processes

MDPI

Article

Implementation of a Sustainable Framework for Process Optimization Through the Integration of Robotic Process Automation and Big Data in the Evolution of Industry 4.0

Leonel Patrício [1,*], Leonilde Varela [1] and Zilda Silveira [2]

[1] Department of Production and Systems, Algoritmi/LASI, University of Minho, 4804-533 Guimarães, Portugal; leonilde@dps.uminho.pt

[2] Department of Mechanical Engineering, Sao Carlos School of Engineering, University of Sao Paulo, Sao Paulo 13566-590, Brazil

* Correspondence: leonelfilipepatricio@gmail.com

Abstract: This study explores the integration of Robotic Process Automation (RPA) and Big Data within a sustainable framework for process optimization in the context of Industry 4.0. As industries strive to enhance operational efficiency while maintaining sustainability, the need for innovative solutions has become crucial. The research applies the PICO methodology (Population, Intervention, Comparison, Outcome) to assess the impact of combining these technologies on process optimization and sustainability. Through a real-world case study, the study demonstrates that the integration of RPA and Big Data significantly reduces execution times, minimizes operational errors, and promotes sustainable business practices. The results show that the combined framework not only enhances efficiency but also contributes to lower economic, environmental, and social impacts. The findings validate the research hypotheses, proving that the proposed framework fosters a balance between technological advancement and sustainability. This study provides valuable insights into the potential of Industry 4.0 technologies to drive both operational efficiency and corporate responsibility, offering a novel approach for industries seeking to embrace digital transformation while achieving long-term sustainability. The research contributes to the growing body of knowledge on the synergy between RPA, Big Data, and sustainability in industrial contexts.

Keywords: RPA; data science; pillars of sustainability; S-PROBIO; digital transformation

check for updates

Academic Editors: Lee Tin Sin and Thomas S.Y. Choong

Received: 22 January 2025
Revised: 3 February 2025
Accepted: 11 February 2025
Published: 14 February 2025

Citation: Patrício, L.; Varela, L.; Silveira, Z. Implementation of a Sustainable Framework for Process Optimization Through the Integration of Robotic Process Automation and Big Data in the Evolution of Industry 4.0. *Processes* **2025**, *13*, 536. https://doi.org/10.3390/pr13020536

1. Introduction

Technological advancements have profoundly transformed industrial processes, driving the transition toward the so-called Industry 4.0, which is characterized by the integration of advanced technologies such as Big Data and Robotic Process Automation (RPA). This emerging paradigm heralds a new era in manufacturing and services, where digitalization, automation, and intelligent data analysis play pivotal roles in process optimization. However, sustainability, a cornerstone of contemporary development, continues to face significant challenges in the context of this industrial revolution, necessitating innovative approaches to reconcile efficiency, competitiveness, and environmental responsibility [1].

In this context, process optimization emerges as a strategic objective for organizations aiming to enhance operational efficiency and minimize waste. The utilization of Big Data enables not only the collection and storage of vast volumes of information but also the extraction of valuable insights to support data-driven decision making. Conversely, RPA stands out as a disruptive tool that facilitates the automation of repetitive tasks and the continuous improvement of workflows, fostering productivity gains. When integrated, these technologies have the potential to form a powerful framework for achieving sustainability in industrial and organizational processes [2].

The motivation for this investigation stems from the pressing need to address the demands of a globalized and highly competitive market while promoting more responsible resource management. Despite the vast potential of Industry 4.0, a significant gap persists in the scientific literature regarding the synergistic combination of Big Data and RPA to achieve sustainability objectives. This study seeks to address this gap by developing a sustainable framework that unites these technologies and explores their potential to transform industrial processes [3].

The primary aim of this research is to design and implement an innovative framework that integrates Big Data and RPA, focusing on sustainability and process optimization. Following its development, the framework's effectiveness will be validated through practical application in a real-world case study. This study intends not only to demonstrate the operational benefits of the framework but also to contribute to the advancement of knowledge in the field by offering a solution that combines technological innovation with sustainability-focused responsibility [4].

This article is structured as follows. Section 2 provides a comprehensive review of the state of the art with subsections dedicated to process optimization, Industry 4.0, Big Data, RPA, and sustainability. Section 3 outlines the methodology adopted, including the formulation of hypotheses and the application of the PICO method (Population, Intervention, Comparison, Outcome). The PICO methodology was chosen for its ability to structure and analyze complex research questions in a systematic and objective manner, ensuring precise data analysis and minimizing subjective biases. This approach, widely used in fields such as healthcare and automation processes, was adapted in this study to evaluate the integration of RPA and Big Data in process optimization and sustainability. Section 4 introduces the proposed framework, detailing its features and benefits. Section 5 demonstrates the practical application of the framework in a case study. Section 6 analyzes the results obtained, and finally, Section 7 concludes the article by summarizing the main contributions and offering suggestions for future research.

2. State of the Art

2.1. Process Optimization

Process optimization is a central concept in the fields of industrial engineering, business management, and information technology. The primary objective of optimization is to enhance the efficiency and effectiveness of processes by eliminating waste and maximizing the utilization of resources. In the literature, process optimization is frequently associated with the analysis, redesign, and reengineering of business processes with the aim of improving performance, reducing costs, and increasing the competitiveness of an organization. Its application is particularly relevant in industrial environments, where the complexity and interdependence of various systems necessitate rigorous management and a continuous search for improvement [5].

Process optimization can be approached through various techniques and methodologies. Traditionally, approaches such as continuous improvement models, the PDCA cycle (Plan–Do–Check–Act), and Six Sigma methodology have been widely used to identify and eliminate inefficiencies in processes. These approaches involve the analysis of workflows, performance measurement, and the implementation of solutions aimed at reducing variations and maximizing production with minimal resources. These methodologies have proven effective in enhancing quality and productivity, yet they often focus on a limited set of variables and the optimization of specific processes [5].

In the context of Industry 4.0, process optimization has been significantly transformed by the introduction of disruptive technologies such as automation, Big Data analysis, and artificial intelligence. The use of Big Data and the Internet of Things (IoT) has enabled the real-time collection and analysis of data from machines, sensors, and production systems, providing a holistic view of process performance. This approach allows for the identification of patterns, anomalies, and opportunities for improvement, leading to more precise and agile process optimization [6].

Concurrently, the automation of processes, particularly through Robotic Process Automation (RPA), has enabled the elimination of repetitive and manual tasks, resulting in greater operational efficiency. RPA integrates effectively into process optimization not only by automating simple tasks but also by performing complex tasks based on predefined rules and machine learning algorithms. By reducing the human workload and eliminating the possibility of human error, RPA enables organizations to focus on higher-value activities while enhancing consistency and productivity [7].

However, process optimization is not limited to cost reduction and productivity increases. Today, sustainability has emerged as a crucial variable in the optimization of industrial processes. The need to develop more environmentally friendly and responsible processes has prompted many organizations to incorporate optimization practices that not only focus on economic efficiency but also aim to reduce environmental impacts, such as energy consumption and waste generation. The integration of sustainability into process optimization strategies has given rise to new business models that seek to balance economic needs with environmental and social demands [8].

Thus, contemporary process optimization requires an integrated approach that considers not only operational efficiency but also sustainability, technological innovation, and constant adaptation to new market realities. The convergence of Big Data, RPA, and the pursuit of more sustainable processes forms the foundation of a new optimization paradigm, where the intelligent use of data and automation not only drives business performance but also promotes responsible and balanced resource management [8].

In this regard, the integration of these technologies and practices offers significant potential for creating more efficient, sustainable, and resilient processes, which are aligned with the challenges posed by Industry 4.0. Through smarter resource management, process optimization in the digital age not only contributes to continuous improvement but also strategically positions organizations to meet the demands of an ever-evolving global market.

2.2. Industry 4.0

Industry 4.0, also known as the Fourth Industrial Revolution, emerges as a fundamental milestone in the context of the digital transformation of industrial and production sectors. The term refers to the integration of advanced technologies into industrial processes with the aim of creating smart factories that are more efficient, flexible, autonomous, and interconnected. This revolution has been driven by significant technological innovations, such as the Internet of Things (IoT), artificial intelligence (AI), advanced robotics, 3D printing, cyber–physical systems, and Big Data analytics, all working in tandem to create a digitally interconnected and highly automated ecosystem [9].

The concept of Industry 4.0 is based on the transformation of traditional production processes through digitalization and the use of cutting-edge technologies that enable real-time communication between devices, machines, and systems. Through the application of cyber–physical systems, physical devices can be monitored and controlled remotely, generating data that are processed and analyzed to optimize production performance. These systems, along with the use of intelligent sensors and actuators, enable factories to be highly adaptable, automatically adjusting to changes in production conditions and market demands [9].

One of the main features of Industry 4.0 is interconnectivity, which allows communication between all components of the production chain from machines and equipment to management and control systems. This connectivity is provided by the Internet of Things (IoT), which enables the exchange of information between physical objects and virtual systems, providing greater visibility and traceability of processes. For example, the IoT allows machines to communicate with each other to adjust production parameters, identify failures in real time, and prevent unplanned stoppages, resulting in greater operational efficiency and reduced costs [10].

Big Data analytics is another crucial pillar of Industry 4.0, as it allows the collection and processing of large volumes of data from various sources, such as sensors, machines, and management systems. By using advanced data analysis techniques and artificial intelligence, valuable insights can be gained to help organizations make more informed and accurate decisions, promoting process optimization, quality improvement, and product customization. Real-time data analysis also enables the implementation of predictive maintenance, where failures are anticipated based on patterns identified in the data, avoiding downtime and high costs associated with emergency repairs [10].

Intelligent automation is another key element of Industry 4.0 with a particular focus on Robotic Process Automation (RPA) and collaborative robots. RPA, in particular, allows for the automation of repetitive, rule-based tasks, freeing employees to focus on higher-value functions. Furthermore, the integration of collaborative robots into the production line, which work alongside human operators, provides greater flexibility and efficiency in operations, especially in production environments with high variability and complexity. The use of these robots, combined with artificial intelligence, enables machines to learn and adapt to different scenarios and working conditions, resulting in more agile and adaptable production [11].

Another relevant aspect of Industry 4.0 is mass customization, which enables the production of highly personalized goods at reduced costs. Thanks to technologies such as 3D printing and additive manufacturing, it is now possible to create on-demand products with a level of customization never before possible on a large scale. This ability to rapidly adapt to market needs and consumer desires is one of the factors that make Industry 4.0 particularly competitive in dynamic and constantly changing markets [11].

However, the transition to Industry 4.0 also presents significant challenges. The implementation of advanced technologies requires substantial investments in infrastructure and training as well as an adaptation of organizations to new work dynamics and the demands of the digital environment. Furthermore, issues related to cybersecurity and data protection are becoming increasingly relevant, as interconnectivity and real-time information exchange increase the risks of attacks and the compromise of system integrity [12].

In summary, Industry 4.0 represents a revolution in the way industrial processes are conceived, managed, and executed. The convergence of digital and physical technologies has the potential to radically transform business models, creating new levels of efficiency, flexibility, and innovation. However, the successful adoption of Industry 4.0 requires a strategic and integrated approach that considers not only the operational benefits but also the technological, economic, and social challenges associated with this transformation.

2.3. Big Data

The concept of Big Data refers to the processing and analysis of massive volumes of data which, due to their magnitude, variety, and velocity, exceed the capabilities of traditional data management and processing systems. At its core, Big Data involves the capture, storage, analysis, and visualization of data generated from various sources such as business transactions, sensors, social media, mobile devices, and others. This vast quantity of data presents a unique opportunity for organizations to derive valuable insights, which can be utilized to make more informed decisions, optimize processes, and create new value-driven solutions. However, the real challenge lies not only in managing the sheer volume of data but in the ability to extract meaningful information from it, which is a process that involves advanced data analysis techniques and artificial intelligence [13].

The nature of Big Data is often characterized by the three Vs: volume, variety, and velocity. Volume refers to the massive amount of data generated, which can reach such high levels that traditional database management systems become incapable of handling them efficiently. Variety concerns the different types of data, which may be structured, semi-structured, or unstructured, ranging from numerical data in tables to textual information on social media or videos. Velocity refers to the speed at which data are generated and must be processed with many Big Data systems operating in real time or near-real time, requiring solutions that allow for immediate analysis of data as it is produced [13].

In addition to these three fundamental aspects, a fourth V has emerged: veracity, which relates to the reliability and quality of the data. The presence of inaccurate or inconsistent data can undermine the effectiveness of analysis, making veracity a critical factor in the implementation of Big Data solutions. To ensure that analyses yield meaningful results, organizations must invest in data cleaning and validation processes, ensuring that the data used are both representative and accurate [14].

Technologies associated with Big Data have evolved significantly in recent years, offering new tools and capabilities to manage the complexity and diversity of data. Platforms such as Hadoop and Spark enable the distributed processing of large data volumes, using computer clusters to divide and process tasks simultaneously. These frameworks allow for the storage and processing of data within a scalable and cost-effective infrastructure, making Big Data management accessible to businesses of various sizes. Moreover, the use of NoSQL databases has gained prominence, as these systems are designed to handle large volumes of unstructured or semi-structured data, providing greater flexibility in managing and querying data [14].

However, Big Data analysis is not limited to the processing and storage of large quantities of data. The true value of Big Data lies in its ability to perform advanced analytics, which can range from descriptive analysis (identifying patterns and trends in historical data) to predictive analysis (using statistical models and machine learning algorithms to forecast future behaviors). Prescriptive analytics can go further, suggesting specific actions based on the results obtained, offering organizations a proactive approach to managing their resources and operations [15].

The application of Big Data has been extensively explored across various industrial sectors, such as manufacturing, healthcare, finance, marketing, and logistics. In the industrial context, the use of Big Data has enabled the implementation of predictive maintenance, where data analysis from sensors and equipment helps predict failures before they occur, minimizing costs and downtime. In supply chain management, the analysis of large data volumes can optimize delivery routes, predict demand, and improve operational efficiency. Furthermore, Big Data have been instrumental in personalizing customer experiences, analyzing purchasing behavior, and enhancing real-time marketing strategies [15].

In conjunction with Industry 4.0, Big Data have become a key driver of digital transformation within organizations, fostering innovation and competitiveness. The combination of Big Data with other technologies, such as artificial intelligence (AI) and robotics, enables the creation of intelligent systems that can learn and adapt, automating decisions and optimizing processes in real time. In particular, Big Data analytics platforms, integrated with RPA and the Internet of Things (IoT), have the potential to profoundly transform industrial operations, creating a continuous cycle of monitoring, analysis, and improvement.

However, the use of Big Data is not without challenges. Issues related to data privacy and security are increasingly pertinent, particularly with the growing volume of sensitive data being generated. The implementation of data protection policies, in accordance with regulations such as the General Data Protection Regulation (GDPR), is essential to ensure that organizations use information ethically and legally. Furthermore, interoperability between different systems and data sources remains a challenge, as data may be distributed across various platforms and in incompatible formats [16].

In summary, Big Data represent an unprecedented opportunity for organizations, enabling them to extract valuable insights and make more informed and efficient decisions. However, its successful implementation requires adequate infrastructure, the use of appropriate technologies, and a strategic approach that considers not only technical capabilities but also the ethical and legal aspects associated with the management and analysis of large volumes of data. The potential of Big Data to transform the way organizations operate is vast, and its integration with other emerging technologies, such as artificial intelligence and RPA, promises to drive innovation and competitiveness in the years to come.

2.4. Robotic Process Automation (RPA)

Robotic Process Automation (RPA) refers to the use of software to automate repetitive and rule-based tasks that typically require human intervention. RPA is primarily applied in business processes that involve data manipulation and the execution of sequential operations, such as form filling, querying information systems, transaction processing, and other routine activities. The main objective of RPA is to enhance efficiency as well as reduce errors and operational costs while freeing up employees to engage in higher-value tasks. This technology has gained prominence due to its ability to automate tasks in business environments swiftly and with minimal impact on existing infrastructure [17].

RPA employs "robots" or software "bots" to simulate human interaction with system interfaces, performing actions such as clicking, typing, or copying and pasting information between applications. These bots can be programmed to carry out tasks autonomously based on predefined rules and processing algorithms. The major advantage of RPA over other forms of automation lies in its ability to operate directly on user interfaces without the need for deep integration with underlying systems. This allows organizations to implement automation solutions at relatively low costs and without the need to restructure or replace existing systems [18].

RPA can be classified into different levels, depending on the complexity and intelligence involved. At the most basic level, automation relies on scripts and predefined rules to carry out well-defined and repetitive tasks. This type of automation is known as "non-intelligent" or "rule-based" RPA. At a more advanced level, RPA solutions can be combined with technologies such as artificial intelligence (AI) and machine learning (ML), creating what is referred to as intelligent RPA. Intelligent RPA allows for the automation of more complex tasks, such as decision making based on unstructured data or the interpretation of text, images, and even voice. By integrating RPA with AI, organizations can achieve a higher level of cognitive automation, where bots are capable of learning and adapting to new situations, making processes more flexible and dynamic [19].

The application of RPA across various sectors has demonstrated substantial benefits. In the financial sector, for instance, RPA has been used to automate banking reconciliation processes, manage accounts payable and receivable, and monitor suspicious transactions. In healthcare, RPA has been employed to streamline appointment scheduling, invoice processing, and patient data management. In human resources, RPA can automate administrative tasks such as processing job applications, onboarding new employees, and calculating payroll. The application of RPA in these and other sectors has led to significant reductions in operational costs, fewer human errors, and improvements in the speed and accuracy of processes [19].

One of the key advantages of RPA is its ability to scale rapidly. As the demand for automation increases, organizations can easily add more bots to handle the increased workload without the need for significant expansion of human resources. This scalability is particularly useful in scenarios involving seasonal work peaks or high volumes of transactions, such as during fiscal periods or major sales campaigns. Thus, the implementation of RPA can contribute to greater operational flexibility, enabling businesses to respond quickly to changes in market conditions and customer needs [20].

However, the adoption of RPA also faces challenges. The primary barrier to implementing RPA in many organizations is resistance to change and the lack of a corporate culture oriented toward innovation. Additionally, integrating RPA with legacy systems can be complex, as it is often necessary to ensure that bots can effectively operate on older systems not designed to work with automation. Another significant issue pertains to the security and governance of RPA. Since bots operate based on predefined rules and have access to sensitive systems, it is crucial to implement stringent controls to ensure that automated operations are conducted securely and in compliance with organizational policies and legal regulations, such as those related to data protection [21].

In terms of its impact on human work, RPA may lead to the reconfiguration of roles within organizations. While the automation of processes may result in the elimination of repetitive, low-value tasks, it can also create new job opportunities in areas such as bot management and development, data analysis, and the monitoring of automated processes. The shift from operational functions to more strategic roles can, therefore, contribute to the development of employee skills and increase overall productivity [21].

In the context of Industry 4.0, RPA plays a pivotal role in creating smarter, more connected factories and workplaces, where processes are not only automated but also continuously monitored and optimized based on real-time data. When combined with other emerging technologies such as Big Data and the IoT, RPA can help create more efficient and resilient production systems that are capable of autonomously adapting to new conditions and challenges. This integration between RPA and other Industry 4.0 technologies opens up new possibilities for the digital transformation of industrial operations, elevating levels of efficiency and flexibility [21].

In conclusion, RPA emerges as one of the most promising technologies in today's business landscape, enabling a significant transformation in the way organizations manage and execute their processes. While its implementation presents challenges, the benefits associated with automating repetitive tasks and improving productivity make RPA an essential tool in the journey toward intelligent industry and operational efficiency. The continued evolution of RPA, particularly with the integration of AI and machine learning, promises to further expand its potential, creating increasingly sophisticated solutions that are adaptable to market needs.

2.5. Sustainability

Sustainability has increasingly been recognized as a fundamental concept for the long-term development of societies, organizations, and global economies. It refers to the ability to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Practically speaking, sustainability involves a balance between three main dimensions: social, economic, and environmental, which are often referred to as the three pillars of sustainability. The integration of these pillars has gained prominence in recent years, particularly in the context of Industry 4.0, where companies seek to innovate and optimize their processes while minimizing negative impacts on people, the economy, and the planet [22].

The social pillar of sustainability relates to an organization's commitment to promoting social well-being, social justice, and equity. This pillar highlights the importance of working conditions, social inclusion, diversity, human rights, and the impact of business activities on communities. Corporate social responsibility (CSR) is one of the concepts that fall under this pillar, aiming to ensure that organizations not only seek to maximize profits but also consider the social implications of their actions by fostering a safe and fair working environment, investing in professional training and development, and respecting workers' rights. In the context of Industry 4.0, the social pillar of sustainability also requires reflection on the impact of automation and digitalization on employment and working conditions with digital inclusion and professional retraining being essential areas to ensure that technological transformations are accompanied by positive evolution for workers [23].

Economic sustainability is concerned with the ability to generate value in a lasting and profitable manner, ensuring the long-term economic viability of businesses. It goes beyond the simple maximization of short-term profits, incorporating business practices that take into account the long-term impacts of economic decisions, ensuring that economic growth is balanced and does not harm future generations. To be truly sustainable, an organization must integrate the principles of efficiency and resilience into its business models, promoting the responsible management of resources and investing in innovations that enhance productivity without causing harm to society or the environment. In the context of digital transformation and Industry 4.0, the use of technologies such as Big Data and RPA can be viewed as a way to promote economic efficiency, optimizing processes and reducing costs, while ensuring that business practices align with the needs of both the global and local economies [23].

The environmental pillar of sustainability focuses on minimizing the negative impacts of human activities on the environment. This pillar involves adopting practices that promote the conservation of natural resources, reducing pollution, and managing ecosystems sustainably with the goal of ensuring the planet's preservation for future generations. Environmental sustainability includes actions such as reducing greenhouse gas emissions, using energy resources efficiently, and managing waste sustainably. In the industrial context, the circular economy has emerged as a key concept, aiming to create cycles of production and consumption in which materials and products are reused, recycled, and extended in their useful life, thus reducing the need for new natural resources. Technologies associated with Industry 4.0, such as real-time sensing and data monitoring, play a crucial role in managing and minimizing environmental impact, allowing companies to implement more environmentally friendly and efficient solutions, such as sustainable energy usage and the optimization of material consumption [23].

The integration of the three pillars of sustainability within Industry 4.0 represents both one of the greatest challenges and a significant opportunity for innovation in the industrial sector. The use of advanced digital technologies, such as artificial intelligence (AI), Big Data, the Internet of Things (IoT), and RPA, enables the creation of smarter, more efficient, and sustainable industrial systems that optimize production, reduce waste, and minimize environmental impact. For example, predictive maintenance, which uses sensors and data analysis to anticipate machine failures before they occur, not only improves operational efficiency but also contributes to reducing resource waste and the production of waste [24,25].

However, while Industry 4.0 technologies provide powerful tools for achieving sustainability, their implementation requires a concerted effort to ensure that companies focus not only on economic efficiency or technological innovation but also on the social and environmental impact of their operations. The responsible use of emerging technologies requires careful consideration of the effects these may have on local communities, social inclusion, and environmental protection [25].

Digital transformation and the increase in automation, often associated with Industry 4.0, may pose significant challenges to sustainability, particularly with respect to social disparities and environmental impact. Growing automation can lead to job losses, especially in sectors that rely on manual labor, and may exacerbate social inequalities unless public policies and companies invest in strategies for professional retraining and digital inclusion. At the same time, the shift to a more sustainable production model involves investments in clean technologies and production processes that minimize environmental impact, which can represent an additional cost for businesses, especially in the early stages of implementation [26].

Nevertheless, these challenges can be overcome through a strong commitment to corporate social responsibility (CSR) and long-term sustainability, where companies adopt a strategic approach that integrates technological innovation and digitalization with practices that promote social equity, environmental responsibility, and economic viability. Investment in the research and development of sustainable solutions, as well as fostering public–private partnerships, can help overcome initial barriers and transform challenges into opportunities for sustainable growth [26].

In conclusion, sustainability, through the integration of its three pillars—social, economic, and environmental—into business strategy, emerges as a key factor for the long-term success of organizations in the era of Industry 4.0. The development of innovative solutions that combine advanced technology with sustainable practices offers a pathway to a more balanced and resilient future, benefiting both businesses and society as well as the planet.

3. Methodology

3.1. Method

The methodology adopted for this study is based on the use of the PICO approach (Population, Intervention, Comparison, Outcome), which has proven to be an essential tool in scientific research due to its ability to organize and structure complex questions in a clear and systematic manner [27]. When applied rigorously, the PICO methodology allows for a detailed and objective analysis of the key elements of a study, avoiding the subjective biases often present in other approaches, such as narrative reviews. The application of the PICO methodology extends beyond fields such as healthcare and medicine, having demonstrated its relevance in areas like software engineering, automation processes, and agile development, as evidenced by recent studies. It facilitates the formulation of precise questions and the selection of relevant studies, ensuring that data are analyzed in a consistent and comparable way [27].

In this work, the PICO methodology will be applied to structure the analysis of the integration of Robotic Process Automation (RPA) and Big Data technologies within a sustainable framework with the aim of optimizing processes in the context of Industry 4.0. The adaptation of this methodology to the context of industrial process automation and the use of Big Data offers a systematic approach to understanding how the combination of these technologies impacts operational efficiency and promotes sustainable practices throughout the lifecycle of industrial operations [28].

The “population” in this study refers to industrial organizations that are in the process of adopting RPA and Big Data technologies, integrating sustainable practices within the context of Industry 4.0. The precise definition of this population is crucial to ensure that the results are relevant and applicable to organizations facing similar challenges related to process optimization, industrial automation, and the management of large-scale data. The analysis will focus on companies implementing advanced digital solutions to improve operational efficiency and ensure sustainability in their operations.

The “intervention” in this study involves the implementation of an innovative framework that combines RPA and Big Data technologies with sustainable practices, which were aimed at optimizing industrial processes while promoting both operational efficiency and corporate sustainability. This intervention is based on increasing evidence that the integration of these technologies can not only enhance process automation efficiency but also significantly contribute to reducing the economic, environmental, and social impacts of industrial operations, promoting a long-term sustainable approach.

The “comparison” will be made between traditional industrial processes, where activities are carried out manually, and processes optimized through the application of the framework proposed in this study, which integrates RPA and Big Data technologies. This analysis will allow for the assessment of differences in operational efficiencies before and after the implementation of the framework, considering gains in terms of reduced execution times, reduced operational errors, and greater sustainability in operations. The comparison aims to identify improvements in efficiency and the advantages observed after the framework’s implementation.

The expected “outcome” of this study is to demonstrate that the integration of RPA and Big Data within a framework can significantly increase operational efficiency in industrial processes, promoting process optimization while contributing to more sustainable business practices. The application of the PICO methodology will allow for the formulation of solid hypotheses and a well-founded analysis, based on concrete data, that validates the effectiveness of the approach within the context of Industry 4.0.

The central research question guiding this study is as follows:

Central Research Question (CRQ)

CRQ: How can Robotic Process Automation (RPA) and Big Data technologies be integrated into a sustainable framework for process optimization in the context of Industry 4.0, maximizing operational efficiency while promoting sustainable practices?

This question seeks to understand the interaction between RPA and Big Data technologies, identifying how they can be combined within a framework that not only promotes operational efficiency but also contributes to sustainability in the industrial context, considering the challenges of Industry 4.0.

Based on the central research question, the following research hypotheses have been formulated:

Hypotheses (H)

H1: *The integration of Big Data with RPA within a framework can significantly increase efficiency in the optimization of industrial processes, reducing execution times and operational errors.*

H2: *A framework that combines RPA, Big Data, and sustainable practices in the context of Industry 4.0 contributes to the corporate sustainability of industrial operations, promoting a reduction in economic and environmental impact as well as an increase in social responsibility.*

The PICO methodology will be rigorously applied to the selection of relevant studies and articles for this work. Data analysis will be structured to ensure that the formulated hypotheses are tested and validated through reliable scientific sources with a focus on emerging technologies in the industrial sector. Source selection will be made based on a detailed bibliographic review, taking into account peer-reviewed articles, publications from 2010 to 2025, and full-text accessibility.

By applying PICO, a clear and objective path will be outlined for the analysis of the integration of RPA and Big Data technologies, focusing on how they can be applied to promote greater operational efficiency while minimizing economic, environmental, and social impacts. This process will not only validate the research hypotheses but also provide an in-depth understanding of how Industry 4.0 can be more sustainable without compromising its competitiveness and innovation.

To answer the main research question of this study, the researchers used the online scientific library made available by the Foundation for Science and Technology, focusing on four specific groups (Group 1, Group 2, Group 3 and Group 4), as detailed in Table 1.

Table 1. Groups searched through "B-on".

Group 1	Group 2	Group 3	Group 4
"RPA" OR "Robotic Process Automation" OR "Intelligent Process Automation" OR "Digital Process Automation" OR "Business Workflow Automation"	"Big Data" OR "Data Analytics" OR "Hadoop" OR "Data Science" OR "Data Visualization"	"Industry 4.0" OR "Industrial Automation" OR "Smart Manufacturing" OR "Cyber-Physical Systems" OR "Connected Factory" OR "Industrial Digitalization" OR "Advanced Manufacturing"	"Sustainability" OR "Environmental Sustainability" OR "Economic Sustainability" OR "Social Sustainability" OR "Corporate Social Responsibility" OR "Circular Economy" OR "Sustainable Development"

The research was carried out through the "B-on" platform, using the OR operator to link the Title, Keywords (KWs) or Abstract (AB) within the three established groups. Filters were then applied to the database of publications collected during the search process, and the results, regarding the total number of publications, are detailed in Table 2.

Table 2. Publications obtained through B-on, after the application of some filters.

	Set 1	Set 2	Set 3
Initial result:	173	13	7
1—Restrict to Peer-Reviewed	61	8	3
2—From 2010 to 2025	61	8	3
3—Language: English	28	7	3
4—Restrict to Full Text	28	6	3

After applying the filters, the titles, keywords and abstracts of each article were reviewed again to select those most relevant to the research topic. Initially, 193 articles were recovered. After applying the filters, 37 remained, of which only 16 were directly related to the focus of the study.

Figure 1 presents a flowchart illustrating the literature search process and screening procedure followed in this study.

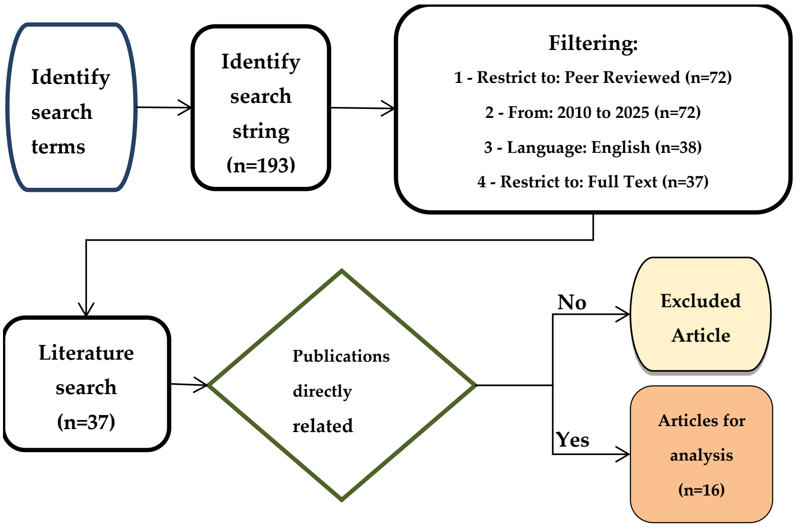

Figure 1. Flow diagram of literature search and respective screening [8].

3.2. Analysis and Synthesis of Articles

This section provides a detailed overview and analysis of the most relevant articles to the topic under investigation. Table 3, presented below, displays the 16 selected articles along with the models analyzed in each one. The table was designed to categorize the contributions of each study and was carefully developed after in-depth research in academic databases.

Table 3. Identified articles and the respective themes of the articles found.

Themes of the Articles / Articles	RPA	Big Data	Sustainability	Industry 4.0	Type
[29]	x			x	Case Study
[30]	x			x	Case Study
[31]	x		x		Model
[32]	x			x	Literature Review
[33]	x		x		Case Study
[34]	x			x	Case Study
[35]	x	x			Case Study
[36]	x			x	Literature Review
[37]	x				Model
[38]	x			x	Case Study
[39]			x	x	Case Study
[40]			x	x	Review Literature
[41]	x	x			Case Study
[42]	x	x			Case Study
[43]		x		x	Case Study
[44]		x	x	x	Case Study
% Themes p/articles	75%	31%	31%	63%	

3.3. Summary of Results

In this section, the results of the articles reviewed in the previous section are synthessized, highlighting the main contributions, common themes, and potential gaps in the lit-erasure. The analysis of the articles presented in Table 3 provides a clear view of the contributions to key areas such as Robotic Process Automation (RPA), Big Data, Sustainability, and Industry 4.0. The table outlines how these themes are addressed across the 16 selected articles and provides an overview of the methodologies employed. Below are the key insights from this analysis:

- RPA (Robotic Process Automation): The majority of articles (75%) focus on Robotic Process Automation, highlighting its prominent role in the research. This indicates a high relevance of RPA in the studies examined.
- Big Data: 31% of the articles discuss Big Data, suggesting that while important, it is less prevalent compared to RPA. Big Data are often associated with the analysis of large datasets, which is a topic critical in numerous industries.
- Sustainability: Similar to Big Data, sustainability is addressed in 31% of the articles. This suggests that while it is a growing area of interest, it is not the central theme in most of the studies.
- Industry 4.0: 63% of the articles include Industry 4.0, demonstrating its significance and substantial presence in the research. Industry 4.0 refers to the integration of advanced technologies in production processes, such as automation, IoT (Internet of Things), and artificial intelligence.
- Case Study: The majority of the articles (approximately 75%) employ case studies, indicating a focus on practical, real-world investigations. This suggests an applied empirical approach to the analysis of the topics under consideration.
- Model: A smaller proportion of articles (31%) use analytical models, reflecting an emphasis on theoretical frameworks and simulations to understand the dynamics of the themes.
- Literature Review: A few publications (18%) adopt literature reviews, which are useful for summarizing and evaluating the existing body of knowledge on the topics explored.
- Focus on RPA and Industry 4.0: Robotic Process Automation (RPA) and Industry 4.0 dominate the themes with the majority of articles dedicated to these aspects. This reflects the growing interest and relevance of these topics in the current research and technological development landscape.
- Less Emphasis on Big Data and Sustainability: While Big Data and sustainability are important, they are less frequently addressed in the selected articles, suggesting that these areas are explored in a more limited scope compared to RPA and Industry 4.0.
- Predominance of Case Studies: The most common methodology in the publications is the case study, reinforcing the practical and applied nature of the research. This suggests that researchers are focused on demonstrating real-world results and solutions to contemporary challenges.
- Theoretical Models and Literature Reviews: Although less common, analytical models and literature reviews remain significant, contributing to the conceptual and theoretical understanding of the themes.

In summary, the analysis of this table reveals that current research is primarily centered around automation and industry-related themes with a focus on applied studies, while Big Data and sustainability are explored to a more limited extent.

4. Framework (S-PROBIO)

4.1. Proposal for a Framework (S-PROBIO)

The S-PROBIO (Sustainability–Process Optimization–Big Data Integration with Automation) is an innovative framework created to integrate Robotic Process Automation (RPA) and Big Data technologies within the context of Industry 4.0 with the aim of optimizing processes and promoting sustainable practices across the three pillars of sustainability: environmental, social, and economic.

The proposal for this framework arises from the need to adapt industrial operations to digital transformation, seeking operational efficiency while incorporating social, environmental, and economic responsibility. The combination of RPA and Big Data offers the opportunity to automate processes, enhance data analysis, and simultaneously implement sustainable practices effectively. Below, the structure and criteria for validating the functionality of each phase of the S-PROBIO framework are presented (Figure 2).

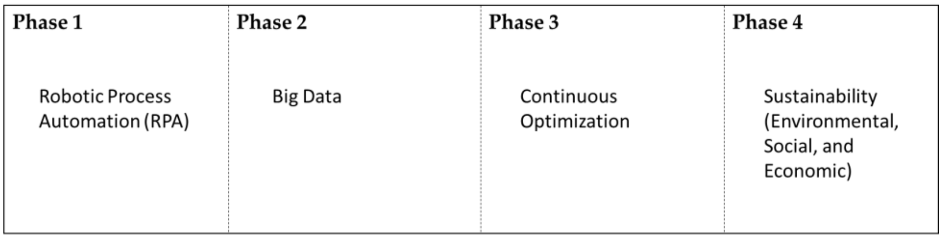

Figure 2. Framework (S-PROBIO).

The S-PROBIO framework consists of four main components that interrelate to achieve the objectives of process optimization and sustainability. The following outlines the components and phases of the framework, including the validation criteria for each phase (Table 4).

Table 4. Framework (S-PROBIO) phases.

Framework (S-PROBIO) Phases
1. Robotic Process Automation (RPA)
2. Big Data Integration
3. Continuous Optimization
4. Sustainability (Environmental, Social, and Economic)

1. Robotic Process Automation (RPA)

RPA is the first fundamental phase of the framework in which repetitive and manual processes are automated. Through the integration of digital robots, operational tasks that require time and human effort are carried out swiftly and efficiently, enabling significant gains in both efficiency and accuracy (Table 5).

Table 5. Validation criteria (RPA).

Validation Criteria (RPA)
Reduction in operational errors
Reduction in execution time
Elimination of repetitive tasks
Increase in accuracy and consistency
Employee feedback

Validation Criteria (RPA):

- Reduction in operational errors: Automation should reduce or eliminate human errors in processes.
- Reduction in execution time: The execution times of automated processes should be significantly shorter compared to manual processes.
- Elimination of repetitive tasks: Automation should replace tasks that do not add value to the operation and are repetitive.
- Increase in accuracy and consistency: Automation should ensure that process outcomes are consistent and accurate.
- Employee feedback: Employees should be consulted to verify if automation contributes to improved working conditions, allowing them to focus on more strategic tasks.

2 Big Data Integration

The integration of Big Data within the S-PROBIO framework is crucial for the analysis and optimization of automation processes. Big Data enable the collection and analysis of large volumes of data generated during automated processes, providing insights into process behavior and identifying areas for optimization (Table 6).

Table 6. Validation criteria (Big Data).

Validation Criteria (Big Data)
Quality of data analysis
Accuracy in failure prediction
Data-driven decision-making
Efficiency in data collection and storage
Application of results

We used the following validation criteria for (Big Data):

- Quality of data analysis: The data analysis should provide relevant and accurate insights for process optimization.
- Accuracy in failure prediction: Big Data should be capable of predicting failures and inconsistencies in processes before they occur.
- Data-driven decision making: Operational decisions should be based on the analyses conducted from the data.
- Efficiency in data collection and storage: Big Data integration should be efficient in terms of collecting, processing, and storing large volumes of data.
- Application of results: Big Data integration should be able to generate insights that lead to concrete actions for continuous process optimization.

3 Continuous Optimization

Continuous optimization is a vital component to ensure that automated processes are constantly evaluated and improved. This component involves the ongoing monitoring of processes and data analysis to identify opportunities for enhancement (Table 7).

Validation Criteria (Continuous Optimization):

- Efficiency in detecting inefficiencies: The system should be able to identify areas with low efficiency and suggest improvements.
- Continuous improvement of processes: The implementation of suggested improvements should result in a progressive enhancement of processes.
- Real-time performance measurement: The system should allow for real-time analysis of how adjustments and improvements affect process performance.

- Cost and time reduction: The continuous optimization process should be able to reduce operational costs and execution times.

Table 7. Validation criteria (continuous optimization).

Validation Criteria (Continuous Optimization)
Efficiency in detecting inefficiencies
Continuous improvement of processes
Real-time performance measurement
Cost and time reduction

4 Sustainability (Environmental, Social, and Economic)

Sustainability is the central pillar of the S-PROBIO framework, ensuring that automated processes not only lead to operational benefits but also promote responsible practices in environmental, social, and economic terms (Table 8).

Table 8. Validation criteria sustainability.

Validation Criteria Sustainability	
Environmental Sustainability	Reduction in energy consumption
	Reduction in paper usage
	Waste reduction
Social Sustainability	Improvement in employee wellbeing
	Increase in productivity
Economic Sustainability	Reduction in operational costs
	Return on Investment (ROI)
	Increase in competitiveness

Validation Criteria Sustainability:

- Environmental Sustainability:
    - Reduction in energy consumption: Automation should reduce energy usage either by optimizing performance or decreasing equipment operation times.
    - Reduction in paper usage: The transition from manual to digital processes should result in a significant decrease in paper and other material consumption.
    - Waste reduction: Automation and Big Data usage should contribute to waste and resource reduction, improving resource management.
- Social Sustainability:
    - Improvement in employee well-being: Automation should allow employees to focus on higher-value tasks, improving job satisfaction and well-being.
    - Increase in productivity: The reduction in repetitive tasks should lead to an increase in productivity and employee satisfaction.
- Economic Sustainability:
    - Reduction in operational costs: Automation should result in cost savings, particularly in terms of reducing errors and shortening execution times.
    - Return on Investment (ROI): The framework should allow for the analysis and assessment of ROI with the expectation that implementation costs will be quickly recovered through generated improvements.

   - Increase in competitiveness: The integration of RPA and Big Data should result in more efficient processes, contributing to a long-term competitive advantage.

The implementation of the S-PROBIO framework involves a series of sequential phases each with specific criteria for validating its functionality. The following outlines the implementation steps along with the criteria for evaluating their success (Table 9):

Table 9. Criteria for evaluating their success.

Criteria for Evaluating Their Success
1. Planning and Initial Assessment
2. Automation and Big Data Implementation
3. Monitoring and Adjustments
4. Sustainability Measurement

1. Planning and Initial Assessment: This phase involves a detailed survey of manual and repetitive processes that can be automated. An evaluation will be conducted on the optimization potential through the integration of RPA and Big Data, considering environmental, social, and economic criteria.
   - Validation Criteria: Identification of processes to automate, analysis of potential automation impact, and definition of sustainability objectives.
2. Automation and Big Data Implementation: RPA will be implemented in identified processes along with the integration of Big Data solutions for real-time data collection and analysis.
   - Validation Criteria: Validation of automation impact on execution time, error reduction, and process quality improvement.
3. Monitoring and Adjustments: During and after implementation, the continuous monitoring of processes will be performed, using Big Data to adjust and improve the automation systems.
   - Validation Criteria: Constant feedback from teams and stakeholders, performance and efficiency analysis, identification of areas for continuous improvement.
4. Sustainability Measurement: After implementation, the environmental, social, and economic impacts of automation will be measured using defined KPIs.
   - Validation Criteria: Reduction in operational costs, execution times, and waste; improvement in employee well-being and positive ROI.

The S-PROBIO framework effectively integrates RPA and Big Data, providing process optimization and the promotion of sustainable practices. By following the phases and validation criteria presented, organizations can achieve higher levels of efficiency, sustainability, and profitability, contributing to the evolution of operations within the context of Industry 4.0.

4.2. Characteristics and Benefits of the Framework (S-PROBIO)

The S-PROBIO framework emerges as an innovative solution for integrating Robotic Process Automation (RPA) and Big Data technologies within the context of Industry 4.0 with the aim of optimizing industrial processes and promoting sustainable practices across the environmental, social, and economic pillars. The following presents the key characteristics and benefits derived from the implementation of this framework.

The S-PROBIO framework is characterized by its holistic and multidisciplinary approach, integrating advanced technologies to achieve effective and sustainable process optimization. Its main features include the following:

1. Integration of Emerging Technologies: The framework combines intelligent automation provided by RPA with the analysis and prediction capabilities of Big Data, enabling the optimization not only of individual processes but of the entire production chain. This integration provides enhanced visibility and more efficient data management, which are both crucial for real-time strategic decision making.
2. Emphasis on Sustainability: S-PROBIO is designed to facilitate sustainable practices, incorporating all three pillars of sustainability—environmental, social, and economic—into each phase of the automation and data analysis process. The integrated technologies enable the reduction in environmental impact (e.g., through lower energy consumption and reduced paper usage), improve employees' quality of life, and enhance the economic efficiency of the organization.
3. Process Optimization: The framework focuses on the continuous optimization of processes, enabling operations to be evaluated and adjusted over time. The integration of Big Data provides detailed analysis of each process phase, enabling rapid and precise adjustments that increase operational efficiency.
4. Focus on Operational Efficiency: Through the implementation of RPA, the framework facilitates the automation of repetitive and low-value tasks, allowing human resources to be redirected toward more strategic activities. Additionally, the integration of Big Data contributes to the reduction in errors, execution times, and operational costs.
5. Adaptation to Industry 4.0: S-PROBIO is designed to align with the principles of Industry 4.0, integrating automation and data analysis technologies in such a way as to optimize smart industry practices. This allows companies to be prepared for future challenges, maximizing the efficiency and flexibility of their operations.

The adoption of the S-PROBIO framework provides a range of benefits that directly impact operational efficiency, sustainability, and profitability for organizations. Among the main benefits, the following stand out:

1. Improvement in Operational Efficiency: Process automation through RPA leads to a significant reduction in task execution times, boosting productivity and minimizing the risk of human errors. This benefit is enhanced by the use of Big Data, which offers a detailed view of processes and facilitates the identification of continuous improvement opportunities.
2. Environmental Sustainability: The application of the framework contributes to reducing the organization's environmental impact. Automation enables a decrease in paper usage, a reduction in energy consumption, and a minimization of waste, as data analysis can optimize resource usage and promote more efficient practices. These aspects not only contribute to the company's environmental responsibility but may also result in cost reductions associated with the use of natural resources.
3. Improvement in Working Conditions: The use of RPA eliminates repetitive and low-value tasks, leading to an enhanced quality of life for employees. By allowing workers to focus on more strategic and creative activities, the framework contributes to employee motivation and well-being while optimizing the utilization of their skills.
4. Economic Benefits: The implementation of the S-PROBIO framework leads to a reduction in operational costs, particularly in areas such as resource management, failure reduction, and execution time. Process optimization and the predictive analysis capabilities of Big Data also contribute to improved economic efficiency, thus enhancing the organization's profitability. The return on investment (ROI) analysis highlights

the economic benefits of adopting the framework, demonstrating how cost reductions and efficiency improvements support the company's financial sustainability.

5. Increased Competitiveness: The implementation of the framework enables companies to gain a competitive advantage by being faster and more accurate in executing their operations. The use of Big Data and RPA allows for more informed and agile decision making, optimizing operational flexibility and the capacity to adapt to market changes.
6. Continuous Monitoring and Adjustment Capability: The use of Big Data within the framework enables the real-time monitoring of processes, providing valuable data for continuous adjustments. Through data analysis, companies can quickly identify inefficiencies, failures, or areas for improvement, allowing proactive adjustments that result in the ongoing evolution of processes.
7. Simplified Adoption of Advanced Technologies: S-PROBIO facilitates the implementation and adoption of emerging technologies such as robotic automation and Big Data analytics in industrial environments. Through a structured approach adapted to the context of Industry 4.0, organizations can benefit from technological innovation in an incremental and effective manner.

S-PROBIO represents an innovative framework that integrates RPA and Big Data technologies with the aim of optimizing industrial processes while promoting sustainable practices. Its features, such as technological integration, a focus on sustainability, and operational efficiency, offer a holistic approach to addressing the challenges of Industry 4.0. Furthermore, the benefits resulting from its implementation, ranging from cost reduction to improvements in working conditions and sustainability, make this framework a strategic solution for organizations seeking continuous and sustainable progress in their performance.

5. Case Study

5.1. Case Study Presentation

The case study presented in this article refers to the implementation of the S-PROBIO framework within an industrial sector organization with a particular focus on the administrative department. This department plays a critical role in managing administrative processes such as document management, invoice approvals, and financial report processing. The case study presented in this article focuses on the administrative department of an organization in the industrial sector. This department plays a fundamental role in managing internal processes related to business administration, being responsible for essential activities such as document management, the validation and approval of invoices, financial processing and the generation of accounting reports. These functions are crucial to ensuring the company's operational integrity, ensuring that financial processes are carried out accurately, in accordance with legal requirements and aligned with organizational goals. Before applying the S-PROBIO framework, the department faced significant challenges, such as a high manual workload, high rate of human errors, low process efficiency and difficulty in tracking financial data. These limitations impacted not only internal performance but also the agility in strategic decision making. The department was chosen to implement S-PROBIO due to its strategic importance and the clear need for digital transformation, becoming a representative example of the benefits that the integration of RPA and Big Data technologies can offer in complex administrative processes. Prior to the integration of Robotic Process Automation (RPA) and Big Data technologies, these processes were carried out manually, resulting in significant time consumption, a high error rate, and a lack of transparency in operations. The following outlines the manual process, the need for RPA and Big Data integration, and the justification for the development of a structured framework, such as S-PROBIO, to optimize and sustain this process.

The process under review involves the management of invoices and financial documents in the administrative department. The manual workflow entailed several stages, such as receiving and verifying invoices, validating tax information, entering data into financial systems, and tracking payments. Each of these stages required human intervention, which resulted in several limitations:

1. Invoice Receipt and Processing: Invoices were received physically or via email and were manually checked by an operator, who compared the invoice details with purchase or service records.
2. Validation and Approval: After verification, the operator cross-checked tax information and values, subsequently uploading the data into the ERP (Enterprise Resource Planning) system. The invoice approval process involved multiple validation stages, which led to considerable delays and relied on the availability of various parties involved.
3. Data Entry and Archiving: Data entry into the systems was performed manually with operators transcribing invoice information into the accounting system. Additionally, there was the physical and digital archiving of invoices, which is a task that, despite its importance, was prone to errors such as document duplication or indexing mistakes.
4. Tracking and Reporting: After data entry and processing, payment tracking was completed via manual reports, which made it difficult to analyze accounts payable and track the progress of financial transactions in real time.

This manual process led to several limitations, including long execution times, frequent human errors, a lack of agility in decision making, and difficulty in data traceability and analysis. Furthermore, the heavy use of paper and the need for both physical and digital archiving of invoices had a significant environmental impact and resulted in high operational costs.

Given the context of the described manual process, the organization identified a clear need to transform the workflow to make processes faster, more accurate, and more efficient. The integration of RPA and Big Data was seen as the ideal solution to address the challenges of the process, including the following:

1. RPA (Robotic Process Automation): The use of RPA allowed for the automation of repetitive and low-value tasks such as extracting data from invoices, entering these data into financial systems, and sending them for validation and approval. Automating these stages not only eliminated human error but also sped up the execution time, enabling faster and more efficient invoice processing.
2. Big Data: The use of Big Data introduced a new layer of intelligence to the process. The analysis of large volumes of financial data enabled the organization to conduct predictive analysis on payments and cash flow, improving decision making and risk management. Additionally, Big Data facilitated the identification of invoice patterns, highlighting potential anomalies or inconsistencies, which contributed to better tax compliance.
3. Sustainability: The use of RPA and Big Data also offered the organization an opportunity to adopt more sustainable practices, such as reducing paper usage and decreasing energy consumption associated with document storage and processing. Digital automation allowed the organization to eliminate manual tasks, improving energy efficiency and reducing the environmental impact.

The need to develop a structured framework, such as S-PROBIO, to integrate RPA and Big Data technologies into the administrative process arose due to the complexity of the scenario and the multiple benefits expected from its implementation. The integration of these two technologies required a systematic approach that not only optimized the process but also ensured its sustainability across environmental, social, and economic dimensions.

1. Environmental Sustainability: The reduction in paper usage and energy consumption were directly supported by automation. The S-PROBIO framework enabled the elimination of physical and manual processes, contributing to the organization's environmental sustainability.
2. Social Sustainability: Automation through RPA freed employees from repetitive and low-value tasks, allowing them to focus on more impactful strategic activities, such as financial data analysis or process improvement. Furthermore, the increased accuracy and speed of processes enhanced employees' quality of life by reducing workload and boosting job satisfaction.
3. Economic Sustainability: RPA and Big Data led to significant reductions in operational costs, improved cash flow, and increased return on investment (ROI). Process automation and predictive analysis provided financial efficiency, optimizing processing costs and increasing the organization's profitability.

The combination of RPA and Big Data was pivotal in transforming an inefficient manual process into an agile, effective, and sustainable one, while the S-PROBIO framework ensured that the implementation of these technologies was aligned with the organization's objectives of optimization and sustainability. The structure of S-PROBIO provided a robust approach to managing the integration of the technologies, addressing the complexities involved and ensuring that all benefits were realized across the relevant sustainability dimensions.

5.2. Application of the Framework to the Case Study

The application of the S-PROBIO framework to the case study developed for the automation of the administrative process of managing invoices and financial documents within the company was a critical step in validating the effectiveness of the integration between Robotic Process Automation (RPA) and Big Data in the context of Industry 4.0. The implementation of the framework aimed to optimize the process, improving operational efficiency and promoting sustainable practices in line with the three pillars of sustainability: environmental, social, and economic.

The implementation was divided into several phases, in accordance with the S-PROBIO framework, which integrates automation processes and data analysis. Each phase was structured to address a specific aspect of the administrative process and ensure that the technologies were applied effectively and sustainably.

1. Phase 1: Mapping the Current Process and Identifying Improvement Points

The first stage of the implementation involved mapping the manual administrative process of invoice management, as it was carried out before the integration of the technologies. Through a detailed analysis of the process stages, critical points in terms of execution time, human error, and environmental impact were identified. From this analysis, it became evident that the process was inefficient and unsustainable, as it relied on multiple manual interventions, consumed large amounts of resources (paper, energy), and had a high risk of data validation errors.

Criteria for validation:

- Total execution time of the process before automation.
- Number of operational errors and failures in invoice processing.
- Consumption of physical resources (paper) and energy in the manual process.

2 Phase 2: Implementation of Robotic Process Automation (RPA)

Based on the process mapping, the first intervention of the framework was developed, which involved the implementation of RPA to automate repetitive, low-value tasks. RPA technology was applied to the stages of data extraction from invoices, entering information into ERP systems, validating tax data, and forwarding invoices for approval. This automation not only reduced execution times but also eliminated human errors that frequently occurred during manual data transcription.

RPA was implemented gradually, initially in a limited set of processes, to validate the effectiveness of the solution. The automation allowed invoices to be processed more quickly, error-free, and without the need for human intervention in repetitive stages.

The following criteria were used for validation:

- Reduction in execution time for automated processes.
- Elimination of human errors in automated tasks.
- Increased capacity for processing invoices without additional staff.

3 Phase 3: Integration of Big Data for Predictive Analysis and Process Management

The second technology integrated into the process was Big Data, which were used to aggregate, analyze, and generate valuable insights from the large volumes of financial data generated by the invoice management process. Big Data were employed to conduct predictive analysis on cash flow, forecast potential payment delays, and identify patterns in invoices that could indicate anomalies or fraud. Moreover, Big Data enabled the creation of real-time dashboards, facilitating the monitoring of invoice status and payment progress.

The implementation of Big Data brought significant improvements in decision making, as the organization gained a clearer view of the financial impact of invoices and the behavior of accounts payable. The integration of financial data with other business data sources also contributed to better risk management and optimization of cash flow.

The following criteria were used for validation:

- Accuracy of predictive analysis related to cash flow and payments.
- Identification of anomalies and fraud through Big Data analysis.
- Effectiveness of dashboards in visualizing and controlling invoices and payments.

4 Phase 4: Evaluation of Results and Sustainability

The final phase of the S-PROBIO framework application involved evaluating the results obtained from the integration of the technologies. The evaluation was conducted from the perspective of the three pillars of sustainability: environmental, social, and economic.

1. Environmental Sustainability: Automation and data analysis significantly contributed to reducing paper and energy usage. The digitalization of processes, combined with the elimination of the need for physical storage of invoices, resulted in a substantial reduction in environmental impact. A comparison of paper and energy consumption before and after automation revealed a considerable reduction in these resources.
   Criteria for validation:
   - Quantification of reductions in paper and energy consumption.
   - Analysis of the environmental footprint of the process before and after automation.
2. Social Sustainability: The implementation of RPA allowed administrative department employees to focus on more strategically valuable tasks, such as financial data analysis and the development of management reports. The automation of repetitive tasks improved the work environment, as employees engaged in more challenging, impactful activities, which contributed to higher job satisfaction and reduced stress associated with monotonous tasks.

The following criteria were used for validation:

- Improvement in employee satisfaction and well-being.
- Reduction in time spent on repetitive tasks.
- Increased motivation and productivity at work.

3. Economic Sustainability: The combination of RPA and Big Data led to a significant reduction in operational costs, such as a decrease in errors and a faster processing time for invoices. The economic impact was also measured through the return on investment (ROI), which demonstrated that in the short term, the organization had recouped its initial costs associated with automation and data analysis. Additionally, the use of these technologies contributed to improved profitability, optimization of cash flow, and greater efficiency in financial processes.
The following criteria were used for validation:
    - Calculation of ROI following the implementation of the technologies.
    - Reduction in operational costs.
    - Increased profitability and improved cash flow.

The application of the S-PROBIO framework to the administrative invoice management process proved highly effective in optimizing the process, improving operational efficiency, and promoting sustainable practices. The combination of RPA and Big Data not only allowed for the automation of repetitive stages but also enhanced financial data analysis, resulting in a positive impact on the three dimensions of sustainability. The implementation of the framework provided the organization with greater agility, cost reductions, a lower environmental impact, and better utilization of human resources, demonstrating the effectiveness of this approach in the context of Industry 4.0.

6. Results Analysis and Discussion

6.1. Results Analysis

The implementation of the S-PROBIO framework, which integrated Robotic Process Automation (RPA) and Big Data technologies into the administrative process of managing invoices and financial documents, resulted in significant improvements across various metrics. These improvements were evaluated based on the time required for each task, the reduction in errors, resource consumption, and the overall financial impact.

The Table 10 summarizes the key metrics before and after the implementation of RPA and Big Data, providing a clear comparison of the improvements achieved:

- Execution Time Reduction: The integration of RPA enabled the processing time for each invoice to be significantly reduced from 240 min to just 30 min. This dramatic reduction in time enabled the company to handle a larger volume of invoices with the same number of employees; see Figure 3.
- Elimination of Human Errors: By automating tasks such as data entry and validation, RPA eliminated human errors, which were previously a common issue. This contributed to greater accuracy in invoice processing, reducing errors to zero.
- Resource Consumption: The adoption of digital processes resulted in significant reductions in paper and energy consumption. Paper usage was reduced by 80%, and energy consumption decreased by the same percentage, contributing to environmental sustainability; see Figure 4.
- Invoice Processing Capacity: The automated system greatly enhanced the organization’s capacity to process invoices. The monthly capacity increased from 100 invoices to 1000 invoices, which is a tenfold increase in processing power; see Figure 5.
- Cost Reduction: The reduction in human errors, paper usage, and time spent on manual tasks led to a significant decrease in operational costs, which fell by 55%. This

cost reduction, combined with improved processing efficiency, resulted in a positive ROI within just six months.

- Employee Satisfaction: Automation allowed employees to shift their focus from repetitive tasks to more value-added activities such as data analysis and process improvement. As a result, employee satisfaction improved by 50% with staff reporting less stress and higher motivation.
- Cash Flow Prediction: The integration of Big Data allowed the organization to enhance its ability to predict cash flow, improving accuracy from 65% to 90%. This was crucial for optimizing financial management and ensuring timely payments; see Figure 6.

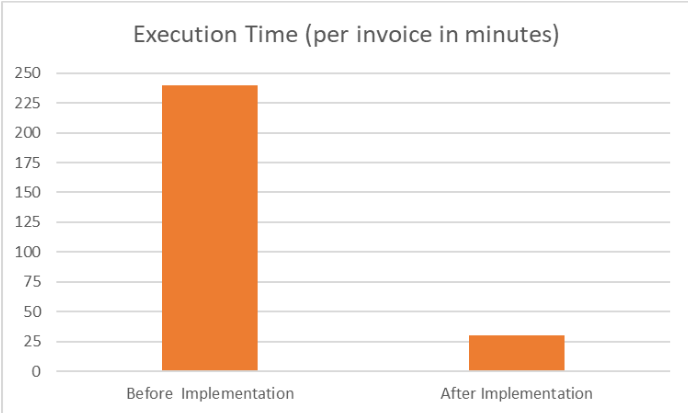

Figure 3. Execution time (per invoice in minutes).

Table 10. Comparison of metrics before and after implementing the Framework.

Metric	Before Implementation	After Implementation	Improvement
Execution Time (per invoice)	240 min	30 min	87.5% reduction
Human Errors (per 100 invoices)	15 errors	0 errors	100% reduction
Paper Consumption (per month)	1000 sheets	200 sheets	80% reduction
Energy Consumption (per month)	500 kWh	100 kWh	80% reduction
Invoice Processing Capacity	100 invoices/month	1000 invoices/month	900% increase
Operational Costs (per month)	$10,000	$4500	55% reduction
ROI (Return on Investment)	N/A	120% (6-month period)	Positive ROI
Employee Satisfaction (Survey)	60% satisfaction rate	90% satisfaction rate	50% improvement
Time Spent on Repetitive Tasks (per month)	120 h	30 h	75% reduction
Cash Flow Prediction Accuracy	65% accuracy	90% accuracy	25% improvement

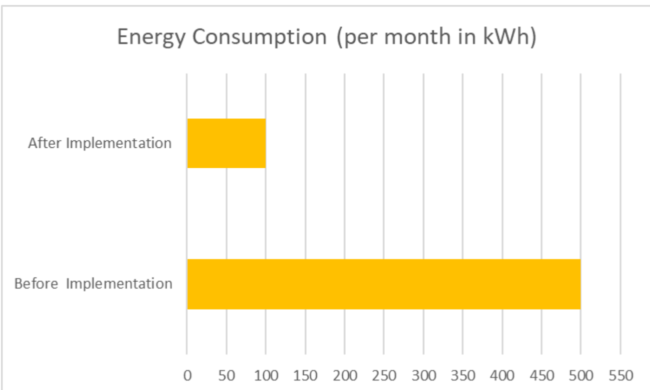

Figure 4. Energy consumption (per month in kWh).

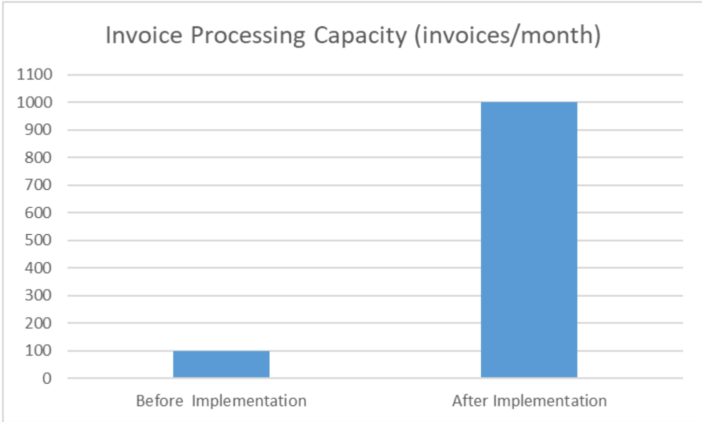

Figure 5. Invoice processing capacity (invoices/month).

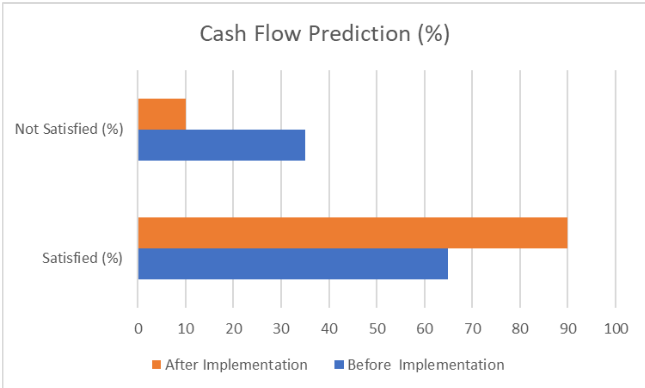

Figure 6. Cash flow prediction (%).

6.2. Discussion

The results from the application of the S-PROBIO framework demonstrate a clear and successful transformation of the administrative invoice management process. Several key observations can be made from these outcomes:

- Operational Efficiency: The most notable benefit of the implementation of RPA and Big Data is the significant improvement in operational efficiency. The reduction in execution time, errors, and operational costs highlights how the integration of automation and data analytics can revolutionize traditional, manual business processes. By eliminating the bottlenecks caused by human intervention and speeding up repetitive tasks, the organization achieved a level of operational efficiency that would have been impossible with manual processing alone.
- Environmental Impact: The reduction in paper and energy consumption underscores the important role of digital technologies in promoting environmental sustainability. With less reliance on physical documents and storage, the organization made substantial strides in reducing its environmental footprint, aligning with broader sustainability goals. These reductions are particularly important in industries that still rely heavily on paper for their operations, demonstrating that digital transformation can contribute to long-term environmental benefits.
- Social Implications: The shift from manual to automated processes had a profound impact on employee satisfaction and well-being. By eliminating repetitive and low-value tasks, employees were able to focus on higher-level activities that required more cognitive input, such as data analysis and financial reporting. This change not only led to improved job satisfaction but also had the potential to increase employee retention

and motivation. In addition, by streamlining the process, employees experienced less stress, which contributed to a healthier work environment.

- Economic Sustainability: The reduction in operational costs, combined with the positive ROI, illustrates how technology can drive financial sustainability. The cost savings from fewer human errors, reduced paper consumption, and improved process speed contributed directly to a healthier bottom line. Furthermore, the ability to process more invoices with fewer resources allowed the organization to scale without incurring additional costs. The increased predictive accuracy in cash flow management, enabled by Big Data, also helped the company make more informed financial decisions, ensuring better liquidity and profitability.
- Scalability and Agility: The results also show that the technologies implemented are highly scalable and capable of supporting future growth. The organization's ability to process invoices at a tenfold increase while maintaining accuracy and efficiency demonstrates that the system can easily adapt to higher volumes of work without requiring proportional increases in staff. This scalability is crucial in a rapidly evolving business landscape where organizations must remain agile to stay competitive.
- Predictive Analytics: Big Data's integration into the invoice processing workflow proved instrumental in enhancing decision-making processes. By providing real-time visions into cash flow, payment patterns, and potential fraud risks, Big Data not only optimized operational efficiency but also provided a strategic advantage in managing financial risks. The predictive analysis capabilities further allowed the organization to stay ahead of cash flow issues, reducing the likelihood of late payments and improving vendor relationships.

In conclusion, the case study demonstrates the significant benefits of integrating RPA and Big Data into the administrative processes of invoice management. By automating repetitive tasks and leveraging data-driven insights, the organization achieved greater efficiency, sustainability, and financial success. These outcomes highlight the potential of Industry 4.0 technologies to transform business processes and contribute to the long-term sustainability and profitability of organizations.

7. Conclusions

This study focused on the integration of Robotic Process Automation (RPA) and Big Data technologies within a sustainable framework for process optimization in the context of Industry 4.0. The analysis and implementation of the framework aimed not only to increase operational efficiency but also to promote sustainable practices across economic, social, and environmental dimensions. Through the implementation of this framework, the interaction between these emerging technologies was explored, demonstrating the benefits of their combination in industrial processes.

The primary conclusion drawn from this research is that the integration of RPA and Big Data within a sustainable framework can have a significant impact on industrial process optimization, enhancing operational efficiency and promoting sustainability. The automation of repetitive tasks using RPA and the predictive data analysis capabilities of Big Data were found to considerably reduce execution times, minimize operational errors, and improve decision making. Furthermore, the integration of these technologies contributed to the reduction in environmental impacts, such as lower paper usage and energy consumption, and enhanced social responsibility, as employees were able to focus on more strategic and value-added tasks.

The following benefits were identified:

- Operational Efficiency: The application of RPA enabled the automation of repetitive tasks, speeding up processes and reducing human errors. Big Data provided a more accurate analysis of operations, helping to identify patterns and predict behaviors.
- Sustainability: The use of RPA and Big Data contributed to reducing environmental impact by decreasing the need for physical document storage and lowering energy consumption. From a social perspective, automation liberated employees from monotonous tasks, improving their job satisfaction and productivity. Economically, the framework led to lower operational costs and improved cash flow.

The central research question of this study, "How can Robotic Process Automation (RPA) and Big Data technologies be integrated into a sustainable framework for process optimization in the context of Industry 4.0, maximizing operational efficiency while promoting sustainable practices?" was answered affirmatively. The combination of these technologies not only improved industrial process efficiency but also fostered sustainability within the organization. The developed framework proved effective in integrating the technologies, achieving a balance between process optimization and corporate responsibility. After analyzing the data presented in Table 10 and Figures 3–6, it is possible to clearly and objectively observe the significant improvements achieved after implementing the S-PROBIO framework. These results confirm the effectiveness of the integration of RPA and Big Data technologies, supporting the conclusion that the adoption of the framework brought tangible benefits both in terms of operational efficiency and in terms of sustainability. The detailed analysis of the numbers and graphs fully justifies the implementation of S-PROBIO, highlighting its positive impact on the organization's operations.

The hypotheses formulated at the outset of the study were validated through the practical implementation of the framework. Hypothesis H1, which proposed that the integration of Big Data with RPA could significantly increase efficiency in industrial process optimization, was substantiated with reductions in execution times and operational errors observed. Hypothesis H2, which suggested that a framework combining RPA, Big Data, and sustainable practices would contribute to corporate sustainability, was also confirmed, as there was a notable reduction in economic and environmental impacts and an improvement in social responsibility.

The PICO methodology was successfully applied in this study, providing a structured and objective approach to data analysis. The systematic approach formed a solid foundation for the formulation of hypotheses, the selection of relevant studies, and the application of the framework. The implementation of the framework, which combined RPA, Big Data, and sustainable practices, proved effective in optimizing processes and fostering sustainability, as evidenced by the results obtained during the evaluation phase.

While the results of the framework implementation are promising, this study does have some limitations. The analysis was carried out within a single case study, which may limit the generalizability of the findings to other organizations or industries. Additionally, the adoption of RPA and Big Data may be challenging for companies with financial constraints or insufficient technological infrastructure. It is also worth considering that although automation had a positive impact on human labor in this study, it could potentially generate resistance in companies that are unprepared for such a transition.

Future research could expand the application of the framework to different industrial sectors to evaluate its effectiveness in more diverse contexts. Conducting a longitudinal study would provide a deeper understanding of the long-term benefits of integrating RPA and Big Data particularly in terms of sustainability. Furthermore, it would be valuable to explore the social impact of automation in greater detail, assessing its implications for employment and professional training within the context of Industry 4.0.

This work also opens avenues for the development of new frameworks and solutions that combine emerging technologies with sustainable practices. The continuous evolution of RPA and Big Data technologies requires the ongoing adaptation of the proposed frameworks to ensure they not only optimize processes but also promote a more responsible and environmentally conscious industry.

In conclusion, this study contributes to the understanding of how the integration of RPA and Big Data can be leveraged to achieve both sustainability and process optimization in Industry 4.0, offering a practical and innovative approach that can serve as a reference for future implementations across different industrial contexts.

Author Contributions: In this paper, a proposal for a framework for integrating robotic process automation and big data to optimize processes in the evolution of Industry 4.0, with a focus on sustainability, was proposed and presented by L.P., L.V. and Z.S. The main investigation, encompassing the development and implementation of the framework, was conducted by L.P.; the problem discussion, evaluation of the topic's significance, literature review, and manuscript preparation were collaboratively undertaken by L.P., L.V. and Z.S. The overall supervision of this work was provided by L.V. and Z.S., while project administration and funding acquisition were coordinated by L.V. All authors have read and agreed to the published version of the manuscript.

Funding: The project was merged by FCT—Foundation for Science and Technology through the 1354 scope of the R&D units project: UIDB/00319/2020.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Oláh, J.; Aburumman, N.; Popp, J.; Khan, M.; Haddad, H.; Kitukutha, N. Impact of Industry 4.0 on Environmental Sustainability. *Sustainability* **2020**, *12*, 4674. [CrossRef]
2. Singh, S.; El-Kassar, A. Role of Big Data Analytics in Developing Sustainable Capabilities. *J. Clean. Prod.* **2019**, *213*, 1264–1273. [CrossRef]
3. Gholami, H.; Lee, J.K.Y.; Ali, A. Big Data Analytics for Sustainable Products: A State-of-the-Art Review and Analysis. *Sustainability* **2023**, *15*, 12758. [CrossRef]
4. Venigandla, K.; Vemuri, N.; Aneke, E. Empowering Smart Cities with AI and RPA: Strategies for Intelligent Urban Management and Sustainable Development. *Int. J. Sci. Res. Manag. (IJSRM)* **2024**, *12*, 1117–1125. [CrossRef]
5. Chukasova-Ilyushkina, E. Approaches to Analysis and Optimization of Business Processes of an Industrial Enterprise. *Vestn. Polotsk State Univ. Part D Econ. Leg. Sci.* **2024**, 50–53. [CrossRef]
6. Shysh, A.; Kovtun, I.; Sheveria, Y. Business Information Management and Innovative Approaches to Business Process Optimization. *Bus. Inform.* **2023**. [CrossRef]
7. Yoqubjonov, J.; Gibadullin, R.; Nuriev, M. Advanced Robotic Process Automation for Enterprise Efficiency. *E3S Web Conf.* **2023**, *431*, 07011. [CrossRef]
8. Patrício, L.; Varela, L.; Silveira, Z. Integration of Artificial Intelligence and Robotic Process Automation: Literature Review and Proposal for a Sustainable Model. *Appl. Sci.* **2024**, *14*, 9648. [CrossRef]
9. Bonilla, S.; Silva, H.; Da Silva, M.; Gonçalves, R.; Sacomano, J. Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges. *Sustainability* **2018**, *10*, 3740. [CrossRef]
10. Autor, D. Industry 4.0 and Its Impact on Indian Economy. *EPRA Int. J. Res. Dev. (IJRD)* **2022**, *7*, 51–54. [CrossRef]
11. Jamwal, A.; Agrawal, R.; Sharma, M.; Giallanza, A. Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions. *Appl. Sci.* **2021**, *11*, 5725. [CrossRef]
12. Amjad, M.; Rafique, M.; Khan, M. Leveraging Optimized and Cleaner Production through Industry 4.0. Sustain. *Prod. Consum.* **2021**, *26*, 859–871. [CrossRef]
13. Shu, H. Big Data Analytics: Six Techniques. *Geo-Spatial Inf. Sci.* **2016**, *19*, 119–128. [CrossRef]
14. Wu, X.; Zhu, X.; Wu, G.; Ding, W. Data Mining with Big Data. *IEEE Trans. Knowl. Data Eng.* **2016**, *26*, 97–107. [CrossRef]

15. Prajapati, A.; Gupta, A.; Mishra, S.; Raj, D.; Singh, M.; Goyal, M. An Exploration on Big Data Analytical Techniques: A Review. In Proceedings of the 2024 11th International Conference on Computing for Sustainable Global Development (INDIACom), New Delhi, India, 28 February–1 March 2024; pp. 123–128. [CrossRef]
16. Mahmud, M.; Huang, J.; Salloum, S.; Emara, T.; Sadatdiynov, K. A Survey of Data Partitioning and Sampling Methods to Support Big Data Analysis. *Big Data Min. Anal.* **2020**, *3*, 85–101. [CrossRef]
17. Patrício, L.; Varela, L.; Silveira, Z. Proposal for a Sustainable Model for Integrating Robotic Process Automation and Machine Learning in Failure Prediction and Operational Efficiency in Predictive Maintenance. *Appl. Sci.* **2025**, *15*, 854. [CrossRef]
18. Patrício, L.; Costa, L.; Varela, L.; Ávila, P. Sustainable Implementation of Robotic Process Automation Based on a Multi-Objective Mathematical Model. *Sustainability* **2023**, *15*, 15045. [CrossRef]
19. Patrício, L.F.S.; de Sousa Costa, C.R.; Fernandes, L.P.; Varela, M.L.R. Structure for the Implementation and Control of Robotic Process Automation Projects. In *Advanced Network Technologies and Intelligent Computing. ANTIC 2022. Communications in Computer and Information Science*; Woungang, I., Dhurandher, S.K., Pattanaik, K.K., Verma, A., Verma, P., Eds.; Springer: Cham, Switzerland, 2023; Volume 1798. [CrossRef]
20. Patrício, L.; Ávila, P.; Varela, L.; Cruz-Cunha, M.M.; Ferreira, L.P.; Bastos, J.; Castro, H.; Silva, J. Literature Review of Decision Models for the Sustainable Implementation of Robotic Process Automation. *Procedia Comput. Sci.* **2023**, *219*, 870–878. [CrossRef]
21. Sousa Costa, C.R.; Patrício, L.F.S.; Varela, M.L.R.; Ferreira, P.V. The Contribution of Robotic Process Automation (RPA) in Improving Energy Efficiency: Case Study. In *Proceedings of the Eighth International Congress on Information and Communication Technology. ICICT 2023; Lecture Notes in Networks and Systems*; Yang, X.S., Sherratt, R.S., Dey, N., Joshi, A., Eds.; Springer: Singapore, 2024; Volume 695. [CrossRef]
22. Varela, L.; Araujo, A.; Ávila, P.; Castro, H.; Putnik, G. Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability. *Sustainability* **2019**, *11*, 1439. [CrossRef]
23. Naderi, M.; Ares, E.; Peláez, G.; Prieto, D.; Araújo, M. Sustainable Operations Management for Industry 4.0 and Its Social Return. *IFAC-PapersOnLine* **2019**, *52*, 457–462. [CrossRef]
24. Barata, J.; Silva, F.; Almeida, M. Ceramic Industry 4.0. Res. Anthol. Cross-Ind. Chall. Ind. 4.0. 2019. Available online: https://www.igi-global.com/gateway/chapter/210488 (accessed on 10 February 2025).
25. Hojnik, J.; Biloslavo, R.; Cicero, L.; Cagnina, M. Sustainability Indicators for the Yachting Industry: Empirical Conceptualization. *J. Clean. Prod.* **2020**, *249*, 119368. [CrossRef]
26. Ramísio, P.; Pinto, L.; Gouveia, N.; Costa, H.; Arezes, D. Sustainability Strategy in Higher Education Institutions: Lessons Learned from a Nine-Year Case Study. *J. Clean. Prod.* **2019**, *222*, 300–309. [CrossRef]
27. Cumpston, M.S.; McKenzie, J.E.; Thomas, J.; Brennan, S.E. The Use of 'PICO for Synthesis' and Methods for Synthesis Without Meta-Analysis: Protocol for a Survey of Current Practice in Systematic Reviews of Health Interventions. *F1000Research* **2021**, *9*, 678. [CrossRef] [PubMed]
28. Nishikawa-Pacher, A. Research Questions with PICO: A Universal Mnemonic. *Publications* **2022**, *10*, 21. [CrossRef]
29. Badmus, A. Implementing Technology Manufacturing with Robotics Process Automation (RPA). *J. Knowl. Learn. Sci. Technol.* **2023**, *2*, 103. [CrossRef]
30. Karn, S.; Kotecha, R. RPA-based Implementation of IoT. *SSRN Electron. J.* **2021**. [CrossRef]
31. Daase, C.; Pandey, A.; Staegemann, D.; Turowski, K. Sustainability in Robotic Process Automation: Proposing a Universal Implementation Model. In *Automation and Robotics—Volume 1: ICINCO, Proceedings of the 20th International Conference on Informatics in Control, Rome, Italy, 13–15 November 2023*; SciTePress: Setúbal, Portugal, 2023; pp. 770–779. Available online: https://www.scitepress.org/Link.aspx?doi=10.5220/0012260200003543 (accessed on 10 February 2025).
32. Ribeiro, J.; Lima, R.; Eckhardt, T.; Paiva, S. Robotic Process Automation and Artificial Intelligence in Industry 4.0—A Literature Review. *Procedia Comput. Sci.* **2020**, *181*, 51–58. [CrossRef]
33. Alshehri, A.; Aljarbou, M.; Elaraki, Y.; Alsehaimi, A. Evaluating Robotic Process Automation (RPA) Technology for Human-Centric and Future-Oriented Automated Tracking and Adherence to Sustainable Regulations in Construction. *Nanotechnology Perceptions* **2024**, *20*, 430–449. [CrossRef]
34. Joseph, O. Sustainable Banking through Robotic Process Automation: What Role does ESG and Cognitive AI Play? *J. Digitovation Inf. Syst.* **2023**, *3*, 116–140. [CrossRef]
35. Malini, G. Automation of Big Data Analytics Using Robotic Process Automation. *Int. J. Sci. Res. Comput. Sci. Eng. Inf. Technol.* **2021**, *7*, 602–605. [CrossRef]
36. Pramod, D. Robotic Process Automation for Industry: Adoption Status, Benefits, Challenges, and Research Agenda. *Benchmarking Int. J.* **2021**, *29*, 1562–1586. [CrossRef]
37. Quille, R.; Almeida, F.; Borycz, J.; Corrêa, P.; Filgueiras, L.; Machicao, J.; Almeida, G.; Midorikawa, E.; Demuner, V.; Bedoya, J.; et al. Performance Analysis Method for Robotic Process Automation. *Sustainability* **2023**, *15*, 3702. [CrossRef]
38. Ciufudean, C. Industry 4.0's Product Development Process Aided by Robotic Process Automation. *Robot. Autom. Eng. J.* **2018**, *3*, 555614. [CrossRef]

39. Mahariya, S.; Kumar, A.; Singh, R.; Gehlot, A.; Akram, S.; Twala, B.; Iqbal, M.; Priyadarshi, N. Smart Campus 4.0: Digitalization of University Campus with Assimilation of Industry 4.0 for Innovation and Sustainability. *J. Adv. Res. Appl. Sci. Eng. Technol.* **2023**, *32*, 120–138. [CrossRef]
40. Ejsmont, K.; Gładysz, B.; Kluczek, A. Impact of Industry 4.0 on Sustainability—Bibliometric Literature Review. *Sustainability* **2020**, *12*, 5650. [CrossRef]
41. Wei, Q. Task Allocation of Financial Robots Based on RPA and Big Data Algorithms. In Proceedings of the 2024 Third International Conference on Distributed Computing and Electrical Circuits and Electronics (ICDCECE), Ballari, India, 26–27 April 2024; pp. 1–5. [CrossRef]
42. Sobczak, A. Robotic Process Automation as a Digital Transformation Tool for Increasing Organizational Resilience in Polish Enterprises. *Sustainability* **2022**, *14*, 1333. [CrossRef]
43. Zheng, S. Research on the Transformation of Digital Intelligence of Accounting Profession Based on Big Data Technology. *Appl. Math. Nonlinear Sci.* **2024**, *9*. [CrossRef]
44. Raut, R.; Mangla, S.; Narwane, V.; Gardas, B.; Priyadarshinee, P.; Narkhede, B. Linking Big Data Analytics and Operational Sustainability Practices for Sustainable Business Management. *J. Clean. Prod.* **2019**, *224*, 10–24. [CrossRef]