent decisions.

Figure 7 summarizes the results achieved by the combined technologies of I4.0 in the company studied. It can be seen that the implementation of the RAST 4.0 system has enabled improvements in flexibility, speed, reliability and quality, as well as the automation of traceability and the integration of different departments. In this way, the research question *RQ1* was answered.

The I4.0 paradigm prioritizes automation, digitalization, and efficiency through the integration of advanced digital technologies. In contrast, I5.0 builds on this foundation by emphasizing human-centered systems, human–machine collaboration, resilience, and sustainability. This approach positions technology as a means to enhance human capabilities rather than replace them. Accordingly, the RAST 4.0 system implementation is discussed as a practical example of how I4.0 technologies can be leveraged to support a gradual transition toward I5.0 principles. In this sense, the study contributes to I5.0 theory by demonstrating that this transition can occur incrementally, through the human-centered reinterpretation of existing digital technologies, rather than through disruptive technological change. We will now discuss how the RAST 4.0 system promoted the principles of sustainability, human centricity, and resilience, three fundamental values prioritized by I5.0.

The traceability system implemented aimed to promote sustainability by accurately tracking the product (or its components) throughout the production chain. The technologies used facilitate monitoring, as they are able to identify the origin of raw materials, optimize the use and allocation of resources, reduce waste and even assess energy efficiency at different stages of the production process. The system also assists in monitoring environmental risks by providing customers with information regarding the environmental

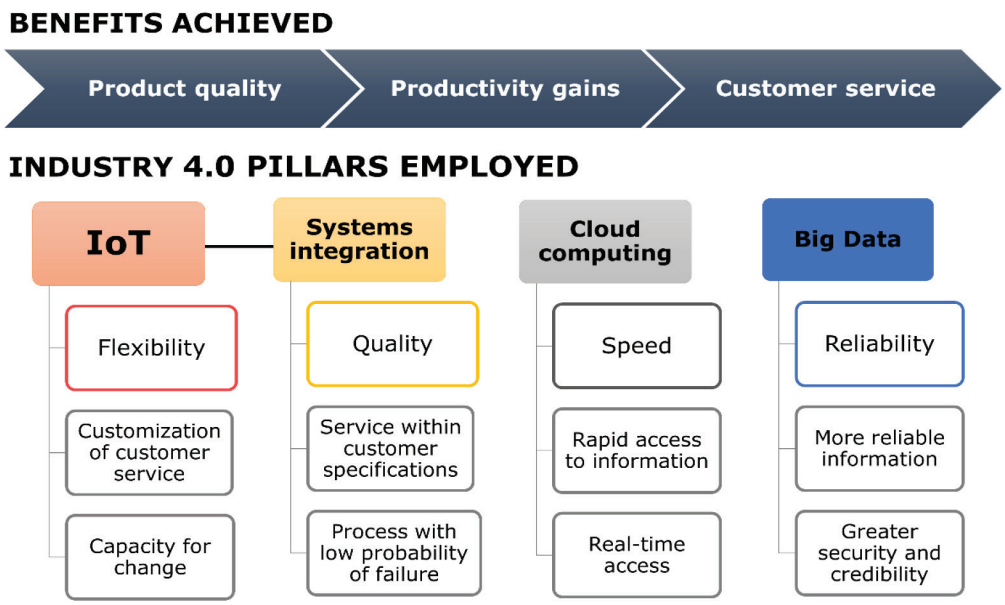

Figure 7. Benefits achieved with RAST 4.0. Source: Authors own work.

compliance of the materials utilized, including any potential harm to the environment. Because the process is monitored in real time, non-conformities are quickly detected and corrected, thereby contributing to a reduction in waste, rework, energy consumption, residue generation, and costs. For Adel [21], these practices lead to the emergence of sustainable policies, such as low waste generation and management, which can contribute to the company's efficiency.

Another issue related to the principle of sustainability is the fact that the factory operators use paper to identify the raw materials and inputs to be used (for example, stainless steel sheets, pallets, and porcelain bushings), as well as the instructions to be carried out according to the production orders. This information is then entered into the computer, which can lead to typing errors and labor costs associated with the time required. The RAST 4.0 system has eliminated most of the paperwork and provides dynamic, real-time information about these assets. The barcode reading is used as a unique identifier linked to the identification number of the steel sheet in the information system. The application developed displays the information to be extracted, such as the type of material, size, and destination of each batch. In this case, reducing the use of paper contributes to sustainability and consequently to reducing the waste of natural resources.

Fraga-Lamas et al. [8] argued that I5.0 enables prosperity in a sustainable way, seeking to increase productivity without eliminating operators. As highlighted by Leng et al. [14], for technology to enhance operator productivity and foster human value, rather than replacing them, it is essential to transform it into intelligent, human-centric technology. The migration from the existing to the desired scenario with the implementation of the RAST 4.0 system required the development of employees' technological capabilities. In this context, the effective adoption of the new system depends on the technological capability of employees, which is related to their prior knowledge, digital skills, and ability to learn and adapt to technological change. By integrating advanced technologies with the knowledge and skills of operators, I5.0 seeks to achieve a balance between operational efficiency and respect for the important role that workers play in the company. This necessitates an approach that prioritizes both innovation and the training of operators, enabling them to interact with technologies in a more autonomous and collaborative manner [26]. In this sense, to focus on the human being, it is necessary to conduct training with operators and stakeholders so that everyone knows their importance and contribution to the process.

During the implementation of the RAST 4.0 system, initial training was provided to all stakeholders, directly supporting the development of the technological capabilities required for system adoption. Furthermore, this system facilitated the identification of employees who experienced difficulties in their tasks, allowing targeted and personalized training to be provided to improve their skills and competencies. Therefore, in addition to automating tasks, the company studied sought to maximize human potential by combining the skills of its operators with the benefits of advanced technologies to increase productivity and achieve better results. As highlighted by Maddikunta et al [9], quality improvement in production is achieved by assigning repetitive and monotonous tasks to machines, while tasks that require critical thinking are assigned to human workers. In this context, I5.0 facilitates the integration of high-precision, high-speed machines with the critical and cognitive thinking of humans. Beyond productivity gains, the human-centric approach adopted in the RAST 4.0 system has the potential to positively influence workers' job satisfaction and professional development, as targeted training and greater autonomy in interacting with technology can reduce resistance to change and strengthen employees' sense of value and belonging within the organization.

Regarding resilience in I5.0, the new traceability system improves online collaboration by providing guidance to help solving incidents and visually clarify certain product events in the production process. The information can be monitored in the system by factory managers, who can react to the problem in real time and make assertive decisions. The system prevents non-conformities from reaching the customer and supports the adoption of preventive actions as well as timely decision-making throughout the production process. Prior to the implementation of the system, there were 51 rework cases involving capacitor tanks, amounting to an annual cumulative rate of 18.42% of the total. For example, some tanks became unidentifiable due to the loss of barcode legibility, particularly after surface blasting processes, which may degrade the identification on the product. This made it difficult to determine the origin of the part, i.e., whether it was manufactured by the company or by a competitor. To mitigate this issue, the system relies on digital records linked to the batch and invoice, ensuring that traceability is maintained even when the physical identification is compromised. However, subsequent to the implementation of the RAST 4.0 system, no such rework cases were recorded (see Table 4). This outcome indicates that the system has facilitated a substantial reduction in rework by offering enhanced process control, facilitating the identification and correction of errors in real time, and thereby preventing their propagation to subsequent stages of production. As discussed in the study by Bougdira et al. [11], intelligent traceability plays an important role in the decision-making process, helping to ensure product safety and quality. In this regard, the system makes a significant contribution to resilience by enhancing the capacity to detect, respond to, and adapt to operational failures, as well as ensuring agility in access to information and continuity of the production process.

Overall, this case study has shown that the implementation of traceability has made it possible to achieve the three essential pillars of I5.0, answering research question RQ2: sustainability, by reducing waste and optimizing resources; human centricity, by valuing and training operators in conjunction with technologies; and resilience, by improving online collaboration and the ability to make quick and assertive decisions in real time when incidents occur in the production chain. Figure 8 shows how the implementation of the RAST 4.0 system contributed to the evolution of the pillars from I4.0 to I5.0 in the company studied.

Table 4. Number of reworked tanks before and after the RAST 4.0 system

Month	*Before RAST 4.0 system*			*After RAST 4.0 system*		
	No. of Capacitor Tanks	*No. of Rework Cases*	*% of Rework*	*No. of Capacitor Tanks*	*No. of Rework Cases*	*% of Rework*
January	196	4	2.04%	203	0	0.00%
February	336	4	1.19%	353	0	0.00%
March	279	3	1.08%	797	0	0.00%
April	196	2	1.02%	447	0	0.00%
May	209	1	0.48%	568	0	0.00%
June	400	12	3.00%	557	0	0.00%
July	318	1	0.31%	240	0	0.00%
August	101	5	4.95%	383	0	0.00%
September	1	0	0.00%	219	0	0.00%
October	454	8	1.76%	190	0	0.00%
November	425	11	2.59%	37	0	0.00%
December	88	0	0.00%	3	0	0.00%
Total	3003	51	**18.42%**	3997	0	**0.00%**

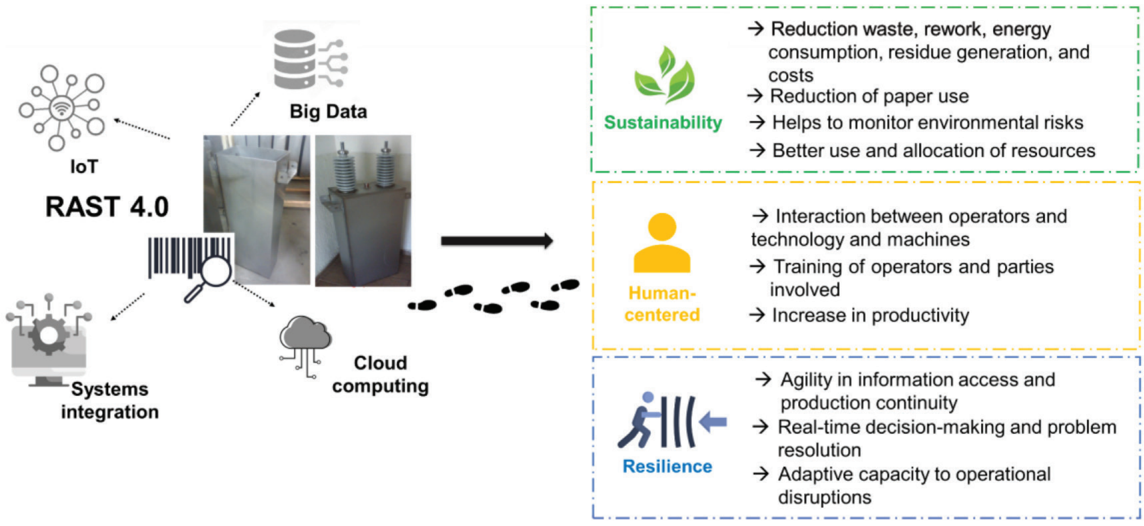

Figure 8. RAST 4.0 system towards I5.0. Source: Authors own work.

The next steps in using the RAST 4.0 system will be to implement traceability continuity when the product is at the customer's site and evaluating the replacement of barcode identification with RFID tags.

5.1 Policy and infrastructure implications for emerging economies

Industrial policies can exert a strong influence on the adoption of new technologies and the implementation of I4.0 and I5.0, especially in developing countries. A study conducted in China indicates that the adoption of industrial policies can help stimulate companies to carry out R&D and innovation activities [46]. Consequently, industrial policy has positive effects on the country's economic growth [47].

Pineli & Narula [48] analyze the historical political/industrial context of Brazil and Mexico, arguing that industrial policies are fundamental to guide the allocation of Foreign Direct Investment (FDI) and generating value in industry. Considering Brazil's history, there has been the adoption of more active industrial policies, such as development banks (BNDES), sectoral incentives, local content policies, and support for strategic sectors. These policies helped attract FDI to sectors with higher added value, strengthen internal production chains, and diversify the industrial base [48].

When it comes to SMEs, the development of industrial policies is considered even more important. Mohiuddin et al. [49] corroborate that favorable government policies and regulations help SMEs become more flexible, adaptable, and innovative, making them open to adopting new ideas and technologies, such as I4.0. Therefore, it is up to the government to provide supportive policies, funding, infrastructure, and skills development to overcome challenges, thus fostering innovation, competitiveness, and economic growth through subsidies, testing environments, and the promotion of public-private partnerships.

For Brazil to compete internationally, it is essential to achieve significant technological advancements in the country's industrial structure. In contrast to economies that are already well-established, the Brazilian scenario necessitates strategies that integrate professional training, government incentives, and solutions adapted to the reality of small and medium-sized companies. According to the report published by UBS for the World Economic Forum [50], Brazil ranks 43rd out of 45 countries analyzed in terms of preparedness for advanced manufacturing (I4.0). Despite the existence of technological and managerial barriers, initiatives to digitalize are occurring in specific sectors, driven by collaborations between industry and academia, as well as by innovation programs promoted by the government.

6. Conclusions

The results of this case study indicate that the implementation of process traceability in a medium-sized Brazilian company, despite encountering certain challenges, facilitates enhanced control over the process and its decisions, enabling continuous improvement and the management of non-conformities. Nevertheless, the system demonstrated its ability to surmount these challenges, conferring substantial advantages in terms of traceability, efficiency, and quality. In the context of I5.0, traceability represents an important step for the industry as it moves into the rhythm of the digital transformation era while aiming to maintain compliance with its quality policies.

The effective tracking of products throughout the production chain of the medium-sized Brazilian company has enabled more efficient management of the resources used. It also allowed for the rapid detection and correction of non-conformities, reducing rework, energy consumption, waste generation, and costs, which is in line with the principles of sustainability. The study highlighted the importance of a human-centered approach, recognizing the crucial role that operators play in the company and seeking to enhance their skills in conjunction with advanced technologies. Finally, the study demonstrated that resilience can be achieved through access to real-time information across the entire supply chain, enhanced control over non-conformities, and improved decision-making. Therefore, the implementation of the RAST 4.0 system in the company under study has led to gains in the three pillars of I5.0: sustainability, human-centeredness, and resilience.

Although barcodes are economical and offer good traceability, barcodes present certain limitations that can impact the efficiency of the traceability system. They require direct access (reading at short distances), do not support simultaneous reading of multiple products, and become unreadable in the event of damage. To overcome these limitations, a strategy would be to evaluate the adoption of RFID tags on the operator's badge and on the tank itself, with the barcode being replaced. The systematization of production and data monitoring is feeding a database, whose Big Data analysis tools will be implemented as future research opportunities. These tools will facilitate the formulation of decisions and strategies aimed at enhancing processes, quality, and other opportunities. It is recommended to introduce additional technologies, such as blockchain, artificial intelligence, collaborative robots, 6G technology, and others, to enhance the effectiveness of the traceability system. Further studies could be conducted with a view to analyzing the benefits of these I5.0 technologies in Brazil and other developing countries, as well as their potential to improve traceability and operational efficiency, with the objective of creating a more humane, productive, and sustainable work environment.

To further validate the model, future studies can implement the traceability system in companies from different sectors and with varying levels of technological maturity. As the system was internally developed using existing infrastructure, it requires low investment, relying on resources already available in the company and a specialized professional for implementation. This configuration facilitates its adaptation and migration to other industrial contexts, including small and medium sized enterprises. Validation can be conducted by comparing pre and post implementation performance across different sectors and maturity levels, assessing its scalability, cost effectiveness, and alignment with I5.0 principles.

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