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BLOCKCHAIN IN SMALL-SCALE LOGISTICS: OPERATIONAL AND STRATEGIC BENEFITS, AND IMPLEMENTATION CHALLENGES FOR MSMEs

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ABSTRACT

The integration of blockchain technology into micro and small logistics enterprises (MSLEs) presents an opportunity for enhanced transparency, traceability, and operational efficiency. Traditionally perceived as suitable only for large-scale systems, blockchain is increasingly becoming feasible for resource-constrained environments. This paper examines technical, economic, and organizational aspects of blockchain implementation within MSLEs, supported by literature analysis, real-world case studies (TradeLens, TE-FOOD, Modum, Slync.io), and simulated applications for two model enterprises — PickupPoint and LastMileCo. The research highlights the value of blockchain in automating delivery confirmation, securing digital invoicing, and improving data consistency across transport and warehouse systems. The study also identifies practical challenges, including cost barriers, integration complexity, regulatory uncertainties, and the need for technical upskilling. These are addressed through stepwise implementation strategies and modular adoption approaches. Findings indicate that even minimal-scale blockchain deployment can lead to measurable gains, with return on investment estimated at 6–18 months. The paper concludes with recommendations for industry adoption and policy development, advocating for regulatory sandbox environments and incentives tailored to the logistics SME context. Blockchain should be seen not merely as a technical tool, but as a strategic enabler of resilient and digitally mature supply chain operations.

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1 INTRODUCTION

1.1 Significance of the Topic

Although digitalization is a widespread phenomenon, its impact on micro, small, and medium-sized enterprises (MSMEs) has only recently entered the spotlight, among both researchers and government institutions. The pace and success of adoption vary across sectors and countries. Entities that adapted effectively have demonstrated notable, sometimes exceptional, results. Others, less prepared for the transition, face increased risks of stagnation or decline.

Studies conducted by the World Trade Organization indicate that MSMEs, despite representing the vast majority of businesses globally, remain underexamined. Their operational needs and technological capacities are often overlooked, underestimated, or dismissed (Bogavac et al., 2019).

The precise number of MSMEs active in transport and warehousing is undefined. Estimates place their share in the EU between 5–7% of total MSMEs—including businesses that manage logistics internally. The subset offering third-party logistics services is likely smaller: 2–4% in developed economies. In urban areas, particularly within e-commerce environments, the share may rise to 6–8%, depending on local demand and the presence of large operators.

Within this sector, micro and small logistics enterprises, whether operating as internal support units or external service providers, play an increasingly important role in modern supply chains. Blockchain technology is recognized as a potentially transformative solution in this context. Its core attributes—transparency, decentralization, and secure record-keeping—may strengthen operational reliability.

This paper explores how blockchain's scalability and adaptability can meet the diverse organizational capacities of MSMEs. It examines associated technical, financial, and workforce-related challenges.

In a rapidly evolving market shaped by shifting consumer expectations, the logistics capabilities of micro and small enterprises are essential for sustaining competitiveness. It is therefore necessary to examine how MSMEs are positioned within logistics flows, what specific value they contribute, and what challenges they encounter.

1.2 The Role of Logistics in Micro and Small Enterprises

Large logistics companies offer scale and standardized infrastructures. However, micro, small, and medium-sized enterprises (MSMEs) contribute to supply chains through flexibility, specialized expertise, and rapid adaptation to local conditions. Micro and small firms often identify market gaps—particularly in last-mile delivery, niche sectors, and rural areas—where large operators struggle to perform efficiently (Cekerevac et al., 2024).

Their presence in urban zones and familiarity with local markets enable them to:

- Respond quickly to demand fluctuations and ad-hoc delivery requests
- Provide specialized services (e.g., pharmaceutical transport, spare parts, cold chain logistics)
- Form outsourcing partnerships with larger companies for warehousing, distribution, and returns processing

Compared to large operators, MSMEs typically operate with limited resources. Nonetheless, their organizational agility allows them to adjust more easily to market changes. They adopt mobile apps for delivery tracking, route optimization software, and basic ERP/TMS modules.

Digital logistics platforms and tools, such as visual shipment verification methods like QR codes and e-confirmations, help reduce transport costs, accelerate processing, and improve reliability. In doing so, MSMEs sustain a competitive edge and cultivate long-term relationships with end customers and business partners, especially in the last-mile segment (Dvorak et al., 2024).

1.3 Technological Acceleration and Digitalization in MSME Logistics

The rapid evolution of information technologies has sparked the emergence of new business models, ranging from local process optimizations to the strategic transformation of global supply chains. Logistics stakeholders, including micro and small enterprises (MSMEs), increasingly rely on smart systems, modular tools, and digital interoperability.

In practice, MSME digitalization typically involves the following components:

- GIS tools and digital mapping for resource planning and allocation (Čekerevac et al., 2010),
- IoT sensors for real-time tracking of temperature, humidity, location, and shipment conditions
- Smart contracts and blockchain layers for secure delivery records, reduced complaints, and automated invoicing
- AI algorithms for route optimization and predictive vehicle maintenance
- API integrations between TMS, ERP, and an external courier service[1], enabling automated data exchange across software components.

Despite these opportunities, MSMEs face multiple challenges:

- Integrating new digital services with existing ERP/TMS systems
- Ensuring data protection and compliance with local and EU regulations
- Limited in-house IT personnel and reliance on external technical support
- Upfront costs for digital transition and infrastructure maintenance

By adopting modular and affordable digital solutions—such as SaaS models and open-source platforms, MSMEs can gradually digitize operations, improve efficiency and competitiveness, and lay the groundwork for continued technological advancement.

1.4 Research Objectives

The primary objective of this paper is to explore the intersection between blockchain technology and the logistics needs of micro and small enterprises (MSEs), whether they operate as part of broader supply chains or manage logistics independently.

A specific focus is placed on evaluating the potential benefits blockchain may offer to the MSE sector, including the following areas:

- Enhancing shipment tracking and reducing administrative costs through recordkeeping automation
- Increasing data security and protecting against manipulation and information loss
- Implementing smart contracts to automate transactions and delivery confirmations
- Analyzing case studies of successful blockchain applications in small logistics companies.

Through this analysis, the paper seeks to identify practical blockchain implementation models in MSE logistics and to highlight technical, financial, and organizational challenges associated with the digital transformation process.

To achieve these objectives, a systematic review of existing literature was conducted, applying standard procedures characteristic of structured review studies—as presented in the following methodological framework.

1.5 Methodology

This study was conducted using methodological procedures commonly applied in review-based academic research. The employed methods included the search, selection, analysis, and synthesis of relevant literature.

The research covered academic databases such as Google Scholar, IEEE Xplore, SpringerLink, and MDPI. Due to the specificity of the topic, relevant websites focused on blockchain applications in the MSME sector were also examined.

To enhance search efficiency and source classification by thematic relevance, the authors utilized artificial intelligence (AI) tools to assist in query formulation, abstract screening, and preliminary literature selection.

The search process was based on keywords such as "logistics," "blockchain," and "small and medium-sized enterprises." Selected papers were

[1] API – Application Programming Interface; TMS – Transport Management System; ERP – Enterprise Resource Planning

included based on thematic relevance, methodological quality, and publication date. Most of the sample consists of publications from the past five years, supplemented by previous works by the authors in the fields of MSMEs, blockchain, and logistics.

The collected material was critically analyzed using academic standards for source validity, reliability of findings, and relevance to the defined research problem. Information was organized and synthesized through thematic analysis, which identified key domains, recurring patterns, and a conceptual framework that integrates current knowledge.

For concise presentation, certain findings are displayed in tabular format to facilitate comparison and readability. Based on the analysis, the authors identified existing gaps in literature and proposed directions for future research, with particular emphasis on the development of small-scale logistics enterprises within the MSME sector.

1.6 Research Question

This study builds on existing research and practical examples to provide a structured overview of blockchain technology's potential in the small logistics enterprise sector.

To guide the analysis, a research question and a working hypothesis have been formulated.

Central research question:

> How can blockchain technology contribute to the improvement of logistics processes in micro and small enterprises, and what are the key implementation challenges in this context?

Working hypothesis:

> Blockchain technology has the potential to significantly enhance the efficiency and transparency of logistics operations in micro and small enterprises. However, successful implementation requires overcoming specific technical, organizational, and regulatory challenges.

This hypothesis will be examined through literature review, case studies, and thematic analysis of potential implementation models.

2 LITERATURE REVIEW

2.1 Digitalization and Logistics Automation in MSMEs

Digitalization has become a key driver of transformation in both society and the economy. Its implementation in micro, small, and medium-sized enterprises (MSMEs) significantly influences business models, particularly within logistics operations. In this context, numerous studies have examined the degree of digital adoption among MSMEs and its impact on business performance (OECD, 2024; Sagala & Ori, 2024; Kahveci, 2025; Bogavac, 2019).

One of the most notable contributions in this field is the analysis of digital maturity among MSMEs using the IDSME Index. Within this framework, Bogavac and Čekerevac (2019) identify two core sub-dimensions:

- *The use of digital technologies* includes indicators such as website ownership, social media presence, electronic recordkeeping, adoption of B2B and B2G e-commerce models, cloud computing, decision-support tools, and automation systems.
- *Electronic commerce* covers indicators such as online sales, e-commerce activity, transaction volume, and cross-border digital trade.

Interestingly, research indicates that the degree of digitalization among MSMEs is not necessarily correlated with a country’s economic development. For instance, in 2018, Qatar achieved a Global Connectivity Index (GCI) score of approximately 71—equal to Italy—despite having a GDP per capita nearly twice as high (Schwab, 2018). A similar trend was observed in 2024, when both countries scored 54.4 and shared 23rd place in the Global Digitalization Index (GDI) Country Rankings (Huawei, 2024; WPR, 2025)

Beyond economic indicators, research suggests that factors such as tradition and prior digital experience play a critical role in the acceptance of digital transformation. Globally, Asia has emerged as the most prepared region for deep digital reform, while the United States leads innovation in digital technologies. By contrast, Europe remains more conservative, progressing through incremental changes (Bogavac & Čekerevac, 2019).

Several authors emphasize the convergence between advanced manufacturing and digital technologies—a process that has driven major innovations in logistics systems. This convergence has led to significant innovations in logistics systems, including megalogistic, macrologistic, and micrologistic systems. (Didenko et al., 2021; Küpper et al., 2022)

The integration of intelligent sensors, referred to as "smart sensors" in the scientific community, represents a major advancement in logistics system capabilities. These sensors are equipped with self-recovery mechanisms, built-in electronics, and microprocessors. They also include digital interfaces that support network protocols for communication. They can be embedded into wireless or wired sensor networks, enabling the creation of social–cyberphysical systems (Mendling et al., 2020; Valebnikova et al., 2019). Technologies such as IoT, production automation, digital design, virtualization, cloud computing, mobile communications, unmanned aerial systems, AI, big data analytics, robotics, and 3D printing are considered among the most influential factors shaping modern logistics systems (Savaglio, et al., 2020; Park, 2017; Tu, 2018; Wu et al., 2013).

Advanced manufacturing technologies, such as automated design, flexible manufacturing centers, robots, and automated storage systems, are increasingly connected into single flexible production systems. These systems can ultimately be integrated into computerized enterprises or logistics systems, enhancing productivity, creating new markets, and enabling innovative business models (Borremans et al., 2018).

Digital transformation in logistics is a multifaceted process, involving the introduction of digital technologies across various stages of production chains and management structures. Automation has evolved to include informatization and digitization, forming the foundation for transformation at micro-, macro-, and mega-logistic scales.

Efficiency across these frameworks is crucial and evaluated using a range of indicators—technological, economic, social, and environmental. Notable impacts include job creation, improved working conditions, cost transparency, and adaptability to external shifts (Anderson, 2025; van Dooren & Galema, 2018; Olmstead, 2024)

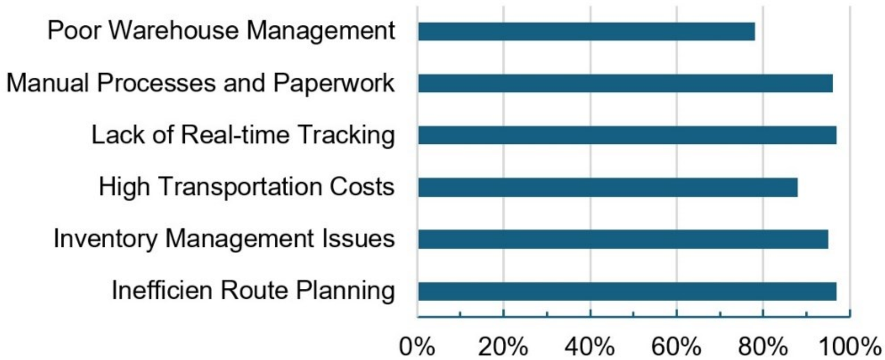

Figure 1. Issues in Traditional Logistics Processes

Source: (Anderson, 2025)

Traditional approaches to logistics operations pose a variety of challenges under current conditions. The most prominent issues are illustrated in Figure 1. Digitalization-related problems are perceived as the most pressing, with ratings well above 90%. Nearly all respondents identified inefficient route management, lack of real-time shipment tracking, manual data processing, and inventory management as critical concerns. Poor warehouse management remains notable as well, rated at 78%, though it ranks lowest on the problem scale. These findings suggest that adopting digital solutions can substantially improve business performance, especially for small firms that lack access to expensive systems and stand to benefit most from technological advancements.

Literature also highlights risks associated with digitalization. For example, Sørensen (2018) noted that digitalization may introduce competition-related risks, such as collusion enabled through algorithms and AI. Gallipoli and Makridis (2017) observed that digital technologies are shifting market structures, expanding service sectors while diminishing industrial ones. Sauter (2019) warned of risks linked to digital dominance, including the potential for unfair treatment of competitors, suppliers, and consumers. Tero Sotamaa, Arto Reiman, and Osmo Kauppila (2025) emphasized risks for MSMEs stemming from underutilized production capacities, outdated equipment, customer complaints, lack of innovation, and logistical shortcomings. Their review underscores the importance of a multidimensional approach to managing risks and capitalizing on opportunities, ultimately enhancing business continuity and long-term success.

In today's landscape, sustainability has become a central theme across industries, including logistics. As pressure mounts to reduce greenhouse gas emissions and conserve natural resources, a key question emerges: how can digitalization and automation contribute to sustainable logistics?

One pathway is through operational optimization. For instance, route optimization algorithms can reduce fuel consumption and emissions. Likewise, robotic systems for warehousing and sorting can lower energy use and spatial requirements.

Additionally, digitalization and automation foster sustainability through innovation. The development of autonomous vehicles, for example, may lead to reduced emissions. Similarly, predictive demand algorithms can help minimize waste.

However, digitalization and automation are not a "magic wand" for sustainability. While they offer numerous benefits, they also introduce new challenges, such as increased energy consumption from expanded use of digital technologies.

Therefore, achieving sustainability through digitalization and automation requires balancing benefits with risks. This means continuously monitoring the environmental impact of operations, adapting to new technologies in sustainable ways, and actively seeking methods to reduce ecological footprints.

2.1 Blockchain in Logistics Chains

The use of blockchain technology in logistics processes among micro and small enterprises (MSEs) is becoming increasingly relevant, driven by the demand for transparent, efficient, and decentralized systems for tracking and management.

Key areas of blockchain application within logistics chains include:

- Traceability and Transparency
  - Enables real-time tracking of goods and origin
  - Essential for combating counterfeits and ensuring quality control
- Smart Contracts
  - Automate transactions and delivery conditions
  - Reduce the need for intermediaries and accelerate processing
- Inventory and Warehouse Management
  - Improve record accuracy and reduce manual input errors
  - Enhance coordination between supply chain actors
- Data Verification and Security
  - Data immutability and decentralization build trust
  - Particularly important for MSEs lacking advanced IT systems
- Sustainability and Waste Reduction
  - Support emissions tracking and resource flow monitoring
  - Enable energy efficiency documentation and recycling metrics

Fernández Moreno and colleagues (2025) conducted a detailed bibliometric analysis of blockchain applications in logistics. The goal was to explore thematic evolution, identify major research trends, and forecast future directions.

Using SciMAT software and co-word analysis, they examined studies published from 2016 to March 2023. Their results revealed eight dominant thematic clusters:

- Blockchain (the most prominent)
- Security
- Sustainability
- Implementation Challenges
- Industry 4.0
- Traceability

- Circular Economy
- Smart Contracts (gaining traction in recent years)

Through longitudinal mapping and strategic diagrams, the authors illustrated how these topics evolved across three study periods. Their analysis concluded that blockchain can improve operational efficiency, lower costs, and strengthen data security, though successful implementation depends on resolving technological, organizational, and regulatory challenges. The study offers a clear snapshot of current research directions and paves the way for developing theoretical frameworks and practical solutions for blockchain in logistics chains.

Aslam et al. (2024) found that empirical, data-driven research is vital for understanding technology adoption. Their study reviews blockchain applications in logistics using a comprehensive theoretical approach. Blockchain's core features—decentralization, transparency, and real-time information sharing—position it as a critical enabler for logistics modernization.

They integrated the Fit-Viability Model (FVM) and Task Technology Fit (TTF) theory to demonstrate how blockchain enhances logistics performance and sustainability. Data from 576 logistics managers were analyzed using partial least squares (PLS) regression, revealing how blockchain improves alignment, resilience, integration, and sustainability across logistics operations. Their research maps blockchain attributes to specific logistics challenges, helping managers implement solutions more strategically. However, the study's scope is limited to logistics and excludes other supply chain functions and emerging technologies such as AI, IoT, cloud computing, and robotics. Future research should expand to include cost analysis and adoption barriers and replicate findings across diverse regions.

Berneis, Bartsch, and Winkler (2021) conducted a comprehensive systematic review focused on blockchain's economic benefits and its application in luxury and high-value supply chains. While prior success was mostly associated with cryptocurrency, a growing number of researchers and practitioners are recognizing blockchain's potential for supply chain optimization.

Despite extensive theoretical literature, the authors identified a lack of published case studies, raising questions about actual value creation and practical feasibility. Their work also offers an introduction to blockchain fundamentals, including the origin of Bitcoin, core technical attributes, and the function of smart contracts.

Their cluster analysis outlined key application concepts, especially for high-value goods, where blockchain's advantages are maximized under low trade volume and high transparency demands, provided confidentiality risks remain manageable. The study presents an idealized logistics process for luxury supply chains, giving managers insights into real-world benefits, current gaps, and implementation opportunities.

Ultimately, the authors argue that blockchain's primary advantage over traditional distributed databases lies in its ability to eliminate intermediaries and centralized control through decentralized architecture. However, high hardware and energy requirements are justified only when transparency benefits outweigh those costs. Their findings highlight the need for further empirical validation, particularly within the MSE logistics sector, where case-based evidence remains limited.

2.2 Regulatory Aspects and Implementation Barriers

The adoption of blockchain technology in the logistics sector among micro and small enterprises (MSEs) faces numerous regulatory challenges. Legal frameworks in many countries are still evolving, making alignment with national and international regulations increasingly complex. One of the most pressing issues is compliance with financial regulations, including invoicing, transaction reporting, data protection, and anti-money laundering measures. Blockchain-based systems must not only meet but potentially exceed the standards of traditional platforms, particularly about speed, efficiency, and regulatory alignment.

Beyond legal considerations, the growing automation of business processes introduces a range of ethical dilemmas. Algorithms and robots are increasingly tasked with making operational decisions, prompting critical questions around responsibility: Who bears the consequences of machine-made decisions—the developer, the system user, or the organization itself?

Equally important is the issue of fairness. Algorithmic systems are used in decision-making that directly affects employees, customers, and partners. It is essential to ensure that these systems do not discriminate based on personal attributes. A third challenge is algorithmic transparency. So-called "black box" models, which produce decisions without human interpretability, raise concerns about reliability and accountability.

In digitally integrated logistics operations—where vast amounts of goods and data are processed daily—privacy protection has become a core business component. This applies both to personal user data and sensitive corporate information. The high volume of digital exchange increases the risk of misuse, making it imperative to implement robust security protocols, conduct regular system audits, and apply proactive security principles starting in the product and service design phase.

Employee education is just as critical. Every member of the organization must be equipped to identify potential threats and respond appropriately. A culture of cybersecurity and data protection must be embedded in all aspects of MSE operations—not as an add-on, but as a fully integrated organizational value.

3 BLOCKCHAIN INTEGRATION IN SMALL-SCALE LOGISTICS

Micro and small logistics enterprises typically operate with limited infrastructure, localized distribution networks, and fragmented documentation systems. In such contexts, adopting blockchain requires a tailored approach that avoids unnecessary complexity and focuses on measurable value.

A key principle guiding this study is modular integration—the idea that SMEs do not need full-spectrum blockchain architectures but can selectively adopt components aligned with their operational priorities. Depending on their scale, technical readiness, and business model, enterprises may implement functionalities such as timestamping, delivery verification, smart contracts, IoT data logging, or document tokenization. This modularity allows for incremental adoption without disrupting existing workflows.

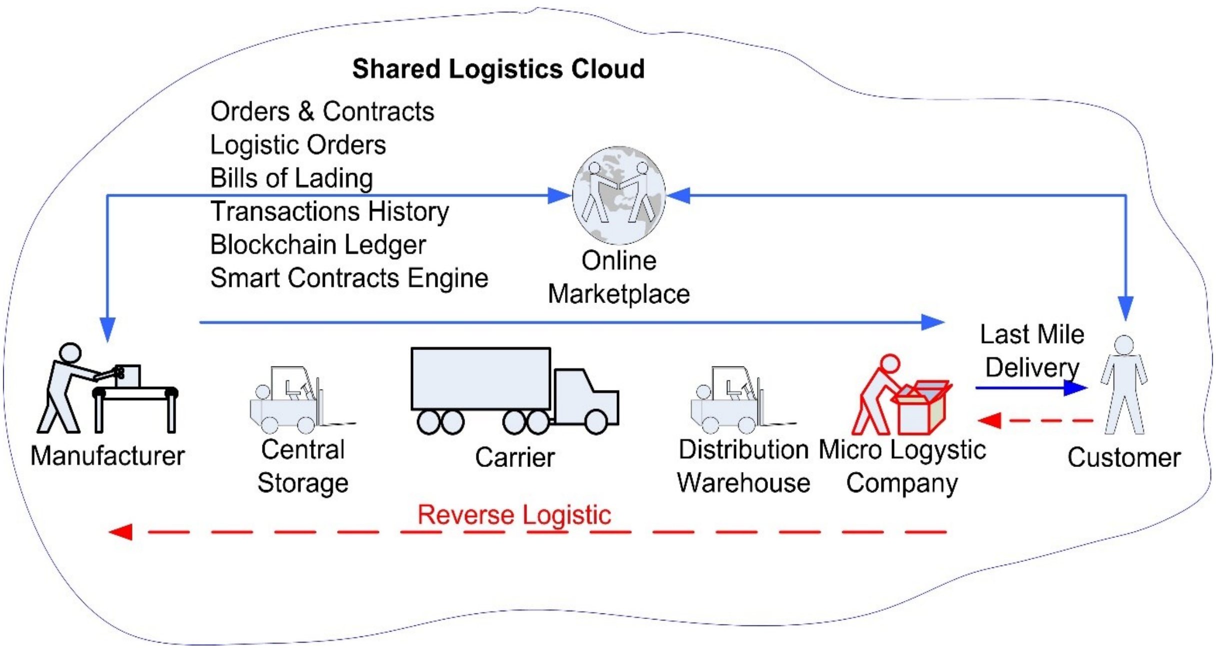

Figure 2. Shared Logistics Cloud — Functional architecture
Source: Adapted from (Novikova, 2019)

To illustrate how this layered approach can be visualized and segmented across logistics workflows, Figure 2 provides an overview of key blockchain modules grouped by business functions. The illustration serves as a conceptual map, guiding SMEs in identifying which components best match their operational scope and digital maturity.

The system includes two main functional layers:

- Business Logic Layer:
  - Orders & Contracts: Digital management of purchase orders and commercial agreements
  - Logistic Orders: Instructions and dispatch requests for shipment processing
  - Bills of Lading: Accompanying documents for goods from dispatch to delivery
- Infrastructure Layer (Blockchain-Based):
  - Transactions History: A transparent and complete record of all business events
  - Blockchain Ledger: Distributed and immutable transaction registry
  - Smart Contracts Engine: Automated execution of business rules and contractual conditions

The order flow begins with the Customer entity and progresses through the following stages:

1. Online Marketplace – A digital platform aggregating customer requests and initiating orders
2. Manufacturer – Entity confirming the order and preparing goods for dispatch
3. Central Storage – Facility for consolidation or distribution
4. Carrier – Transport service managing physical delivery
5. Distribution Warehouse – Regional unit for sorting and routing
6. Micro Logistic Company – Enterprise responsible for final-mile delivery
7. Customer (End-User) – Final recipient of goods

Solid blue lines represent the directional flow of goods and information within the logistics process. Communication between actors is bidirectional, enabling direct data exchange at any point in the system.

The dashed red line labeled Reverse Logistics depicts the return flow of goods in case of complaints, product returns, or recycling—moving from the end-user back to the manufacturer.

All entities (except the end-user) are connected to the central cloud, which allows for direct participation in:

- Document exchange
- Smart contract execution
- Shipment status tracking
- Creation of a single authoritative version of business truth.

In addition to creating a single version of truth, blockchain consistently delivers three operational benefits for micro and small logistics enterprises:

- *Transparency*, enabling traceable and auditable delivery records
- *Security*, ensuring data integrity and controlled access within distributed systems; and
- *Automation*, streamlining repetitive workflows through smart contracts and event triggers.

These benefits are not uniform across use cases, but they serve as a foundational framework referenced throughout the simulations and implementation strategies in Sections 4 and 5.

3.1 Potential Applications of Blockchain in Micro Logistics

Micro logistics enterprises typically operate at the final stage of the logistics chain and maintain the closest contact with customers, as shown in Figure 2. Small businesses such as local retailers and delivery services increasingly rely on digital invoicing and shipment tracking. Blockchain offers not only enhanced transactional security but also new collaboration models, automation capabilities, and trust among stakeholders.

3.1.1 Security and Integrity of Digital Invoices

Micro enterprises often rely on manual, centralized systems for invoice dispatch and storage, leaving them vulnerable to errors and fraud. Blockchain adoption can address these risks by providing:

- *Immutability and cryptographic protection*: Each invoice registered on the blockchain receives a unique timestamped record that cannot be altered or deleted, preventing unauthorized changes to amounts, dates, or recipient information. This approach strengthens fraud prevention and builds trust with customers and suppliers. (Piankov, 2023)
- *Reduced intermediaries and cost savings:* Smart contracts embedded in invoices allow payment conditions—such as 15-day payment terms or early-payment discounts—to be executed automatically, eliminating the

need for third parties like banks or payment processors. This reduces transaction fees and delays. (Davies, 2025)

- *Micro-payments and tokenization*: Blockchain supports token-based micro-payments, ideal for parcel-based services or digital transactions. Platforms like dexFreight—a peer-to-peer delivery network—use tokenized assets for collateral and courier payments, accelerating liquidity for small shippers and carriers. (Daley & Urwin, 2023)

3.1.2 Real-Time Shipment Tracking Transparency

Local deliveries require precise and reliable tracking that traditional databases often fail to provide. Blockchain enables micro enterprises to benefit from:

- *IoT integration and smart contract automation*: Chronicled, for example, combines IoT sensors and blockchain to record shipment conditions—temperature, humidity, GPS location—and instantly notifies stakeholders via smart contracts. This allows small businesses to monitor sensitive goods (e.g., food, pharmaceuticals) without investing in proprietary servers or costly licenses. (Daley & Urwin, 2023)
- *Distributed shipment status registry*: Platforms like CargoLedger and Oracle Intelligent Track and Trace maintain all status updates—from pickup to handover to final delivery—on a permissioned blockchain. All participants (retailers, couriers, consumers) share access to a single "source of truth" with cryptographically secured, tamper-proof records. (Oracle, 2024; Cargoledger, 2025)
- *Faster dispute resolution*: When a customer reports a problem (e.g., damaged parcel, delay), all relevant data—scan timestamps, route logs, sensor records—are instantly accessible on the blockchain. This shortens investigation times and streamlines complaint processing, saving time and money for micro firms.

One of the most promising pairings within SME logistics is the combination of smart contracts and IoT devices. When sensors (e.g., RFID, GPS, temperature) feed real-time data into blockchain networks, smart contracts can automatically execute predefined actions, such as confirming delivery, releasing payments, or flagging anomalies. This integration creates a trusted environment for autonomous transactions and event-driven workflows, especially in contexts requiring traceability, responsiveness, and minimal human intervention.

3.1.3 Smart Contracts and Task Automation

Smart contracts on blockchain platforms enable automated execution of key operations and facilitate decentralized process control.

Table 1. Smart Contract Applications in Micro-Scale Logistics

Function	Benefits for Micro Enterprises	Example
Automated Payments	Instant payment upon delivery confirmation without bank delays	TradeLens partners use smart contracts for rapid financial data exchange, cutting transit time by 40% (Novikova, 2019)
Service Contracting	Automated signing and execution of agreements with couriers	MuleChain P2P network uses MCX tokens as collateral for delivery agreements between sender and courier (Daley & Urwin, 2023)
Data Consensus	Single version of truth without a central authority	Guardtime blockchain in maritime logistics maintains transaction integrity and prevents data tampering (Daley & Urwin, 2023)

3.1.4 Implementation Pathways

Blockchain deployment in micro and small logistics enterprises faces several key challenges:

- Limited IT development resources
- Need for specialized knowledge of distributed architectures
- Integration with existing ERP, WMS, or TMS systems
- Costs associated with node setup and network maintenance

Without a dedicated technical team, any new technology requires learning, piloting, and process adaptation. Micro enterprises typically succeed best through collaboration with Blockchain-as-a-Service (BaaS) providers or within permissioned networks, starting with small-scale pilots and gradually expanding usage.

Recommended implementation phases include:

1. *Business Case Analysis*: Identify specific operational challenges (e.g., return tracking, temperature monitoring).
2. *Small*-Scale Pilot Project: Test blockchain tracking on a selected route or product type to evaluate feasibility.
3. *Vendor or Accelerator Selection*: Choose between consulting BaaS providers or joining logistics consortia. Micro firms may form local consortium blockchains to co-finance infrastructure, share costs, and reach critical mass. Services like Azure Blockchain or IBM Food Trust allow micro-operators to quickly adopt blockchain functions without in-house development, paying per transaction volume. (Daley & Urwin, 2023)
4. *Training and Process Adaptation*: Include all relevant personnel and define new procedures and KPIs.
5. *Gradual Integration and Expansion*: Begin with a single use case (e.g., digital invoicing) and extend to shipment tracking and contract automation. Once a pilot succeeds, the enterprise can scale blockchain deployment across operations and increase node participation.

3.2 Blockchain Scalability in MSME Logistics

Small logistics enterprises are typically engaged in regional transportation and operate mid-sized warehouses. Many of them already provide last-mile delivery services, especially in urban and metropolitan areas, where flexibility and local market knowledge offer advantages over large-scale systems.

In addition to internal and external transport and warehousing operations (including potential repackaging), these businesses increasingly handle inventory management, contract verification, and decentralized tracking.

Compared to micro enterprises, small firms manage more diverse logistics flows, coordinate with multiple partners, and face greater demands for technical interoperability. Core distinctions between micro and small enterprises in the context of logistics and blockchain application are shown in Tables 2 and 3.

Table 2. Operational Capacity and Logistics Complexity

Aspect	Micro Enterprises (1–9 employees)	Small Enterprises (10–49 employees)
Number of employees	1–9	10–49
Logistics scope	Limited to local deliveries and warehousing	Regional distribution, multiple delivery points
Technological infrastructure	Minimal (Excel, phone, GPS)	Basic ERP/WMS systems, mobile apps
Type of services	Last-mile, courier, and ad hoc transport	Warehousing, distribution, contract-based logistics

Table 3. Blockchain Application Parameters

Element	Micro Enterprises	Small Enterprises
Technical readiness	Low – often no internal IT staff	Moderate – potential for engaging external consultants
Blockchain solution type	Plug-and-play tools, mobile apps	Modular systems, smart contracts
Application focus	Delivery verification, receipt confirmation	Inventory management, partner agreements
Investment capacity	Limited – dependent on grants or open-source tools	Capable of pilot projects and interoperability testing
Need for decentralization	Low – typically direct end-user interaction	Higher – multiple supply chain actors involved

These differences stem from distinct strategic approaches:

- Micro enterprises prioritize simple mobile tools that offer basic transparency (e.g., QR codes for delivery confirmation, blockchain timestamping without dedicated infrastructure). As such, they are well-suited for experimental, low-budget blockchain applications that solve specific problems, such as proof of delivery.
- Small enterprises can support more complex operations, such as smart contracts for automated post-delivery payments, multi-point tracking, and integrated partner coordination (e.g., with distributors and warehouses). They are positioned to lead interoperable solutions that connect multiple stakeholders and foster standardization within regional logistics networks.

A synthesized matrix showing how blockchain functionalities can be applied based on enterprise size—from micro to large firms—is presented in Table 4. The matrix includes specific examples of available tools and software providers, matched to business scale[2] and implementation feasibility.

Table 4. Matrix of Blockchain Functionalities with Example Tools

Functionality	Micro Enterprises (1–9)	Small Enterprises (10–49)	Medium & Large Enterprises (50+)
⏱ **Timestamping & Verification**	OpenTimestamps (free timestamp service), OriginStamp (web API)	BlockCerts (digital document seals), POA Network (private Ethereum)	IBM Blockchain Platform (Hyperledger Fabric), Amazon Managed Blockchain
Smart Contracts	Remix IDE + Ganache (local testing), Truffle Suite	Quorum (JP Morgan), BlockApps STRATO	R3 Corda, Hyperledger Fabric, SAP Blockchain Framework
Product Tracking	TE-FOOD Mobile (QR delivery app), Provenance (cloud tracking)	VeChainThor, IBM Food Trust Lite	Project Provenance, Microsoft Azure Blockchain + IoT
Tokenized Access & Documents	IPFS + Textile, Pinata Cloud	Filecoin Gateway, Access Protocol	Microsoft Confidential Consortium Framework, ConsenSys Mesh
Decentralized Partner Network	Akasha Network, 3Box (Web3 profiles)	Kaleido (Hyperledger B2B), Lumedic (Corda for healthcare)	Baseline Protocol (ERP–Ethereum), TradeLens (Maersk–IBM)
Document Storage & Exchange	Pinata / Infura IPFS (free up to 1 GB), Textile Powergate (IPFS + Filecoin backup)	Storj DCS (decentralized cloud storage), Sia (flexible payment model)	Cofound.it (tokenized digital assets), Kaleido Marketplace (enterprise-grade IPFS + blockchain integration)
Financial Tracking & Micro-Payments	BTCPay Server (open-source crypto POS), Coil (content micro-payments)	Stripe + Polygon Bridge (fiat–crypto micro-payments), Request Network (automated blockchain invoicing)	RippleNet (real-time interbank transfers), Symbiont Assembly (complex financial transactions)

Building upon the functional framework illustrated in Figure 2, Table 4 helps enterprises identify suitable blockchain tools according to their operational capacity, thereby supporting strategic adoption planning across scales.

[2] The author maintains no commercial or financial ties with the manufacturers of the software mentioned. All references to digital tools are provided solely for informational purposes and do not constitute a commercial endorsement.

To demonstrate how this mapping translates into real-world implementations, Section 4 presents two proof-of-concept simulations. The first targets the micro-enterprise PickupPoint, selecting only lightweight modules—dynamic QR-code timestamping and basic smart-contract payment triggers—to match its minimal infrastructure. The second focuses on the small enterprise LastMileCo, combining smart contracts, IoT tracking, and client portal into an integrated architecture. These scenarios will show how SMEs can pick and implement the most relevant blockchain components from the matrix to suit their operational needs and resource constraints.

4 COST-BENEFIT ANALYSIS

This section explores the following aspects:

- Initial costs of blockchain implementation
- Long-term benefits—cost reduction, data security, delivery efficiency
- Case studies of successful implementations in small logistics firms
- Simulations of blockchain adoption within micro and small enterprises.

4.1 Initial Costs of Blockchain Implementation

Deploying blockchain technology in micro and small logistics enterprises requires thoughtful investment planning, factoring in technical, organizational, and human resource demands. Although the initial investment may seem challenging, the growing availability of modular and SaaS solutions allows for relatively affordable adoption, even for the smallest players.

Key cost components include:

- *Consulting services*: Process analysis and solution tailoring to MSME environments
- *Digital infrastructure development*: Servers, cloud hosting, API integrations
- *Application customization*: QR code integration, data verification tools, developer engagement, testing, and UX design[3].
- *Employee training and operational adjustment*: Usage protocols and security education
- *Technical system integration*: Compatibility with existing tracking platforms.

Estimated investment ranges:

- *Micro enterprises*: €3,500–5,000
- *Small enterprises* (wider operational scope): €18,000–27,000
- *Open-source pilot solutions*: €5,000–25,000
- *Enterprise-grade platforms* (e.g., Quorum[4] and Hyperledger Fabric[5]: 30.000–100.000 EUR, because both platforms require specialized knowledge and technical infrastructure.

These figures include:

- Licensing and support (e.g., ConsenSys Quorum with SLA agreements)
- Module development (e.g., delivery confirmation, shipment tracking, audit trail)
- System integration (TMS, WMS, ERP via API or middleware)
- Security configuration (identity management, encryption, access control)
- Documentation and training
- Testing and production deployment

The implementation time frame is estimated at 4-12 months, depending on the complexity of the system.

Many MSMEs opt for SaaS blockchain solutions (e.g., Baseline, Kaleido, IBM Blockchain Platform), subscribing to monthly plans (typically €300–1,000), which helps bypass high upfront costs and accelerate rollout.

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[3] *User Experience (UX) design* refers to the intentional structuring of user–system interaction to ensure it is intuitive, efficient, pleasant, and functionally effective.

[4] *Quorum* is a modified version of the Ethereum blockchain designed for enterprise use, featuring support for private transactions and consensus mechanisms such as Raft and Istanbul BFT. (Banerjee, 2024)

[5] *Hyperledger Fabric* is a modular blockchain platform developed under the Linux Foundation, well-suited for permissioned logistics networks. It supports Chaincode (smart contracts) and offers fine-grained access control. (Arpit, 2024; Hyperledger Foundation, 2025)

4.2 Long-Term Benefits for MSMEs in Logistics

Despite the initial costs, blockchain offers numerous long-term and sustainable benefits for logistics-focused MSMEs. It supports smoother goods flows, reduces downtime between delivery phases, and ensures more reliable data exchange. Smart contracts facilitate transaction automation, while decentralized shipment verification enhances trust and transparency.

Core benefits include:

- *Operational cost reduction*: Delivery confirmation automation, error minimization, and intermediary elimination
- Data security and error-proofing
- Accelerated payment processing
- Improved delivery efficiency

Beyond the operational efficiencies and technical innovations, blockchain adoption brings subtle but meaningful shifts in the business landscape of MSME logistics. As systems grow more transparent and transactions become verifiable in real-time, trust between clients and service providers naturally deepens. Regulatory compliance also becomes more attainable—not through added complexity, but through the seamless traceability of goods. Enterprises gain the ability to demonstrate the origin and movement of products with clarity, reinforcing both consumer confidence and institutional accountability.

Over time, these improvements translate into measurable financial outcomes. Case data indicate that for successfully deployed blockchain systems, the return on investment typically ranges from 6 to 18 months, depending on the business model and level of digital integration. In this context, blockchain emerges not only as a technological upgrade but as an economically sustainable and competitive choice for the MSME sector, particularly as it navigates the demands of digital transformation.

4.3 Empirical Case Studies

In the MSME context, implementations that demonstrate the scalability and adaptability of blockchain solutions within small logistics systems show the greatest potential for operational transformation. Literature and case studies highlight real-world applications in local courier services, distribution hubs, and warehouses, where QR codes linked to blockchain records are used to automate deliveries and confirmations.

One particularly notable simulation involves a microenterprise that employs a mobile app and a unique verification code to confirm both the receipt and release of parcels, eliminating manual recordkeeping, reducing errors, and accelerating communication with the seller.

4.3.1 Application of the TradeLens Platform in MSMEs

In his graduate thesis, Šeatović (2025) examines how TradeLens—a blockchain solution jointly developed by Maersk and IBM—can be adapted to the needs of micro and small logistics actors. Although originally designed for large global supply chains, the author identifies specific functionalities that, with appropriate customization, enable MSMEs to:

- Verify deliveries using timestamps and digital signatures
- Exchange documents transparently and in real time
- Automate invoicing through smart contracts

The study suggests that this "lightweight" approach—selectively integrating only the core TradeLens services—can reduce development costs and expedite blockchain adoption in small-scale environments (Šeatović, 2025).

Although TradeLens processed more than 70 million containers and over 4 billion logistics events during its operational period, TradeLens was officially discontinued on March 31, 2023, as confirmed by IBM’s support portal. The decision was first announced by Maersk and IBM in November 2022, citing strategic misalignment and lack of full industry adoption (Maersk, 2022; IBM, 2023).

Key reasons for its termination included a lack of commercial viability, limited industry cooperation, and hesitancy from competitors toward a platform controlled by a dominant sector player (Cecere, 2022; Haselhorst, 2024).

Nevertheless, TradeLens remains a relevant example of blockchain infrastructure, whose conceptual and functional components can be adapted to the MSME context, especially through modular strategies and open-source technologies.

4.3.2 Application of TE-FOOD: Blockchain in Local Food Logistics

Launched in 2016, TE-FOOD implemented a public blockchain system for food traceability in Vietnam, with a focus on micro and small enterprises—including farms, slaughterhouses, distributors, and retail stores. The system aims to record every critical event in the supply chain using immutable blockchain entries, while mobile scanners and QR codes printed on packaging allow seamless interaction for end-users.

Key system components include:

- IoT/QR integration for logging product movement at each supply chain node
- Decentralized ledger capturing HACCP checkpoints and transport events (Pham, et al., 2023)
- A web portal for MSMEs offering shipment history overview and deviation alerts

Operational impact in Vietnam:

- More than 2,400 farms and 6,000 distributors onboarded
- Product recall time reduced from seven to two days
- Consumer trust improved and complaint rates lowered by 30%, attributed to visible audit trails

Estimated implementation costs (average projections):

- Basic package (mobile app + QR printing): €8,000–12,000
- Additional modules (IoT sensors, API integrations): +€5,000
- Monthly SaaS subscription: ~€150

This case illustrates how MSMEs in the agri-food sector can leverage blockchain to increase transparency, security, and operational efficiency, without the need for complex infrastructure investments.

4.3.3 Case Study: Chronicled and IoT Integration

Chronicled, founded in 2014 in San Francisco, combines blockchain with IoT sensors (RFID, GPS, temperature) to:

- Record transport conditions (temperature, humidity, location) in an immutable ledger
- Automate ownership transfer confirmations via smart contracts
- Provide a robust audit trail for small courier firms

This implementation reflects the sensor-driven automation model described in Section 3.1.2, wherein IoT data triggers smart contract execution, enabling secure, event-based logistics coordination. This approach offers Micro, Small, and Medium Enterprises (MSMEs) secure records of storage and shipment conditions, while leveraging the smart contract–IoT integration framework described in Section 3.1.2 to trigger automatic payment upon verified delivery, reducing disputes and accelerating cash flow. Based on a consensus blockchain and distributed IoT nodes, the system exemplifies a modular strategy for adopting advanced technologies in small environments, validating selective integration of large-scale solution components to optimize SME implementation costs and risks. (Daley & Urwin, 2023)

Additional benefits for MSMEs include (MediLedger, 2025; Pribich & Cooper, 2023):

- Access to an existing consortium without capital expenditure, through subscription and transaction fees
- Hyperledger Fabric-based architecture (Hyperledger, 2018) that allows selection of only the modules relevant to the SME business model
- API integrations with leading ERP/PLM systems, reducing technical implementation time and cost
- A web portal and mobile application tailored for end users (distributors, pharmacies), featuring a simple interface for reviewing shipment history, reporting, and performance tracking

To achieve rapid, scalable deployment, MediLedger adopted a cloud-native, high-availability architecture and partnered with a DevOps team (Kelly, 2025). This collaboration reduced client onboarding time from days to 1–2 hours, eliminated implementation errors, and produced reusable Infrastructure-as-Code modules. The architecture is cloud-migration ready (e.g., AWS), and dedicated technical support further strengthens solution agility and scalability for SMEs.

4.3.4 Modum Case: Monitoring Pharma Shipments

Modum, a Swiss startup founded in 2016, integrates temperature and humidity sensors with Ethereum blockchain verification (Modum, 2017). Their plug-and-play devices enable small logistics firms to (Huang et al., 2019):

- Monitor and record environmental conditions in real time
- Automatically generate immutable compliance reports for regulators
- Integrate sensor data into existing TMS/WMS via REST APIs
- Minimize risks of product recalls and losses due to improper transport

Focusing initially on pharmaceutical deliveries—where SMEs handle sensitive products locally and regionally—Modum operationalizes the smart contract–sensor framework described in Section 3.1.2. Sensor readings are continuously matched against predefined thresholds, and compliance actions are triggered automatically, minimizing manual oversight. Key advantages for SMEs include:

- A scalable model requiring no proprietary blockchain infrastructure
- Easy sensor installation and companion mobile app
- Compliance with EU GDP regulations for drug transport

This example illustrates how SMEs in the agri-food and pharma sectors can leverage blockchain for regulatory alignment, automated transactions, and operational efficiency—without heavy infrastructure investments.

4.3.5 Case Study: Slync.io for SME Logistics

Slync.io, a Dallas-based startup launched in 2017, marries blockchain with artificial intelligence to provide small and medium logistics firms with:

- Real-time visibility of domestic and international shipments
- Automation of repetitive operational workflows
- Congestion prediction and route optimization

The platform leverages a distributed ledger for immutable event logging, while an AI layer aggregates and analyzes data to produce timely alerts and trigger automated corrective actions. This hybrid solution allows SMEs to elevate digitalization and transparency without building complex, in-house infrastructure, while benefiting from lower integration costs and faster deployment (Daley & Urwin, 2023). Research shows that such blockchain-AI convergence can significantly reduce errors and delays, boosting operational efficiency.

Despite its innovative promise, Slync.io failed. Between 2019 and 2022, the company generated only $1.7 million in revenue against cumulative losses exceeding $80 million (Sunset, 2024). In 2023, founder and CEO Chris Kirchner was arrested for financial misconduct (Dooley, 2024), leading to a loss of investor confidence and inability to secure further funding. By October 2023, Slync.io ceased operations and entered liquidation. This cautionary tale underscores the necessity of transparent governance and sustainable business strategies, especially for tech startups targeting the SME sector.

These case studies confirm that blockchain can deliver tangible benefits to the SME logistics sector, whether through direct sensor-triggered automation (as discussed in Section 3.1.2) or broader AI-integrated workflows, provided implementations follow a selective integration approach.

4.4 Proof-of-Concept Simulations

Following the modular structure outlined in Figure 2 and applied through the tool matrix in Table 4, the following subsections present two simulations:

- A detailed case study for the microenterprise *PickupPoint*
- A conceptual implementation model for the small enterprise, *LastMileCo*

Together, these simulations assess the applicability of TradeLens-inspired modular principles in concrete, small-scale operational settings.

4.4.1 Sources Informing the Simulation

The simulations were constructed using technical and economic sources that explain blockchain–QR code principles and support preliminary cost estimation. These include:

1. *Technical principles of blockchain-linked QR codes:*
   a. Casandra (2025) describes how QR codes can be linked to blockchain records to enable transparency and verification, particularly in logistics. The approach uses dynamic QR codes that reference hashed blockchain transactions.
   b. MyMap.AI (2025) explains identity and product status verification via QR technology, directly applicable to micro-logistics operations.
2. Cost estimation frameworks**:**
   a. Open-source development tools (e.g., Solidity, React Native, Polygon SDK) and commercial platforms with published pricing (e.g., Infura, Polygon.io) offer SMEs clear access to technical specifications and costs. Solidity and React Native are open-source, while Infura and Polygon.io provide paid APIs. Polygon also maintains open-source modules such as zkEVM, available under permissive licenses. (Infura, 2025; Polygon, 2025)
   b. Application and smart contract development costs were estimated based on freelance blockchain mid-level developer rates in the EU (€15–30/hour) (Index, 2025). SMEs may source developers globally to optimize pricing.
   c. SaaS blockchain infrastructure providers (Alchemy, Moralis, QuickNode) offer scalable pricing models, with estimated costs for micro enterprises around €100/year. (Alchemy, 2025; Moralis, 2025; QuickNode, 2025)

4.4.2 Simulation Methodology for SMEs in Logistics

The simulations employ a modular, proof-of-concept methodology to model blockchain implementation tailored to SME logistics workflows.

For the microenterprise, the simulation assumes:
- Use of a mobile app, QR codes, and manual event registration
- Operations within a single warehouse or distribution point, staffed by a few employees handling a limited volume of daily shipments
- Blockchain is used for transparent delivery logging and smart contract-triggered payment after QR scanning

For the small enterprise, the simulation expands the scope:
- Integration of the blockchain layer into an existing TMS/WMS system via API
- Operations across multiple facilities with digital bills of lading (e-BL) and IoT-based event automation
- Smart contracts enabling dynamic invoicing, environmental condition monitoring, and regulatory audit trails

Common steps across both scenarios include:

1. Shipment registration (identity creation on blockchain)
2. Receipt and scanning (QR code or RFID tag)
3. Ownership transfer confirmation (smart contract activation)
4. Verification and audit via client/operator-facing interface

These models reflect operational capacity and implementation feasibility at two scales. The next case study applies the methodology to the *PickupPoint* microenterprise.

4.4.3 Simulation: Micro Enterprise “PickupPoint”

PickupPoint is a local mini shop that receives parcels from couriers and hands them over to final customers.

Before blockchain implementation:

- Courier delivers a package; staff manually scans and logs it into a physical record
- Customer receives an email/SMS with pickup code and time
- Upon pickup, the staff verifies the code (and possibly ID) and manually confirms delivery to the seller, triggering payment authorization
- If unclaimed, the parcel is returned through the courier, following the same process in reverse

Blockchain-enabled workflow:

1. Each parcel is assigned a dynamic QR code linked to a hashed public blockchain transaction (e.g., on Polygon)
2. Upon arrival, the staff scans the QR; the mobile app generates a “received” event published to the blockchain with unique metadata

3. Customer scans QR and inputs a one-time PIN; app verifies receipt, checks the PIN, and posts "picked-up" event
4. Smart contracts automatically notify the seller and logs income for the microenterprise

Technical setup and estimated costs:

- Frontend: Mobile app built with React Native
- Backend: Node.js with REST API for blockchain interaction
- Blockchain layer: Polygon for low-cost transactions; access via Infura or RPC
- Smart contract: Written in Solidity for event logging

Table 5. Estimated Blockchain Implementation Costs for PickupPoint

Item	Cost Estimate
Development & integration (2–4 weeks)	€2,000–3,500
UI design (1–2 weeks)	€1,000–1,500
Blockchain infrastructure (annual)	~€100 subscription
Training & support	~€400
Total initial investment	**€3,500–5,000**

Projected Return on Investment (ROI): Estimated at 6–9 months, based on projected reductions in dispatching time, customer service labor, and delivery errors. Calculations assume an average transaction value of €18, ~150 successful deliveries per month, and a 30% drop in customer complaints and dispatch rework.

This investment level is accessible for micro enterprises and activates the core blockchain benefits summarized in Section 3, particularly transparency and error reduction within delivery workflows.

4.4.4 Simulation: Small Enterprise "LastMileCo"

LastMileCo is a regional delivery company with 15 couriers and three warehouses, operating last-mile logistics, "from warehouse to doorstep."

Blockchain integration includes:

- Smart contracts deployed on Quorum or EVM-compatible platforms such as Hyperledger Besu, defining delivery and payment conditions triggered upon status "delivered"
- IoT and GPS tracking to record delivery paths, with each key event registered on the blockchain and timestamped
- Client portal providing automated access to delivery history, recipient digital signatures, and auto-generated delivery confirmations

Table 6. Technical Architecture and Estimated Blockchain Implementation Costs for LastMileCo

Item	Estimated Cost
Smart contract and backend development	€8,000–12,000
IoT integration (RFID/GPS sensors)	€5,000–8,000
Enterprise blockchain node (SaaS with SLA support)	~€6,000/year
Client-facing web portal	€3,000–5,000
Staff training and process adaptation	€2,000
Total initial investment	**€18,000–27,000**

Return on Investment (ROI): Estimated at 12–18 months, reflecting reduced delivery disputes, fewer failed shipments, and accelerated billing, cutting average invoice clearance from 15 to 7 days. Calculations follow the same transaction-level ROI model established in the PickupPoint scenario (Section 4.4.3), scaled to LastMileCo's enterprise size, infrastructure, and delivery volume.

These simulations validate the feasibility of selecting and integrating blockchain modules as mapped in Figure 2, reaffirming that even small enterprises can benefit from targeted adoption strategies.

5 RECOMMENDATIONS FOR MICRO AND SMALL ENTERPRISES

Amid growing demands for logistics process digitalization, micro and small enterprises (SMEs) face the challenge of balancing operational efficiency with financial sustainability. While blockchain adoption may appear technically demanding, there are well-defined scenarios in which it delivers tangible value at reasonable investment levels. On the other hand, it remains a complex and potentially costly endeavor.

Therefore, when developing a blockchain implementation strategy, SMEs should consider:

- *Business volume* – Is the current transportation volume sufficient to justify a blockchain investment?
- *Implementation costs* – Affordable options exist, but long-term viability must be evaluated
- *System integration* – Will blockchain be compatible with current transport management software?
- *Regulatory context* – Are there legal barriers to using blockchain in the logistics sector?

If blockchain is determined to be both justified and necessary, enterprises must carefully plan implementation phases and anticipate key challenges.

5.1 Phased Implementation Strategy

Before committing to a full-scale blockchain deployment, micro and small enterprises should assess their operational priorities against specific digital functionalities. This assessment can be guided by modular frameworks such as the one presented in Figure 2, which organizes blockchain components by logistics function and enterprise scale.

To avoid technological and organizational shocks, SMEs should adopt blockchain gradually through the following phases:

i. *Business process analysis and needs identification:* Map logistics workflows to pinpoint inefficiencies, bottlenecks, or trust gaps, such as goods intake, quantity verification, and delivery confirmation.
ii. *Pilot project initiation:* Define goals and test blockchain within a limited scope (e.g., one location, route, or product cycle). Open-source platforms such as Ethereum Lite or Hyperledger Sandbox allow cost-effective prototyping.
iii. *Integration with existing software*: Connect the blockchain layer with systems like TMS, WMS, or ERP using standardized APIs or middleware, without major architectural modifications.
iv. *Employee training and operational adaptation*: Successful implementation depends on users' understanding and using the system effectively. Training should cover logistics operations (storage, confirmation, verification) and security protocols (encryption, private keys, access control).
v. *Scaling across broader environments*: If the pilot proves successful, the system can be expanded to multiple warehouses, production lines, IoT nodes for automated asset tracking, and external partner integration.

5.2 Key Challenges and Mitigation Strategies

Although blockchain adoption is viable for logistics-focused SMEs, they may encounter several implementation barriers. The most common challenges and recommended strategies are outlined in Table 7. SMEs that adopt blockchain with a clear objective, phased functionality expansion, and proper employee support can achieve not only operational improvements but also a competitive edge in digitally transformed logistics environments.

Table 7. Key Blockchain Implementation Challenges and Mitigation Strategies

Challenge	Recommended Strategy
💰 High initial investment costs	Use open-source platforms and SaaS subscriptions to reduce upfront expenses
🛠️ Limited technical expertise	Partner with IT firms, outsource developers, and leverage educational guides
🔗 Integration with existing software	Apply modular architectures, API connectors, and consulting packages for compatibility
📘 Legal and regulatory uncertainty	Monitor EU guidelines on digital records and consult legal experts in tech law
😟 Employee resistance to new technologies	Involve staff in the pilot phase, provide customized training, and use familiar interfaces (e.g., mobile apps with visual confirmations)

6 CONCLUSION

The adoption of blockchain technology by micro and small logistics enterprises represents a strategic shift toward greater reliability, transparency, and operational efficiency. Although blockchain is often seen as a solution for large corporate systems, the simulated implementations at PickupPoint and LastMileCo demonstrate that resource-constrained operators can execute rational, cost-effective deployments.

Based on our analysis of technical requirements, organizational change, and cost frameworks, blockchain is most justified when an enterprise:

- Manages high-value or sensitive goods requiring indisputable authenticity and traceability
- Collaborates with multiple external partners and needs a neutral, tamper-proof event registry
- Seeks to automate core processes such as delivery confirmation, service billing, or digital signing
- Encounters inconsistent records across legacy systems (TMS, ERP) and needs an interoperability layer
- Aims to eliminate manual errors and miscommunications inherent in paper-based workflows

Under these conditions, blockchain should be viewed not merely as a technical add-on but as a foundational infrastructure that ensures reliable record-keeping, accelerates contract execution, and enhances supply-chain reputation.

Our modular models confirm that even small-scale operations can integrate blockchain affordably and with controlled risk, paving the way for broader digital transformation in the logistics sector.

Key decision factors for pursuing blockchain include:

- *Business domain:* Is the enterprise engaged in digital transactions, contracts, or logistics processes that benefit from unified, verifiable data?
- *Implementation cost:* Do available open-source or SaaS options provide a measurable return relative to business goals?
- *Regulatory environment:* Are there industry-specific or national regulations affecting blockchain-based records and e-signatures?
- *Technical support capacity*: Can the enterprise manage a blockchain system internally, or must it rely on external expertise, impacting budget and sustainability?

These criteria not only guide evaluation but also form the bedrock of a sustainable digital-transformation strategy tailored to the resources, needs, and compliance requirements of small firms.

7 PROPOSALS FOR FUTURE DEVELOPMENT AND REGULATORY REFORM

The preceding analysis confirms that blockchain can function as a viable solution for micro and small logistics enterprises. However, its broader adoption will depend not only on technical feasibility but also on sustained research efforts and thoughtful regulatory adjustments.

On the research front, several directions merit particular attention. First, tailored ROI models must be developed to reflect the operational realities of SMEs. These models should account for resource constraints, gradual implementation strategies, and sector-specific dynamics. In parallel, the evaluation of hybrid architectures—those that combine blockchain and IoT—could unlock new efficiencies in traceability and automation. Attention to user experience design is also crucial. For low-tech operational environments typical of many SMEs, simplified and intuitive interfaces may significantly boost staff adoption and mitigate resistance.

Equally valuable is comparative technological analysis. By examining platforms such as Polygon and Hyperledger, researchers and practitioners can help small firms navigate the landscape of available tools and identify solutions best suited to their scale, interoperability needs, and cost structures.

Among the most promising opportunities lies blockchain's application in Environmental, Social, and Governance (ESG) reporting. Through measurable and verifiable data, SMEs can demonstrate alignment with sustainability, ethics, and transparency goals. Such reporting offers more than just internal insight; it empowers stakeholders, including investors, partners, regulators, and the public—to make informed assessments about the enterprise's integrity and strategic direction.

From a regulatory standpoint, establishing sandbox environments would allow SMEs to test blockchain applications under relaxed compliance constraints. Such frameworks would reduce legal risk and encourage innovation without compromising oversight. National and international laws must also evolve to formally recognize blockchain-authenticated digital confirmations, such as delivery receipts, invoices, and certificates of origin. This recognition should build upon existing global standardization efforts, including ISO TC 307, IEEE initiatives, and the Blockcerts protocol.

Data protection remains a critical concern, particularly for SMEs lacking in-house legal teams. Clear guidelines must be established to govern the treatment of sensitive information across distributed networks. Furthermore, targeted incentive schemes—such as public grants, tax credits, or cooperative infrastructure programs—could play a decisive role in making technological transition both attainable and sustainable.

Taken together, these proposals offer an actionable roadmap for integrating SMEs into the emerging landscape of digital logistics. Rather than passive adopters of new technologies, micro and small enterprises are poised to become co-creators of a logistics ecosystem defined by transparency, resilience, and long-term sustainability.

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