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LOGISTICS 5.0 MATURITY MODEL: A HUMAN-CENTRIC AND SUSTAINABLE APPROACH FOR THE SUPPLY CHAIN OF THE FUTURE

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ABSTRACT

Logistics 5.0 represents a transformative advancement by integrating advanced technologies such as artificial intelligence, machine learning and blockchain with a human-centric and sustainability-focused approach. Unlike Logistics 4.0, which prioritized automation and digitalization, the new approach emphasizes collaboration between humans and machines to create more efficient and resilient supply chains. Maturity models specific to this emerging phase are crucial to assess technological readiness, human-machine integration capabilities and commitment to sustainable practices. The application of technologies such as autonomous vehicles, predictive algorithms and collaborative robots optimize processes, reduce errors and minimize environmental impacts, aligning with global sustainability goals. In addition, green logistics practices, such as the use of renewable energy and the circular economy, are essential to reduce companies' carbon footprint. However, the transition to Logistics 5.0 faces significant challenges, including the need for investment in infrastructure, employee training and overcoming cultural barriers. Yet companies that adopt this approach not only increase their competitiveness, but also contribute to a more sustainable and resilient economy, positioning themselves ahead in a dynamic, innovation-driven global market.

I. INTRODUCTION

Technological evolution, marked by the transition from Industry 4.0 to Industry 5.0, has promoted significant changes in the logistics sector. While Industry 4.0 focused on the automation and digitalization of processes through the Internet of Things (IoT), robotics, and artificial intelligence (AI), Logistics 5.0 introduces a more humanized approach, emphasizing collaboration between humans and machines to create more efficient and personalized processes [1].

eIn this context, [2] state that Logistics 5.0 emerges as a response to the needs of an increasingly dynamic and demanding market, promoting a deeper integration between human and technological capabilities.

Among the innovations arising from Logistics 5.0, advanced technologies such as blockchain, big data, and AI (or blockchain, big data, respectively) stand out to improve the transparency, efficiency, and sustainability of logistics operations. This new phase not only aims to improve the speed and accuracy of deliveries, but also seeks to reduce environmental impact and increase the resilience of the supply chain, especially in sectors such as electronics, where flexibility and responsiveness are essential [3]. Thus, the introduction of these technologies allows organizations to anticipate demands, optimize resources and improve customer service, creating a more efficient and adaptable value chain.

According to [4] indicate that the transition to Logistics 5.0 also brings considerable challenges, especially in terms of measuring maturity and adopting new technologies. One example pointed out by the author is that existing maturity models developed for Logistics 4.0 may not fully capture the specific nuances and needs of Logistics 5.0, such as the need for human-machine collaboration and the focus on sustainable practices.

In this sense, therefore, it is essential to develop new maturity models that can manage industries in assessing their readiness to adopt these advanced technologies and implement smarter and more sustainable logistics practices.

II. THEORETICAL REFERENCE

II.1 IMPACTS OF LOGISTICS 4.0 ON LOGISTICS 5.0

Logistics 5.0 represents a significant advance over previous approaches, integrating advanced technology with a strong emphasis on sustainability and human centrality. According to [5] explain that, unlike Logistics 4.0, which focused predominantly on the automation and digitalization of industrial processes, Logistics 5.0 places humans at the center of technological transformation, promoting a more harmonious collaboration between humans and machines. This type of approach is interpreted as a response to criticism that Logistics 4.0, by prioritizing efficiency and automation, has neglected important aspects of sustainability and human well-being. Therefore, [6] define that human centrality in Logistics 5.0 is facilitated by emerging technologies such as cyber-physical systems, collaborative artificial intelligence, and intelligent robots, which work in synergy with human operators to improve productivity and reduce physical workload. This integration of humans and machines not only increases operational efficiency, but can also improve safety and job satisfaction, creating a more inclusive and safe work environment.

It is also worth noting that sustainability is another fundamental pillar of Logistics 5.0. According to [7] explain in their study that the concept of green logistics is integrated into logistics processes to minimize environmental impact and promote more responsible business practices. Another study according to [8] also highlighted that the adoption of sustainable technologies, such as electric vehicles and the use of renewable energy in logistics operations, can significantly reduce the carbon footprint of companies and increase their long-term resilience [4].

Studying maturity models in Logistics 5.0 can be essential for several reasons, especially as organizations seek to improve their logistics operations in an environment that is becoming increasingly complex and technological Oran and Cezayirlioglu [9]. Therefore, maturity models for logistics 5.0 need to be adaptive and comprehensive, covering the various dimensions of digital and sustainable transformation. Certainly, one of their functions is to assess technological readiness, human-machine integration capacity and commitment to sustainable practices.

Namely, a recent study by [10] proposed a maturity model based on decision support systems that considers initial investments, return on investment, implementation complexity and exploitation as essential criteria for assessing the maturity level of companies in adopting logistics 5.0. This is because the transition to logistics 5.0 requires a well-defined strategic approach that incorporates big data analysis to predict trends and adjust operations in real time, thus increasing the flexibility and responsiveness of the supply chain [4]. To this end, the implementation of collaborative and human-centered practices can promote a more innovative and resilient work environment, capable of facing future challenges and adapting quickly to market changes.

II.2 INTEGRATION OF TECHNOLOGIES AND SUSTAINABILITY

Therefore, the application of advanced technologies in logistics 5.0 is not limited to automation and digitalization. Some tools play the role of a compass to provide greater transparency and security in the supply chain. According to [11] point out that the blockchain can facilitate product tracking and ensure compliance with environmental and safety standards. In addition, artificial intelligence and machine learning algorithms can also enable more effective predictive analysis, helping companies to optimize their logistics operations and reduce waste.

At the same time, other studies by [12] suggest that sustainability and logistics efficiency are greatly benefited by adopting a holistic approach that incorporates green technologies and sustainable practices from the beginning of the logistics planning process. Undoubtedly, one of the motivating factors in the implementation of green warehousing is social responsibility, while one of the biggest barriers was local laws and regulations. Therefore, [13] suggest that top management should be the main initiator of the implementation of green technologies in organizations.

Likewise, reducing waste through green management can improve the living conditions and productivity of employees, by the sustainable and human-centered standards of logistics 5.0. Strategically, [14] also state that the integration of technologies and sustainability not only adds value to the corporate image of companies, but also contributes to the creation of an adaptable logistics ecosystem, capable of responding to global crises and market fluctuations more effectively.According to [15] argue that blockchain is emerging as a disruptive technology in logistics 5.0, as it offers a new layer of transparency and security to supply chain operations. In the same sense, [16] point out that by providing an immutable and verifiable record of all transactions and movements of goods, blockchain helps to increase trust between business partners and reduce fraud and errors.

In the same vein, According to [17] state that blockchain technology enables greater administrative efficiency by eliminating the need for intermediaries and traditional auditing processes. Similarly, this can not only speed up logistics operations, but also reduce operational costs, providing a significant competitive advantage [18]. In this vein, research indicates that the interoperability of blockchain systems with other technologies, such as IoT and AI, can also expand the benefits of logistics 5.0, enabling more comprehensive automation and a faster response to unexpected events in the supply chain. However, for [4], the large-scale implementation of blockchain faces challenges, such as the need to standardize protocols and resistance to change on the part of the parties involved. This integration between possibilities can result in more resilient and adaptable operations, essential characteristics in an increasingly dynamic and unpredictable business environment, mainly adding value to Brazil.

II.3 AI AND MACHINE LEARNING (ML)

The transition to logistics 5.0 involves not only the adoption of new technologies, but also the integration of AI and machine learning (ML) to optimize processes and improve decision-making. For [19], these technologies allow logistics systems to be more responsive and adaptable, analyzing large volumes of data in real time to predict demands, optimize routes and manage inventories more effectively. In this context, maturity models become fundamental, as they help organizations identify their readiness to implement and take advantage of these advanced technologies.

Research by [20] indicates that AI and ML play roles in the transformation of logistics 5.0, providing new capabilities to automate and optimize complex logistics processes. Certainly, these technologies are fundamental to the creation of more intelligent logistics systems, which not only improve efficiency, but also the adaptability and resilience of the supply chain, for example. In the same vein, the application of AI and ML in logistics 5.0 enables a more predictive and data-driven approach,

essential for managing the growing complexity of global supply chains [21]. In this context, logistics 5.0 uses AI to analyze large volumes of data generated throughout the supply chain, helping companies identify patterns and trends that would be impossible to detect manually. For [22], for example, machine learning algorithms can accurately predict future demand based on a variety of factors, such as economic conditions, historical purchasing patterns, and even weather factors.

This predictive capability helps companies optimize their inventories and improve production planning, reducing costs and increasing customer satisfaction [23]. For [24] AI, in addition to enabling the automation of many logistics processes that traditionally required human intervention, its automated systems, such as autonomous vehicles and warehouse robots, are capable of operating 24 hours a day without rest, improving efficiency and reducing human error. For information, these systems are often integrated with AI platforms that continuously monitor their performance and make adjustments in real time to optimize operations [22].

In fact, [23] state that AI also contributes significantly to personalization and flexibility in the supply chain. In a logistics 5.0 environment, intelligent systems can quickly adapt to changes in market demands or disruptions in the supply chain, automatically adjusting production and logistics processes to minimize the impact. For [25], this flexibility is particularly important in a world where volatility and uncertainty are the norm, allowing companies to maintain business continuity amid unforeseen challenges. Another important aspect of the application of AI in logistics 5.0 highlighted by [26] is its ability to improve the sustainability of logistics operations.

Through route optimization and efficient resource management, AI algorithms can reduce fuel consumption and carbon emissions, helping companies meet sustainability goals. For example, AI-based systems can calculate the most efficient route for delivery vehicles in real time, taking into account factors such as traffic, weather, and road conditions, resulting in significant fuel savings and reduced emissions.

In addition, for [27], AI also facilitates the creation of safer and more efficient work environments. In warehouses and distribution centers, for example, AI-based computer vision systems are used to monitor activities and identify potential safety risks, such as obstructions or risky behavior by employees. These systems can automatically alert supervisors or take corrective action to prevent accidents, contributing to a safer work environment [28].

Concurrently, [29] state that machine learning, a subcategory of AI, is particularly useful in analyzing unstructured data such as product images, security camera videos, and customer feedback. Through techniques such as deep learning, companies can extract valuable information from this data to improve their logistics processes and customer experience. In this case, deep learning algorithms can be used to analyze product images to detect damage or inconsistencies before products are shipped to customers, thus reducing returns and improving customer satisfaction [30].

In addition to practical applications, [31] indicate that AI and machine learning also offer opportunities for continued innovation in Logistics 5.0, since by automating data collection and analysis, these technologies allow companies to experiment with new strategies and business models with minimized risk. In this regard, [32] explain that a company can use AI to simulate different supply chain scenarios and identify the most effective model before implementing it on a large scale. In theory, this not only saves time and resources, but also increases the company's agility and responsiveness to market changes.

According to [14] highlight that it is important to note that, although AI and machine learning offer many benefits for logistics 5.0, their successful implementation requires a significant investment in technological infrastructure and human skills. That is, companies must ensure that their employees are properly trained to work with these advanced technologies and that IT infrastructures are sufficiently robust to support the processing of large volumes of data in real time. Furthermore, [33] attest that companies must be prepared to deal with ethical and privacy issues associated with the use of AI, ensuring that customer data is protected and used responsibly. Therefore, it is essential that studying maturity models in logistics 5.0 is essential for the market to seek to evolve its logistics operations in a strategic and effective manner. It is in this sense that in [34] indicate that AI and machine learning in logistics 5.0 are intrinsic to the ways in which these technologies are shaping the future of the supply chain. By adopting these technologies, organizations can not only improve their efficiency and sustainability, but also better position themselves to face the challenges and seize the opportunities of an increasingly dynamic global market.

For [35], the application of these technologies (artificial intelligence (AI) and machine learning for lane detection and steering control in autonomous vehicles) provides greater precision and safety, crucial elements for both the development of autonomous vehicles and for Logistics 5.0.

It is also worth noting that the incorporation of computer vision techniques and high-resolution neural networks, such as HR-Net, mentioned by [35], can be applied in parallel in Logistics 5.0 to optimize processes and increase the resilience of logistics operations. HR-Net, for example, allows capturing details at different scales of resolution, which can be advantageous for real-time monitoring and optimization of complex logistics operations, such as inventory management and vehicle traffic analysis in warehouses. This level of detail improves the ability of neural networks to predict demands and dynamically adjust routes, responding to unexpected changes, such as adverse weather conditions or peaks in demand.

In addition, Logistics 5.0 can benefit from semantic segmentation techniques used for lane detection in autonomous vehicles, applying these methods to identify flows and patterns in supply chains. The ability to accurately segment and analyze logistics flows can reduce waste and optimize the use of resources, aligning with sustainability principles. These AI tools not only increase efficiency but also contribute to the personalization of logistics services, an important feature of Logistics 5.0, which seeks to integrate technological solutions focused on human well-being and sustainability.

Following the same reasoning, [36] state that by applying such technologies in a logistics context, the use of AI and machine learning for route prediction and process optimization is expected to promote a safer and more adaptable operational environment, essential to achieve higher levels of logistics maturity.

Therefore, the implementation of technologies such as HR-Net for segmentation and monitoring tasks can be a strategic differentiator, allowing logistics companies to quickly adapt to changes in the business environment, improving their responsiveness and resilience.

Therefore, the use of advanced AI techniques in logistics solutions can be a powerful tool for achieving higher logistics maturity, helping companies not only remain competitive but also

position themselves as leaders in a market that is increasingly driven by data and operational efficiency.

II.4 MATURITY MEASUREMENT TOOLS

Given the growing focus on sustainability and the adoption of green logistics practices, it is essential for companies to continually assess and monitor their progress on this journey. According to [1] explain that maturity measurement tools are essential in this context, as they allow organizations to identify their current level of adoption of sustainable and technological practices, in addition to providing a clear roadmap for continuous improvement.

By using these tools, organizations can systematically assess their processes and identify opportunities for improvement that not only drive operational efficiency but also strengthen their commitment to sustainability.

Thus, measuring logistics maturity not only helps integrate green practices into day-to-day operations, but also positions companies to become leaders in a market that is increasingly oriented towards environmental and social responsibility. In Logistics 5.0, maturity measurement tools are compasses for assessing companies' progress and readiness to adopt advanced technologies and sustainable practices. According to [37] state that these tools provide a structured framework that helps organizations understand their current level of technological integration, operational efficiency, and sustainability, and identify areas for future improvements. The use of well-defined maturity models is essential to guide digital transformation strategies and ensure that companies are prepared to face the challenges and seize the opportunities of Logistics 5.0 [38].

One of the most widely used maturity measurement tools is the digital maturity model (DMM). For [39], this model assesses a company's digital readiness in several dimensions, including the ability to integrate information and communication technologies (ICTs) into logistics processes, the effectiveness of using big data and analytics to optimize operations, and the ability to adopt artificial intelligence practices for automation and decision-making. Thus, according to [40], the DMM is structured into different levels of maturity, ranging from the initial stage of digitalization to full digital maturity, where the company uses advanced technologies in an integrated and strategic manner.

Another relevant model is the Sustainable Logistics Index (ILS). This index measures the adoption of sustainable practices in a company's supply chain and logistics operations, evaluating factors such as the use of renewable energy, resource consumption efficiency, waste management, and the implementation of green technologies, such as electric vehicles and recyclable packaging. SLI helps companies monitor and improve their environmental performance, ensuring compliance with environmental regulations and meeting the expectations of increasingly sustainability-conscious stakeholders [11].

According to [13] explain that the Industry 5.0 maturity model is a significant emerging tool focused on human-centricity. This model assesses how companies are incorporating aspects of human well-being and human-machine collaboration into their logistics operations. In addition to considering automation and digitalization, the Industry 5.0 maturity model also assesses the impact of these technologies on workers and society at large. This includes analyzing factors such as worker adaptation to new technologies, the impact of automation on employment, and initiatives to ensure safe and inclusive work environments [41].

As companies advance on their Industry 5.0 maturity journey, integrating aspects of human-centricity and human-machine collaboration, it is equally important for organizations to assess their progress against industry standards and competitors [42].

To this end, logistics benchmarking tools can be applied as an essential category in measuring maturity. These instruments allow companies to compare their logistics performance with that of other industry players, providing input to improve their operations and align them with best market practices.

Another essential aspect of logistics 5.0 is predictive simulation, which allows companies to test future scenarios and develop strategies to deal with possible dysfunctions in the supply chain. The goal is to predict challenges before they happen, as suggested by [43], who point out that these techniques use artificial intelligence and machine learning models to anticipate the impact of changes in market conditions, such as variations in demand or supply disruptions. By predicting these changes, companies can proactively adjust their operations, increasing the resilience and agility of the supply chain [44].

Thus, the ability to respond quickly to unforeseen events becomes a competitive advantage in the market in the era of logistics 5.0. Another important tool is the supply chain sustainability assessment (SCSA). According to [45] state that this tool is used to assess the environmental and social impact of the entire supply chain, from the acquisition of raw materials to final delivery to the consumer. The SCSA analyzes energy efficiency, carbon footprint, use of natural resources and waste management at all stages of the supply chain, helping companies identify critical points for improvement and develop strategies to reduce their environmental impact [46].

By considering the environmental and social impact of their operations, companies not only fulfill their sustainability responsibilities, but also identify areas for improvement that can lead to more efficient operations. However, as logistics 5.0 evolves, it is not enough to simply assess the impact; it is important to make decisions based on accurate and real-time data to quickly adapt to changes in the market and operational conditions. In this context, According to [47] share that AI-based decision support tools are becoming increasingly relevant, as they can enable managers to make more informed and effective decisions by using machine learning algorithms to analyze large volumes of data and identify patterns and trends that might not be evident through traditional methods.

In this sense, the integration of AI into decision support tools enables more accurate demand forecasting, optimization of logistics routes, and efficient allocation of resources, promoting operations that are not only sustainable, but also more economical and resilient [48].

In addition to promoting more efficient and sustainable operations, the use of AI in decision support tools highlights the importance of an integrated and collaborative approach in Logistics 5.0. However, for these technologies to reach their full potential, it is essential that all parties involved in the supply chain are aligned and connected.

In this regard, [21] point out that in this context, digital collaboration platforms play a substantial role, facilitating communication and coordination between different decision makers. These platforms not only allow the sharing of real-time information, such as demand forecasts and inventory availability, but also help to build more integrated and resilient supply chains, where collaboration becomes key to achieving common efficiency and sustainability goals [49].

This transparency and connectivity significantly improve supply chain efficiency, enabling rapid responses to market changes and contributing to more resilient and integrated chains [50]. However, for these supply chains to remain efficient and adaptable, it is equally strategic to address the risks that may arise throughout logistics operations. In this context, logistics risk management tools become indispensable. Using predictive models and big data analytics, these tools help identify, assess and mitigate potential risks, such as natural disasters, supplier failures or regulatory changes, ensuring that companies can develop effective contingency plans and reduce the impact of adverse events [51].

II.5 CHALLENGES AND OPPORTUNITIES OF LOGISTICS 5.0

The adoption of Logistics 5.0 brings significant challenges, including the need for substantial investment in technological infrastructure and the training of a skilled workforce to operate and maintain advanced technologies. Furthermore, the transition to more sustainable and human-centered practices requires a cultural shift within organizations, where innovation is seen not only as a means of increasing efficiency, but also as a path towards sustainable and inclusive development [52].

On the other hand, the opportunities offered by Logistics 5.0 are considerable. Companies that adopt this approach can not only improve their operational efficiency, but also strengthen their long-term resilience and their capacity to innovate. The integration of sustainable practices and advanced technologies can result in a significant competitive advantage, particularly in sectors where sustainability and social responsibility are increasingly valued by consumers and regulators [53].

III. MATERIALS AND METHODS

This research aimed to develop a maturity model for Logistics 5.0, based on a human-centered approach, with an emphasis on sustainability and human-technology integration. The methodology adopted included the definition of the universe and sample, the justification for the methods and procedures used, as well as the details of data processing, ensuring rigor and reproducibility.

The transition from Logistics 4.0 to 5.0 presents significant gaps, especially regarding the measurement of maturity in the context of human-machine integration and sustainable practices. Among the limitations faced, the scarcity of robust data on emerging practices and the difficulties of the participating companies in adapting to the research stand out. In addition, restricted access to financial indicators of sustainable impact limited the scope of the economic analyses.

The study universe included companies operating in strategic sectors for Logistics 5.0, such as manufacturing, technology and distribution. The sample consisted of 28 companies, selected based on criteria of sector relevance, economic size and previous experience with Logistics 4.0 technologies. Representativeness was ensured by the diversification of sectors and alignment with the research objectives. Data collection was carried out using a structured questionnaire, based on studies by [10] and [54], adjusted to the Brazilian context. The questions addressed essential dimensions such as automation, sustainable practices and human-machine integration.

Quantitative data, such as operational efficiency and use of emerging technologies, were supplemented with information extracted from reports provided by the companies. The methodological procedures were divided into three main stages: (1) Systematic review of the literature in databases such as Scopus and Web of Science to identify gaps and guide the development of the model; (2) Application of the structured questionnaire digitally via Google Forms, with validation of the responses by Cronbach's Alpha coefficient ($\alpha > 0.8$), ensuring consistency; and (3) Case study in five sample companies, with technical visits for direct observation and interviews with managers, providing an in-depth qualitative analysis.

The technical infrastructure used included statistical analysis software (SPSS 27.0), multicriteria modeling tools (DEMATEL), and videoconferencing platforms for remote interviews. Precise specifications of this equipment ensured the reliability of the data collected.

Data processing involved the development of a practical theoretical basis. The maturity model used equations derived from the DEMATEL methodology to identify causal relationships between maturity dimensions. The algorithm was implemented in Python and validated through sensitivity analysis. Standardized metrics, such as carbon footprint and delivery cycles, were used to ensure robust and comparable analysis.

Data were obtained from audited reports and reliable secondary sources, ensuring integrity. The methodology was carefully designed to be replicable, with sufficient detailing of materials and procedures. This rigor allows the application of the study in other contexts or sectors, contributing significantly to the advancement of Logistics 5.0.

IV. RESULTS AND DISCUSSIONS

The results of this research point to significant contributions to the understanding of Logistics 5.0, highlighting technological advances and practical limitations observed in the transition between logistics phases. The application of the proposed maturity model revealed that, of the 28 companies analyzed, 35% presented an intermediate level of maturity, 50% a basic level, and only 15% reached an advanced stage. These findings highlight the need for greater technological capacity and human-machine integration in the sector.

The companies that achieved the best performance stood out for adopting emerging technologies, such as artificial intelligence for demand forecasting and blockchain for supply chain traceability. In addition, green logistics practices, such as the use of electric vehicles and renewable energy, demonstrated a direct impact on reducing the carbon footprint, contributing to the achievement of environmental goals. However, most organizations still face challenges such as high implementation costs, cultural resistance, and gaps in team training.

The analyses using the DEMATEL methodology identified relevant causal relationships between dimensions of the maturity model, highlighting the central role of human-machine integration as a catalyst for advances in sustainability and operational efficiency. The validation of the algorithm in Python demonstrated accuracy in mapping interdependencies, contributing to the robustness of the model. From the perspective of the discussions, it is observed that Logistics 5.0 requires a balance between automation and human centrality.

Although technologies offer efficiency and agility, the human factor remains essential for adaptability and innovation. In addition, sustainability practices, when incorporated from the logistics planning stage, add both economic and social value to operations. Regarding limitations, the need for standardization of data provided by companies stands out, as well as challenges in measuring direct financial impacts associated with sustainability. Such issues reinforce the importance of future studies that explore

more precise metrics and complementary qualitative methods. Finally, the results obtained in this research provide practical guidelines for companies seeking to align themselves with the principles of Logistics 5.0. It is recommended that training programs be expanded and investments in technological infrastructure be made as fundamental steps for the sector's evolution. In addition, future studies could explore the impact of these practices on global supply chains, consolidating Logistics 5.0 as an essential pillar for more resilient and sustainable operations.

Table 1: Maturity Levels in Logistics 5.0 by company

Maturity Level	Key Characteristics	Percentage of Companies
Basic	Limited automation, low use of AI, little human-machine integration	50%
Intermediate	Moderate use of emerging technologies, early sustainability initiatives	35%
Advanced	High human-machine integration, consolidated sustainable practices, extensive use of AI	15%

Source: Authors, (2025).

Table 1 shows the results of this research, which show that the maturity of Logistics 5.0 in the companies analyzed still presents significant disparities, with the majority positioned at basic or intermediate levels, reflecting the need for greater investment in emerging technologies, team training, and human-machine integration. Organizations that have reached advanced levels have demonstrated that the adoption of sustainable practices, such as green logistics and the use of AI and blockchain, not only improves operational efficiency and resilience, but also contributes to reducing environmental impacts and meeting global sustainability goals. However, challenges such as high costs, cultural resistance, and lack of data standardization persist as barriers to the evolution of the sector.

This study reinforces the importance of well-structured strategies that align technological innovation with sustainability, highlighting human-machine integration as a critical factor in driving transformations in supply chains. It is therefore recommended that companies prioritize training, infrastructure and cultural change initiatives, in addition to fostering strategic partnerships that accelerate the transition to a more advanced, competitive and sustainable Logistics 5.0 model.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Nazaré Toyoda.
Methodology: Nazaré Toyoda.
Investigation: Nazaré Toyoda.
Discussion of results: Nazaré Toyoda.
Writing – Original Draft: Nazaré Toyoda.
Writing – Review and Editing: Nazaré Toyoda.
Supervision: Nazaré Toyoda.
Approval of the final text: Nazaré Toyoda.

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