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Article

Edge Intelligence in Enhancing Last-Mile Delivery Logistics

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Abstract: *Background:* The last-mile delivery phase, the final stage where goods move from a distribution center to customers, is pivotal but faces significant inefficiencies and high costs due to its complexity. Recent advancements in Edge AI or Edge Intelligence (EI) offer promising solutions to these challenges. *Methods:* This study explores how AI-driven technologies and real-time data processing, combined with EI, can enhance last-mile delivery operations. A thorough literature review was conducted to assess technological advancements and a Delphi method was used to systematically and empirically assess the impact of EI solutions on both operational efficiency and customer satisfaction. *Results:* Although EI technologies offer substantial benefits, EU companies are hesitant to adopt these innovations due to high implementation costs. However, firms that have embraced these technologies report significant improvements, including better route optimization, reduced delivery times, and enhanced service reliability. These findings highlight the need for a culture of innovation and the recruitment of experts with advanced qualifications to drive technological advancement in last-mile logistics. *Conclusions:* The integration of EI represents a significant step towards more efficient, cost-effective, and customer-focused last-mile delivery solutions. Future research should aim to refine these technologies and explore their long-term impacts on the logistics industry.

Keywords: artificial intelligence; autonomous delivery vehicles; customer satisfaction; Delphi method; distribution centers; edge intelligence; last-mile delivery logistics; real-time decision-making; supply chain management

1. Introduction

The last-mile delivery phase, the final stage in the supply chain where goods are transported from a distribution center to the end customer [1,2], is a pivotal component of the logistics ecosystem [3]. This phase is characterized by its complexity and operational challenges [4], historically contributing to significant inefficiencies and high costs. However, recent advancements in Edge AI or Edge Intelligence (EI) have demonstrated substantial potential for addressing these challenges and optimizing last-mile logistics processes [5]. Moreover, as e-commerce grows, the challenges associated with last-mile delivery—such as high costs, complex logistics, and increasing consumer demands—are becoming even more pronounced [6]. Traditional delivery methods often struggle with issues such as route inefficiency, high operational costs, and customer dissatisfaction [7].

Hence, in recent years, technological advancements have introduced innovative solutions aimed at overcoming these challenges. Among these, EI has emerged as a promising tool to enhance last-mile delivery logistics [8,9]. AI technologies, including machine learning algorithms [10,11], predictive analytics [12], and autonomous systems [13], have demonstrated potential in optimizing delivery routes and forecasting demand.

Concurrently, EI, which refers to the processing of data at or near the source of data generation, offers real-time decision-making capabilities essential for dynamic last-mile operations [5]. In their 2019 study, Zhou et al. [5] highlights that EI is gaining significant interest despite being in its nascent stages. The authors conducted a thorough survey of research efforts in EI, covering the history and motivation behind running AI at the network edge. They provided a comprehensive overview of the

architectures, frameworks, and emerging key technologies enabling deep learning models for training and inference at the network edge. Additionally, they discussed potential future research directions in EI. Building on Zhou et al.'s [5] seminal work, our contribution aims to expand on the future research perspectives they identified. Specifically, we focus on issues related to EI ecosystems and the close collaboration and integration among different service providers. This collaboration is crucial for broad resource sharing and one-piece service transfer. For instance, in an EI service model, a user can simultaneously be a service consumer and a data generator. This dual role necessitates a new smart pricing scheme that accounts for both the user's service consumption and the value of their data contribution.

To explore this phenomenon, the role of AI and EI in revolutionizing last-mile delivery logistics, we started by studying the application of AI-driven technologies and real-time data processing. To do so, we conducted a comprehensive literature review to evaluate current technological advancements [14]. Moreover, we supplemented the literature review with the Delphi method to systematically and empirically assess the impact of AI-driven solutions on operational efficiency and customer satisfaction. Therefore, we employed a multi-method approach [15], integrating two qualitative methods to complement each other. Specifically, the literature review will establish the theoretical foundation, while the empirical analysis will serve to validate or challenge the initial theoretical findings. To conduct this research, we formulated the following research question: How can Edge Intelligence contribute to the development of more sustainable last-mile delivery solutions?

Preliminary results reveal that despite the recognized advantages of EI, EU companies remain hesitant to fully embrace these technologies. This reluctance is primarily driven by concerns regarding the high implementation and maintenance costs. This barrier is particularly pronounced among SMEs, which often face greater challenges in adopting these innovations due to limited financial resources and expertise. Nevertheless, companies that have successfully integrated these technologies report notable improvements in operational outcomes, including enhanced route optimization, reduced delivery times, and increased service reliability. These observations show the necessity of fostering a culture of innovation and development, which includes recruiting experts with advanced academic qualifications and a strong focus on technological advancement in the field.

This article follows the IMRaD structure [16], organizing its sections into Introduction, Methods, Results, and Discussion. In the Introduction, we discuss the problem to be studied, define the research question, and present preliminary results to provide the reader with the necessary background knowledge. The Methods section offers a detailed description of the methodological process we followed. In the Results section, we organize our findings into three primary subsections. First, we provide a conceptualization of Edge Intelligence, addressing the diverse interpretations of the term and defining it within the context of business and management, including logistics. Following this, we review the literature to clarify and establish the key concepts crucial to our study. The final subsection is dedicated to the empirical validation of the conceptual framework, where we analyze how our data aligns with or challenges the proposed theories and end with a summary that integrates the main findings and discusses their implications. In the Discussion, we highlight the originality of our work, its contributions to existing theory, and the most significant managerial implications for practitioners. The final section addresses the limitations of our study and suggests avenues for future research.

2. Methods

This research employs a multi-method approach [15], utilizing two qualitative typology methods. The first method is a systematic literature review (SLR) [17], leveraging two renowned scientific databases: the EU Elsevier Scopus and the US Clarivate Web of Science (WoS) Core Collection. These databases were chosen for their source-neutral, abstract, and citation collections, curated by independent subject matter experts who are recognized leaders in their fields [18]. Academic search engines like Google Scholar were excluded due to their lack of guaranteed blind peer review [19]. For our searches, conducted on July 7, 2024, we used the terms "Edge Intelligence" or "Edge Artificial Intelligence" and "Logistics" in the manuscript Title, Abstract, and Keywords

(Topic in WoS). From a temporal perspective, this research commenced in September 2023. Before submitting the article, we updated the entire bibliography to ensure the most current information. In Scopus, we identified eleven relevant articles in English. In WoS, we found six relevant articles, which overlapped with those found in Scopus, as detailed in Table 1.

Table 1. State-of-the-art of EI in Logistics.

Database	Document Type	Document Title	Authors	Source	Year
Scopus WoS	Journal Article	Edge intelligence empowered delivery route planning for handling changes in uncertain supply chain environment	Peng et al. [20]	Journal of Cloud Computing	2024
Scopus WoS	Journal Article	Securing clustered edge intelligence with blockchain	Dehury et al. [21]	IEEE Consumer Electronics Magazine	2022
Scopus WoS	Journal Article	KeepEdge: A knowledge distillation empowered edge intelligence framework for visual assisted positioning in UAV delivery	Luo et al. [22]	IEEE Transactions on Mobile Computing	2022
Scopus	Conference Paper	A Comparison of Temporal Encoders for Neuromorphic Keyword Spotting with Few Neurons	Nilsson et al. [23]	International Joint Conference on Neural Networks	2023
Scopus	Conference Paper	Research on Fast Adaptive Transmission Models for International Inland Port Based on Edge Intelligence	Yiwen [24]	International Conference on Cyber Security and Cloud Computing (CSCloud)	2023
Scopus	Journal Article	Effective methods based on distinct learning principles for the analysis of hyperspectral images to detect black sigatoka disease	Ugarte Fajardo et al. [25]	Plants	2022
Scopus WoS	Journal Article	Allocation of applications to Fog resources via semantic clustering techniques: With scenarios from intelligent transportation systems	Xhafa [26]	Computing	2021
Scopus WoS	Conference Paper	An edge based federated learning framework for person re-identification in UAV delivery service	Zhang et al. [27]	IEEE International Conference on Web Services	2021
Scopus WoS	Journal Article	Edge computing in industrial Internet of Things: Architecture, advances and challenges	Qiu et al. [28]	IEEE Communications Surveys & Tutorials	2020
Scopus	Journal Article	Secure and privacy-preserving automated machine learning operations into end-to-end integrated IoT-edge-artificial intelligence-blockchain monitoring system for diabetes mellitus prediction	Hennebelle et al. [29]	Computational and Structural Biotechnology Journal	2024
Scopus	Conference Paper	IoT-Empowered Drones: Smart Cyber security Framework with Machine Learning Perspective	Mahamkali et al. [30]	International Conference on New Frontiers in	2023

Communication, Automation, Management and Security

A preliminary analysis reveals the scarcity of articles on this topic in the two most widely used and internationally recognized scientific databases. Particularly, the most recent article dates to 2020, indicating that the subject is quite new. Among the identified manuscripts, 64% are scientific articles and 36% are conference papers, suggesting a significant interest in journals and a need for more extensive academic and scientific discussion on this topic. Geographically, the Popular Republic of China (PRC) leads with five manuscripts, followed by Australia and India with three each, the USA with two, and Austria with one. This distribution highlights the global interest and varying levels of research activity in different regions. In terms of subject areas, computer science accounts for 39%, engineering for 26%, and decision sciences for 9%. Interestingly, Business and Management comprise only 4% of the identified manuscripts, which is far below our expectations and underlines the relevance and necessity of our article in filling this gap. A qualitative analysis framework, specifically the content analysis technique [31], was employed to evaluate the effectiveness of cutting-edge AI and intelligence technologies. This framework involved categorizing these technologies based on their applications in last-mile delivery.

The second method we used is the Delphi method. This method was employed primarily to validate the technological advancements identified in the literature review. This method involved consulting a pre-selected group of experts. Data collection was extensive, encompassing a sample of various companies operating in a European Union (EU) country (Portugal) and multinationals from diverse sectors such as the automotive industry, electrical grid, healthcare, multinational technology conglomerates, and retail. It was also targeted, aiming to gather insights from highly specialized individuals with expertise in both IT and management logistics. A total of 28 experts were invited to participate, with 7 responding and agreeing to take part in the study. For more details, see Table 2.

Table 2. Elements of the Delphi Study.

ID	Job Title	Company	Rounds
P1	IT Support Specialist	Multinational Automotive Company	2
P2	Director of Logistics	(Company A)	2
P3	IT Director/IT Manager	National Electric Grid Company (Company B)	2
P4	Chief Technology Officer	National Health Company (Company C)	2
P5	Head of IT	Multinational technology conglomerate	2
P6	Director of Logistics	(Company D)	2
P7	Director of Operations/Logistics	Multinational Retailer (Company E)	2

The main challenge in securing expert participation was their availability. To encourage participation, we committed to sharing detailed information on the investigation's results via email, extending beyond the findings presented in this article. For confidentiality reasons, only summarized information is provided here, not the full interviews. All participants signed a declaration of informed consent under the Helsinki Treaty. The study involved two rounds of consultation, during which experts were encouraged to converge on a unified position while allowing for the representation of minority views that diverge from mainstream opinions. Additional refinements were made to the proposed statements between rounds to increase support. Moreover, face-to-face meetings were occasionally convened to facilitate the consensus-building process. Despite the collected insights, the study has limitations too, mostly regarding the generalization of results. A comprehensive discussion of these limitations is provided in Section 4.3 of this article. We are

confident that combining the two methods (i.e., SLR and Delphi) enhances the robustness of the results, as each method complements and reinforces the other. Therefore, employing a multi-method approach was the most appropriate choice for this article.

The content analysis technique was also employed for qualitative research. Initially, we organized all the collected data and conducted a thorough review to identify discrepancies between various sources. To enhance the visibility of these discrepancies, we implemented a scoring system. This system also aided in determining codes and thematic categories. Furthermore, NVivo 14 facilitated the process, particularly in the more advanced phases, by expediting the integration, coding, and analysis of the dataset. The insights gathered from the content analysis are presented in Tables 4 and 5.

3. Results

As previously described, this section is structured into three key parts. We first define EI in the specific context of business and management. After establishing this definition, we move on to investigate the impact of EI on Last-Mile Delivery Logistics, analyzing how EI can improve these logistics processes and addressing areas of theoretical debate. The section wraps up with a summary that brings together the main findings and implications of our analysis.

3.1. EI Broad Conceptualization

Before proceeding with the core analysis of the results, we recognized the importance of briefly conceptualizing EI. To do so, we conducted a search on Scopus on July 7, 2024, using the terms "Edge Intelligence" or "Edge Artificial Intelligence" in the title, abstract, and keywords of the manuscripts. Overall, we observed an exponential growth in publications on EI from 2017 to 2024. The PRC leads with 915 manuscripts, followed by the USA with 357 and India with 217. The PRC significantly differs from the United States. Meanwhile, EU countries exhibit numbers similar to the US, though EU research tends to focus on the national interests and specific priorities relevant to each member state. Most of the identified manuscripts are in the field of computer science (41%), with significant contributions from engineering (26%) and mathematics (7%). This indicates a strong focus on applied sciences, with a relatively modest interest in the business and management sector (1%). Most publications are journal articles (52%), while conference papers account for 35%. To conceptualize the EI term, we used scientific articles from journals written in English, specifically from the "Business, Management, and Accounting" domain, as this area is most relevant to our article. This search yielded 14 scientific articles.

Table 3. EI conceptualization for business and management areas.

Author(s)	Definition(s)
Sinha et al. [32]	"Edge Intelligence is a methodology where the prediction by the AI algorithm is processed within the embedded processor connected to the actuator and sensors of the device for faster response by the architecture" (p. 6)
Himeur et al. [33]	"Edge AI refers to the local processing of AI algorithms on edge device (...) Edge AI brings processing and computational tasks closer to the point of interaction with the end-user, whether that be a smartphone, single board computer (SBC), domestic appliance, IoT device, or edge serve" (p. 2)
Da et al. [34]	"Fog computing (or Edge computing) is a paradigm that has recently been put forward to provide real-time/low latency services and decrease the bandwidth requirement. The fog nodes, extend the cloud to be closer to the edge by enabling computations to be carried out at the sensors/devices that produce and act on IoT data" (p. 210)
Amadeo et al. [35]	"Edge computing allows caching and processing services directly at the edge of the network, close to where data is produced and consumed" (p. 2)

Pradhan et al. [36]	"Edge computing (EC) is a distributed computing paradigm that brings computing capabilities closer to the end-users and improves the quality of service (QoS) and user experience". (p. 1)
Alrashdi et al. [37]	"Edge intelligence has developed as a favorable paradigm to enable effective and instantaneous processing of data at the network's edge (...) Edge Intelligence emerged as a decisive computational paradigm, dedicated to redefining and reshaping the boundaries of data analytics as well as decision-making" (pp.1-2)
Dalabehera et al. [38]	"Fog computing, an innovative paradigm, extends the capabilities of cloud computing to the edge of the network, bringing computing resources closer to end-users" (p. 2)
Huang et al. [39]	"Intelligent edge has accelerated the Internet of Things (IoT) revolution towards next-generation operational efficiency and massive connectivity (...) The deployment of machine learning algorithms to the edge is made possible by edge intelligence (EI), which integrates artificial intelligence (AI) and edge computing technologies" (pp. 1-2)

In Table 3, we present eight definitions of EI, as not all 14 articles provided explicit definitions. Our analysis revealed that not all authors use the terms "Edge Intelligence" [32,37,39] or "Edge Artificial Intelligence" [33]; some prefer competing terms such as "Fog Computing" [34,38] and "Edge Computing" [34–36]. We conducted a careful analysis of the four most relevant definitions of Edge Intelligence [32,33,37,39] and developed an integrated definition tailored to the business and management sectors:

Edge Intelligence (EI) is a transformative computational paradigm that integrates artificial intelligence and edge computing technologies, such as machine learning algorithms, for the real-time processing of data at the network's edge, closer to the point of interaction with the end-user. This paradigm is redefining the boundaries of data analytics and decision-making.

In contrast, Edge Computing (EC) is a distributed computing paradigm that brings computing capabilities closer to the end-users and improves QoS [36], enabling caching and processing services directly at the edge of the network, near where data is produced and consumed [35]. While both EI and EC enhance data processing efficiency and effectiveness by leveraging the network edge, EI specifically incorporates AI to provide advanced, real-time analytical capabilities, whereas EC focuses on localized data handling and processing to improve overall system performance. In practical terms, EI is relevant in scenarios where real-time data analysis and decision-making are critical [37]. Examples include autonomous vehicles, smart manufacturing, and predictive maintenance, where instantaneous decisions can significantly impact performance and safety. The objective of EI is to enhance decision-making capabilities at the edge, making systems more responsive, intelligent, and autonomous. On the other hand, EC is used to improve the efficiency and performance of a wide range of applications by minimizing the need to transmit data to distant cloud servers for processing. Use cases include content delivery networks (CDNs), remote monitoring systems, and IoT deployments where bandwidth and latency considerations are paramount. The objective of EC is to reduce latency, increase processing efficiency, and improve the reliability of services by decentralizing computational tasks.

Fog Computing (FC) is another paradigm that extends cloud computing capabilities to the edge of the network. While it shares similarities with Edge Computing in bringing computing resources closer to end users [38], FC also includes intermediary devices such as gateways and routers, which provide additional layers of computation and storage between the cloud and the edge devices. FC aims to provide real-time, low-latency services and reduce bandwidth requirements by distributing computing tasks across various points in the network infrastructure [34]. This makes FC particularly suitable for complex, large-scale IoT environments where data processing needs to be distributed efficiently across different network layers. In summary, while EI, EC, and FC aim to enhance the efficiency and responsiveness of data processing at the network's edge, they differ in their specific

focus and implementation. EI integrates AI for advanced real-time analytics, EC focuses on localized processing to reduce latency and improve performance, and FC adds an intermediary layer to further distribute computing resources and manage large-scale network demands.

3.2. EI in Enhancing Last-Mile Delivery Logistics

Out of the eleven articles selected, we extracted relevant information from seven, enabling us to analyze EI technologies and their impacts on Last-Mile Delivery Logistics. From Table 4, it is evident that the convergence of emerging technologies is revolutionizing last-mile delivery. This transformation is marked by advancements in prediction [29], speed [27], and risk reduction [30]. By analyzing the literature, we can see that technologies embedded with sensors [30], sophisticated software, and algorithms [20], along with physical networks of objects such as UAVs [22,30], are driving these changes. One of the major advances has been the integration of IoT, EC, AI, and blockchain [29]. Together, these technologies enable highly efficient predictions that aid in real-time decision-making. As a result, integrated systems combining these technologies and physical objects have greatly enhanced precision and reliability in last-mile delivery [22,30].

Table 4. EI Technologies and their Impacts on the Last Mile – insights from the SLR.

Author	Technology	Impact on Last-Mile Delivery
Hennebelle et al. [29]	IoT-edge-Artificial Intelligence (AI)-blockchain system	“Diabetes prediction based on risk factors. The results show that the proposed system predicts diabetes using RF with 4.57% more accuracy on average in comparison with the other models LR and SVM, with 2.87 times more execution time” (p. 212)
Zhang et al. [27]	Fed-UAV (Federal-Unmanned Aerial Vehicle)	“Solve the person re-identification problem in the UAV delivery service which is a typical AI application in smart logistics (...) This framework enables the UAV to efficiently locate the target receivers, and effectively reduce the data transmission between the UAV and the cloud server to improve the response time and protect the data privacy” (p. 500)
Qiu et al. [28]	Edge computing in IIoT (Industrial Internet of Things)	“Allows improved health management (PHM), smart grids, manufacturing coordination, intelligent connected vehicles (ICV), and smart logistics” (p. 2462)
Mahamkali et al. [30]	Internet of Drone Things (IDT)	“Method that reduces the risk of cyber-attacks by shoring up the foundation of a NoD (network of drones) with cutting-edge artificial intelligence-inspired approaches” (p. 1)
Luo et al. [22]	KeepEdge	“UAV delivery is being increasingly used in the field of logistics. It is highly challenging for a UAV to precisely identify the position for parcel delivery if it is only aided by the GPS. KeepEdge achieves visual information-assisted positioning for the last mile UAV delivery services” (p. 4729)
Peng et al. [20]	Mixed-integer programming model & Cloud-edge collaborative mode	“The cloud server comprehensively considers customer demand and road condition changes and employs adaptive genetic algorithms and A-star algorithms to adjust the delivery routes dynamically” (p. 1)

Dehury et al. [21]	Blockchain-based solution for “CEI allows the devices to share their knowledge and events with other devices and the remote fog or cloud servers” (p. 22)
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From the list of articles analyzed from the table above, PRC prioritizes EC in the IIoT [28] and the use of UAVs in logistics and supply chain management [20,22]. Similarly, Australia stands out in the areas of IoT-edge-artificial intelligence-blockchain integration [29] and UAV delivery services [27]. One of the most significant studies in this domain is by Hennebelle et al. [29], which investigates the capability of monitoring and predicting diabetes incidence using EI. The study proposes an advanced IoT-edge-Artificial Intelligence (AI)-blockchain system designed to predict diabetes based on identified risk factors. This innovative system employs blockchain technology to consolidate patient risk factor data from multiple hospitals, thereby ensuring both comprehensive data integration and the security and privacy of user information. Additionally, the study presents a comparative analysis of various sensors, devices, and medical methodologies utilized to measure and collect risk factor values within the proposed system. Another noteworthy study is by Qiu et al. [28], which extensively examines the role of EC in the IIoT. The authors propose a forward-looking architecture for IIoT, emphasizing the contributions of EC. They analyze the technical advancements in routing, task scheduling, data storage and analysis, security, and standardization. Additionally, the study explores the opportunities and challenges of integrating edge computing in IIoT, particularly focusing on 5G-based edge communication, load balancing, data transfer, edge intelligence, and data sharing security. The authors conclude by discussing several key application scenarios for edge computing in IIoT, including prognostics and health management, smart grids, manufacturing coordination, intelligent connected vehicles, and smart logistics. One final article we would like to highlight for stimulating discussion is by Peng et al. [20], which presents an innovative two-phase delivery route planning method incorporating advanced intelligence technology. The distinctive feature of this approach is the use of EC devices to monitor real-time changes in road conditions and dynamically adjust delivery routes accordingly. This method provides an effective solution for improving efficiency and flexibility in logistics operations.

The convergence of emerging technologies, such as IoT, edge computing, AI and blockchain, has been significantly influencing last-mile delivery. These technologies have been enabling efficient and robust forecasts, better decision-making in real time, and also greater precision and reliability. As demonstrated by the studies analyzed [20–22,27–30], these advances are paving the way for more effective and adaptable logistics solutions in most sectors of activity.

3.3. Empirical Validation

In the Delphi Study, we analyzed emerging technologies identified in the literature and explored their implications for the final phase of logistics. Due to the limited number of companies in a single EU country, we were unable to comprehensively examine the entire technological spectrum presented in Table 4 and are currently under investigation in the PRC and USA. Even if we had attempted a broader analysis, it is unlikely we would have approached the level of advancements seen in the PRC and USA. There are two main reasons for this. First, the volume of research in this field within the EU is significantly lower compared to these two countries. Secondly, the EU strategy might not necessarily follow the same path as that of the US and the PRC. This limitation represents a challenge to the generalizability of our research findings. Nevertheless, our study concentrated on several technologies that are actively transforming industrial and commercial processes in Portugal. Our findings reveal a consensus among companies regarding the significant impact of the below technologies on the logistics sector (see Table 5), which further justifies the relevance of the topic addressed in this article. However, despite the literature review highlighting potential applications for UAVs, our research did not uncover any specific industrial or commercial initiatives involving UAVs, nor did we find any plans for their implementation within the five companies surveyed.

Table 5. EI Technologies and their Impacts on the Last Mile – insights from the Delphi Study.

ID– Company	Technologies	Consensus	Participant comments (Sample)
P1–A	IoT-edge-AI- blockchain	85%	"In my perspective, the IoT-edge-AI-blockchain system can significantly enhance predictive capabilities and runtime efficiency, thereby improving overall logistics". According to the IT specialist, Company A uses IoT sensors in connected vehicles to collect real-time data. Edge Intelligence assists by providing real-time data. The integration of blockchain is in progress to ensure vehicle data security and manage transactions between vehicles and infrastructure.
P2–A	IoT-edge-AI- blockchain	81%	"We use a device that connects to our company's application, installed on our customers' cell phones. This allows us to use our customers' internet to receive data from their vehicles. EI analyzes the data at the source, while we make decisions downstream. In practical terms, the EI Improved demand forecasting and resource allocation. Although there is an ongoing blockchain project, which I find very interesting, we are still in the preliminary phase - so, there is a lot to do in that regard".
P3–B	IoT-edge-AI- blockchain	78%	"IoT-edge-AI integration has allowed us to process data at the source, optimizing power generation and predicting failures. We use sensors to monitor wind turbines and solar panels". Although Company B only plans to integrate blockchain, they recognize that this technology can create a decentralized energy management system, where energy production and consumption are recorded securely and transparently.
P4–C	IoT-edge-AI- blockchain	92%	"The integrated system significantly enhances logistics accuracy and efficiency, particularly in our field. Some of our colleagues conduct scientific research to improve the systems we use. Practically, we remotely monitor our patients using IoT devices. Edge Intelligence provides real-time analytics and alerts, while blockchain secures sensitive data and manages access". Several examples illustrated the advancement of technology in this company. One example is the use of Edge Intelligence, where data is processed at the source rather than being sent to a central server. This approach reduces latency, enabling faster decision-making and real-time alerts for healthcare providers through the Internet of Things (IoT). For instance, a smart insulin pump can continuously analyze glucose levels and adjust insulin delivery in real-time, thanks to sophisticated AI algorithms. Additionally, blockchain technology plays a crucial role in maintaining data integrity and access control by tracking and verifying patient records.

P5-D	Edge computing in IIoT	93%	"In our company, Edge Computing (EC) in the Industrial Internet of Things (IIoT) enables us to collect and process data from industrial machines and devices on-site. This approach significantly improves efficiency by facilitating predictive maintenance, which is a more advanced method compared to the preventative maintenance practices used a few years ago".
P6-D	Edge computing in IIoT	89%	"A few years ago, our supported preventive maintenance, but this approach involved recurring downtime and frequent maintenance costs. One of the biggest paradigm shifts in our company's EC strategy for the IIoT was the automation of maintenance procedures. Early on, we launched projects to implement predictive maintenance, which proved successful and delivered financial benefits within the first few months". As the participant explained, EC enabled the complete automation of maintenance procedures for IIoT devices by utilizing local data analysis to determine the appropriate actions. The participant further elaborated that CE in IIoT goes beyond collecting data from industrial structures. He said that this technology not only continuously monitors but also takes proactive actions. Through ongoing monitoring, the maintenance team can receive detailed diagnostics and reports. In addition to these insights, CE in IIoT can recommend to his office (logistics) component purchases or suggest the replacement of devices.
P7-E	Mixed-integer programming model & Cloud-edge collaborative mode	75%	"Our company is one of the largest retailers in Portugal, operating a diverse chain of supermarkets, clothing stores, and shopping centers. The EI application enables us to analyze real-time data from various sources, including traffic, weather conditions, and stock availability. This allows to dynamically adjust delivery routes, enhancing efficiency. We also face challenges such as unexpected changes in product demand across different stores, but these are highly specific and manageable".
P1-A	IoT-edge-AI-blockchain	93%	"Our integrated IoT-edge-AI system has significantly improved our logistics and operational efficiency. The blockchain component is still in development but shows great promise for enhancing data security and transaction management between devices. However, from a practical standpoint, technology has significantly enhanced our operational and logistical capabilities, enabling true just-in-time efficiency."
P2-A	IoT-edge-AI-blockchain	91%	"By using IoT and edge AI, we can process data locally, reducing latency and improving real-time decision-making. Blockchain will further enhance our security measures once fully integrated. From a

			logistical perspective, we now produce only what is necessary while maintaining a safe stock of products". Between the P1 and P2-A employees at Company A, there is a consensus that EI has brought disruptive changes to the organization and significantly improved downstream logistics management.
P3-B	IoT-edge-AI-blockchain	92%	"Our implementation of IoT and edge AI in monitoring energy systems has optimized performance and predicted equipment failures more accurately. Blockchain is the next step for securing and decentralizing our energy management systems". In the companies analyzed, we found that blockchain is an area that still needs further exploration. However, there is a consensus that IoT-edge-AI has brought disruptive and widespread changes across most companies. Both Company A and Company B can predict needs more easily and accurately, allowing for greater resource allocation in record time, which would not be possible without this technology.
P4-C	IoT-edge-AI-blockchain	96%	"The combination of IoT, edge AI, and blockchain has revolutionized our healthcare services, providing real-time patient monitoring and data security. Blockchain ensures the integrity and confidentiality of patient records". In this healthcare company, several employees conduct scientific research, necessitating the recruitment of highly specialized personnel. Given the critical importance of privacy in this sector, they invested in blockchain to protect confidential data and manage information effectively. The integration of IoT, edge AI, and blockchain has had significant real-world impacts on users' lives.
P5-D	Edge computing in IIoT	94%	"Edge computing has transformed our maintenance processes by enabling predictive maintenance and reducing downtime. This proactive approach has significantly cut maintenance costs and improved operational efficiency". In this multinational technology conglomerate, there was no significant percentage change. The company predominantly uses EC in IIoT and is almost entirely aligned with other companies. It operates in a more comprehensive sector, providing technological support to several market-leading firms.
P6-D	Edge computing in IIoT	92%	"Automation of maintenance through edge computing has delivered substantial logistic benefits. The technology continuously monitors and provides actionable insights, enhancing our maintenance strategies". The second participant from Company D is somewhat less optimistic than P5 but recognizes that EC in IIoT has introduced disruptive changes to the logistics industry. He emphasizes that this technology offers transformative benefits, particularly through

			actionable measures and recommendations, which were not available before. While final decision-making remains with humans, he believes that technology plays a crucial role in supporting this process.
P7-E	Mixed-integer programming model & Cloud-edge collaborative mode	93%	"Using edge computing and mixed-integer programming models, we can dynamically adjust delivery routes based on real-time data. This improves efficiency and helps manage demand fluctuations across our retail network". P7-E is among those least aligned with the rest due to its focus on Cloud-edge collaboration. However, after further interaction, the participant acknowledges that there is still much to be done but recognizes that EC offers significant benefits in terms of efficiency, particularly in managing delivery routes. As the Director of Operations/Logistics, this practical application is of particular interest to him.

As illustrated in the table above, one significant impact of the EI (IoT-edge-AI) technology on Last-Mile Delivery at Company A is the enhancement of predictability. This advancement has led to reduced delivery times and decreased costs associated with accumulated stock. The company employs IoT sensors to collect real-time data, which is then processed immediately using EI technologies. Although the blockchain initiative for vehicle data security and transaction management is still in the exploratory phase, the integration of IoT and advanced AI technologies has already resulted in relevant improvements in operational efficiency, cost reduction, and increased customer satisfaction. These improvements are due to the company's ability to allocate resources more effectively and provide just-in-time services as needed. In this context, we focus on the challenges and opportunities associated with EI ecosystems, particularly the essential collaboration and integration between service providers and clients. Such collaboration is critical for broad resource sharing and the continuous transfer of services. For instance, within an EI service model, a user can simultaneously be both a service consumer and a data generator. According to the empirical data, this dual role necessitates the development of a new, intelligent pricing scheme that accounts for both the user's consumption of services and the value of their data contributions. Lastly, both participants of Company A report that despite the recognized advantages of IE, companies in the EU remain hesitant to fully adopt these technologies. This reluctance is mainly motivated by concerns regarding high implementation and maintenance costs. This barrier is particularly pronounced among Portuguese SMEs, which often face greater challenges in adopting these innovations due to limited financial resources and expertise.

Company B applied IoT-edge-AI technologies for monitoring wind turbines and solar panels, resulting in optimized power generation, enhanced failure prediction, and improved resource management. Although blockchain integration remains a planned future endeavor, there is recognition of its potential for developing a decentralized energy management system. B Corp participants agreed with A Corp on how these technologies have transformed performance monitoring and future blockchain applications, focusing on their ability to minimize latency, reduce costs, and make faster, data-driven decisions.

Company C operates within the comprehensive EI ecosystem, which integrates IoT, edge computing, AI, and blockchain technologies as identified by Hennebelle et al. [29]. The specialist from this company explains that IoT-edge-AI-blockchains have led to substantial advancements in both precision and efficiency in the domains of healthcare and logistics. In the healthcare sector, this IT ecosystem has significantly enhanced real-time patient monitoring and improved data security. Blockchain technology, in particular, has played a crucial role in ensuring data integrity and privacy, while AI-driven solutions have enabled highly personalized decision-making processes that adapt to

the unique needs of each patient and require ongoing medical supervision. This approach contrasts sharply with the EC applications in IIoT, where technology supports decision-making based on predefined criteria. In the IIoT context, the financial stakes of decision-making are high, but the consequences of a wrong decision are less critical compared to healthcare, where errors can endanger human lives. As a result, decision-makers in healthcare must have greater caution and are often more reliant on medical expertise rather than solely on technological recommendations. Additionally, it was noted that some healthcare organizations have recognized the need to foster a culture of innovation and hire specialists with advanced qualifications to drive technological advancements, especially in last-mile logistics.

Returning to the comparative analysis with Company A, another key consensus emerged – the necessity to readjust the financial model for EI services. Specifically, the pricing scheme should consider both the user's consumption of services and the value of their data contributions. According to the interviewed specialist, patients already experience clear benefits. For instance, patients who require continuous hospital care can receive it at home, leading to significant savings by reducing the need for frequent hospital visits. This approach not only provides real-time, more comfortable service for patients but also eases their physical and financial burden. For hospitals, the benefits include a reduction in waiting lists and decreased foot traffic, which helps improve the return on investment. This dual advantage shows the importance of rethinking the financial model to better reflect the value provided to both patients and healthcare institutions. Overall, the effective integration of cutting-edge technologies for real-time analytics, combined with blockchain for ensuring data integrity, has demonstrated a profound impact on healthcare logistics. This innovative approach underlines the potential of EI to revolutionize sensitive fields like patient care.

Company D's emphasis on edge computing within the Industrial Internet of Things (IIoT) illustrated how this technology has advanced predictive maintenance and reduced downtime. By shifting from preventive to predictive maintenance, edge computing has enabled on-site data collection and proactive maintenance measures. The participant from Company D argued on the transformative nature of edge computing for improving maintenance processes, reducing costs, and enhancing logistics efficiency.

Company E utilized a mixed integer programming model combined with a cloud collaborative mode for dynamic delivery route adjustments. This approach has improved predictive capabilities, reduced delivery times and costs, and enabled faster route adjustments. Table 6 summarizes our analysis, highlighting the EI technologies examined and their impacts on last-mile logistics.

Table 6. EI Technologies and their Impacts on the Last Mile – combined summary.

Technology	Impact on Last-Mile Delivery
1. IoT-edge-AI-blockchain	Improves predictive capabilities and runtime efficiency.
	Reduces delivery times and company costs.
	Improves demand forecasting and resource allocation.
	Improve customer satisfaction and reduce costs.
2. EC in IIoT	Makes decisions and actions according to pre-established criteria.
	Minimizes latency/reduced downtime.
	Reduce costs.
3. Mixed-integer programming model & Cloud-edge collaborative mode	Make faster decisions and route adjustments.

Overall, our study reveals a broad consensus on the potential of IoT, edge computing, AI, and blockchain technologies. This answer to our research question, as these innovations are widely recognized for significantly enhancing operational efficiency, data security, resource management, and customer satisfaction across diverse sectors, including automotive, energy, and healthcare. Additionally, EI technologies improve predictive capabilities, reduce latency, and support better

decision-making and cost reduction for technological conglomerates through IIoT, as well as in the retail sector via cloud-edge solutions.

4. Discussion

4.1. Theoretical Contributions

This research makes several contributions to the theoretical understanding of EI. Firstly, it expands the conceptual framework of EI by integrating it with last-mile logistics, a field that has been relatively underexplored within the context of EI. Secondly, the study reveals that despite substantial advancements by the People's Republic of China and the United States of America, companies in the European Union remain hesitant to fully embrace EI. This reluctance is primarily driven by concerns about high implementation and maintenance costs. In particular, our research highlights that Portuguese SMEs face pronounced challenges in adopting these innovations due to limited financial resources and expertise. Nonetheless, some companies (e.g., healthcare) are investing in EI and recognizing the importance of fostering a culture of innovation. They are hiring specialists, often PhDs with advanced scientific research qualifications, to drive technological advancements, especially in last-mile logistics. Finally, the research finds that EI enables actionable decision-making in contexts where tasks require mechanical intelligence, significantly impacting company decisions. However, in scenarios where decision-making affects human beings (i.e., healthcare services), human decision-makers continue to play a more prominent role.

4.2. Managerial Contributions

From a managerial perspective, this study provides practical insights for logistics managers in various sectors, including automotive, healthcare, and retail. The findings highlight the potential of EI to significantly enhance last-mile delivery performance by reducing delivery times, optimizing resource allocation, and improving customer satisfaction. Managers can leverage these results to adopt EI technologies such as IoT-edge-AI-blockchain to streamline operations and achieve cost reductions, despite the need for significant initial investments in financial and human resources. Hence, the study also highlights the importance of fostering a culture of innovation within organizations. It suggests that managers should invest in recruiting and training staff with expertise in advanced technologies. Additionally, the research advocates for a reassessment of financial models to better capture the value generated by EI, particularly regarding data contributions and service consumption. This recommendation is essential for managers seeking to justify initial investments in EI technologies and develop sustainable business models.

4.3. Limitations and Future Research Avenues

Despite its contributions, this study has several limitations that suggest avenues for future research. One primary limitation is the scope of the sample, which, although diverse, is confined to a specific geographic region of the European Union (Portugal) and a limited number of sectors. Future studies could expand the sample size and include a broader range of industries and geographic locations to enhance the generalizability of the findings. Another limitation is the reliance on qualitative methods, which, while providing depth, could be complemented by quantitative analyses to offer a more comprehensive perspective. Additionally, further research is needed to explore the integration of EI with other emerging technologies and its implications for logistics and supply chain management. These future research directions can contribute to a more holistic understanding of EI and its transformative potential in the logistics industry.

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