MODELLING OF CRITICAL BARRIERS TO INDUSTRY 4.0 IMPLEMENTATION IN LAST MILE DELIVERY: TISM BASED APPROACH

Thesis Submitted
in Partial Fulfillment of the Requirements for the
Degree of

MASTER OF TECHNOLOGY
in
Industrial Engineering and Management
by

Dhruv Shankar Saxena
(23/IEM/10)

Under the Supervision of

Dr. Mohd Shuaib
Assistant Professor, Department of Mechanical Engineering
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To the
Department of Mechanical Engineering

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Shahbad Daulatpur, Main Bawana Road, Delhi – 110042, India

June, 2025

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(4) Degree for which the thesis is submitted: **M.Tech.**
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3	23/IEM/02	AATIF AMEER	A+	B+	O	A+	A+	8.65	17	
4	23/IEM/03	MAHESH SAROHA	O	A	A	A+	A+	8.88	17	
5	23/IEM/04	REDDI DUSHYANTH VENKATA SAI KRISHNA	A+	B	A	A	A+	8	17	
6	23/IEM/05	DIVYANSH	B+	P	B	B+	A+	6.65	17	
7	23/IEM/06	RAJENDER	A+	B	A	A	O	8.24	17	
8	23/IEM/07	PIYUSH KUMAR	A	B	A	A	O	8	17	
9	23/IEM/08	ISHAN KOTNALA	P	C	B+	B+	A	6.06	17	
10	23/IEM/09	LOKESH KUMAR	A+	A	A+	A+	A+	8.76	17	
11	23/IEM/10	DHRUV SHANKAR SAXENA	A+	A	O	O	O	9.29	17	
12	23/IEM/11	SHISHIR ACHARYA	A+	A	A	A+	O	8.88	17	
13	23/IEM/12	MORIE MEYER KOUNA FERRAND	A	C	A	A	A	7.29	17	
14	23/IEM/13	FREDRICK KABWE	A	B	A	A	A	7.53	17	

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IEM601 : MAJOR PROJECT I IEM6201 : E- Commerce IEM6305 : GLOBAL BUSINESS MANAGEMENT IEM6405 : Advanced Operation Research

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4	23/IEM/03	MAHESH SAROHA	A	O	A+	O	9.25	12	
5	23/IEM/04	REDDI DUSHYANTH VENKATA SAI KRISHNA	A+	A+	A+	A+	9	12	
6	23/IEM/05	DIVYANSH	A+	A	B+	B	7.33	12	
7	23/IEM/06	RAJENDER	O	A+	A	A+	9	12	
8	23/IEM/07	PIYUSH KUMAR	A+	A+	B+	B+	7.83	12	
9	23/IEM/08	ISHAN KOTNALA	A+	A+	A+	B+	8.33	12	
10	23/IEM/09	LOKESH KUMAR	A+	A+	A+	B+	8.33	12	
11	23/IEM/10	DHRUV SHANKAR SAXENA	O	O	O	O	10	12	
12	23/IEM/11	SHISHIR ACHARYA	O	O	O	O	10	12	
13	23/IEM/12	MORIE MEYER KOUNA FERRAND	A+	A	A+	A	8.5	12	
14	23/IEM/13	FREDRICK KABWE	A+	A+	A+	A+	9	12	

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Dhruv Shankar Saxena

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CANDIDATE'S DECLARATION

I, **DHRUV SHANKAR SAXENA**, hereby certify that the work which is being presented in the thesis entitled "**MODELLING OF CRITICAL BARRIERS TO INDUSTRY 4.0 IMPLEMENTATION IN LAST MILE DELIVERY: TISM BASED APPROACH"** in partial fulfillment of the requirements for the award of the Degree of Master of Technology, submitted in the Department of Mechanical Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from Jan 2025 to May 2025 under the supervision of Dr. Mohd Shuaib, Assistant Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.

The matter presented in the major project has not been submitted by me to any other Institute before.

Candidate's Signature

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

Signature of Supervisor(s) **Signature of External Examiner**

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CERTIFICATE BY THE SUPERVISOR(s)

Certified that **Dhruv Shankar Saxena** (23/IEM/10) has carried out the research work presented in this thesis entitled **"MODELLING OF CRITICAL BARRIERS TO INDUSTRY 4.0 IMPLEMENTATION IN LAST MILE DELIVERY: TISM BASED APPROACH"** for the award of Master of Technology from Department of Mechanical Engineering, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

Date: 31/05/25

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MODELLING OF CRITICAL BARRIERS TO INDUSTRY 4.0 IMPLEMENTATION IN LAST MILE DELIVERY: TISM BASED APPROACH

Dhruv Shankar Saxena

ABSTRACT

The final mile of delivery the very last step in delivering a product to the customer—has one of the most intricate and costly components of the logistics chain within the B2C space. As online business has evolved to meet customer demands. Consumers now expect not only rapid shipping but also accuracy, adaptability, and convenience in when and how exactly their orders will be delivered. This segment of the supply chain continues to be marred by such problems as delivery failures, traffic jams, unproductive routing, and environmental factors, all of which present major challenges for logistics companies. Even though there has been significant progress in other supply chain management domains LMD still lags.

Industry 4.0-related technologies like real-time monitoring, route planning through AI, and self- driving cars have the potential to address these issues. These solutions could potentially reduce costs, enhance dependability, and enhance the customer experience. But even these technologies have been implemented in an unbalanced manner. Most businesses are hindered by factors such as high capital expenses, technological constraints, change aversion, and strategy ambiguity. This research delves into such challenges in detail, seeking to determine and comprehend the key impediments to embracing Industry 4.0 in LMD. Through the integration of Total Interpretive Structural Modelling (TISM) and MICMAC analysis, the research depicts such impediments in a schematic structure, illustrating how they intersect and what is most important. This allows for organizations to tackle the right issues first in strategizing for improvement.

The significance of this research lies not merely in its theory contribution but also in its practical implication. Resolving last mile issues is central to making delivery systems more sustainable, responsive, and customer oriented. As the digital economy expands and green concerns deepen, overhauling this terminal phase of delivery is more imperative than ever before. The findings presented can help inform improved decision-making among logistics practitioners, business executives, and policy makers endeavoring to update urban logistics.

Keywords: Last Mile Delivery, Industry 4.0, Logistics 4.0, Digital Transformation, Structural Modeling, Total Interpretive Structural Modelling (TISM), MICMAC Analysis

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
AR/VR	Augmented Reality / Virtual Reality
B2C	Business-to-Consumer
CPS	Cyber-Physical Systems
CSV	Comma Separated Variables
EV	Electric Vehicle
GHG	Greenhouse Gases
IoT	Internet of Things
ITS	Intelligent Transportation Systems
LMD	Last Mile Delivery
MICMAC	Matrice d'Impacts Croisés Multiplication Appliquée à un Classement
RPA	Robotic Process Automation
SSIM	Structural Self-Interaction Matrix
TISM	Total Interpretive Structural Modelling
WMS	Warehouse Management System

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the fast-evolving, tech-centric climate of the 21st century, digital transformation has been a defining feature of progress in nearly all sectors. At the heart of this transformation is the phenomenon of Industry 4.0, which was coined in Germany as a part of a strategic initiative to enhance Germany's manufacturing prowess by including digitalization in it (Kagermann, Wahlster, & Helbig, 2013). A term not only coined by the marketing frenzy itself, Industry 4.0 is a real-life evolution towards smart, interconnected systems that are capable of autonomously sensing, analyzing, and controlling industrial processes through technologies such as Cyber-Physical Systems (CPS), the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, Cloud Computing, etc. (Lasi et al., 2014; Xu et al., 2018). As the technologies advance, their application has extended far beyond the assembly lines—penetrating into the intricate world of supply chain and logistics management (Lu, 2017).

This has given rise to what is currently termed as Logistics 4.0. This term has been built around the application of Industry 4.0 principles to logistics systems with a prospective aim towards automating, digitalizing, and optimizing every part of the supply chain (Winkelhaus & Grosse, 2020). Logistics 4.0 leverages platforms such as real-time data sharing, Intelligent Transport Systems (ITS), AI-based delivery routing, blockchain for transparency, and predictive analytics to generate a much more responsive, efficient, and customer-centric system than traditional logistics models (Barreto et al., 2017; Bibri, 2021). The most critical—and least obvious—segment of the logistics value chain is probably Last-Mile Delivery (LMD). This latter part of the supply chain, tasked with the distribution of products from distribution centers to the consumer's doorstep, has become more visible in the B2C platform in recent times (Lim et al., 2018).

The rise of giant e-commerce platforms like Amazon, Flipkart, and Alibaba has increased customer aspirations manifold. Today's consumers want not only quick delivery but also flexible planning, real-time tracking, and hassle-free service (Gevaers, Van de Voorde, & Vanelslander, 2011). Therefore, the ability of LMD to directly and permanently influence brand loyalty and customer satisfaction (Mangiaracina et al., 2019). Despite its growing importance, LMD is often cited as the most expensive and operationally demanding part of the supply chain—representing up to 53% of the total logistics costs (McKinsey & Company, 2016). This is because there is a multitude of recurring issues. Urban road congestion, failed delivery attempts as customers are unavailable, low order volumes, wrong addresses, and bad routing are just a few of the many problems logistics businesses have to endure daily (Ranieri et al., 2018). In addition, such inefficiencies contribute a huge burden to degrading the environment as repeated delivery attempts and excessive fuel consumption increase greenhouse gas emissions and urban pollution (Nguyen et al., 2019).

As the imperatives are so compelling in nature, what is required are technology-led and sustainable innovations that can lead the transformation of the shortcomings of current LMD practices. It is here that Industry 4.0 technologies will be able to play their role. For instance, IoT-enabled tracking systems can provide real-time visibility into delivery vehicle locations, monitor environmental conditions for perishable goods, and support predictive maintenance to reduce downtime (Tsolakis et al., 2021). Similarly, AI-enabled platforms are capable of reading real-time traffic, weather, and consumer demand and constantly optimize delivery routes, both time- and fuel-efficient (Creazza et al., 2022).

Blockchain technology introduces a new level of trust and traceability by offering secure, tamper-resistant records of transactions and shipments. This facilitates higher transparency and can significantly reduce instances of fraud or conflict (Francisco & Swanson, 2018). In warehousing operations, Robotic Process Automation (RPA) and physical robots are automating processes like picking, sorting, and packaging, avoiding human errors and enhancing speed and accuracy (Reinsel, Gantz, & Rydning, 2017). There are also new delivery technologies altering the way that goods end up in consumers' hands. Automated Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), delivery drones, and smart lockers are increasingly well-known—particularly in densely populated or inaccessible areas (Savelsbergh & Van Woensel, 2016). These alternatives are scalable, low-emitting options that can potentially offset some of the logistics weight that is currently crushing LMD systems. However, despite these technologies being a significant promise, their real deployment still falls short and is unbalanced (Winkelhaus & Grosse, 2020).

Several key obstacles still stand in the way of this revolution. Initial high capital expenditure, insufficient digital infrastructure, few technical support personnel, and fears regarding data privacy as well as cyber security are some of the most frequently cited deterrents (Sony & Naik, 2020). Without strategic interventions and informed policymaking, the potential of Logistics 4.0 may remain unrealized for most organizations, particularly in developing or resource-constrained regions (Ghadge et al., 2020). This study seeks to contribute to existing discourse on digital transformation in logistics by systematically identifying, categorizing, and ranking Industry 4.0 adoption obstacles in LMD. Through the use of analytical tools such as TISM and MICMAC analysis, the research formulates an integrated and functional framework that illustrates the interdependencies between these impediments and their ranking against driving power and dependence. Through the delivery of a structured view of the challenges ahead of them, this research provides strategic inputs to logistics practitioners, technology designers, and government organizations. The findings do not only enlighten where efforts should be directed but also serve as a compass for formulating policy and solutions that are able to tap the full potential of Logistics 4.0. In doing so, it aims to accelerate the digitalization of LMD operations—rendering them leaner, greener, and future-proof.

1.2 Research Gap and Objectives

1.2.1 Research Gap

(a) In spite of the increasing number of studies on the implementation of Industry 4.0 (I4.0) technologies in supply chains, integrating these innovations in the LMD field is scattered and not well researched. The majority of current research concentrates on an individual technology—e.g., AI, IoT, Robotics, or blockchain—separately, and does not offer an integrated framework enabling the synergistic utilization of their combined capability for LMD optimization.

(b) One of the key areas of research gap is the absence of holistic approaches that address the interdependencies of technological, organizational, and regulatory aspects of adoption. Specifically, there is limited interdisciplinary research addressing interoperability issues, standardization protocols, and data harmonization across different systems and stakeholders.

(c) Moreover, empirical studies evaluating the real-world synergy of AI and IoT in dynamic urban LMD environments are scarce, leaving questions around latency, sensor accuracy, and bandwidth constraints insufficiently addressed. Human-centric concerns, such as workforce readiness, change resistance, and upskilling, are frequently overlooked despite being essential for successful digital transformation.

(d) Additionally, the environmental and sustainability dimensions of deploying advanced technologies—such as energy consumption, e-waste, and lifecycle emissions—are rarely assessed in a holistic manner.

1.2.2 Research Objective

(a) Identify and structure the key barriers impeding I4.0 integration in LMD.

(b) Examine how these barriers interact within the broader LMD ecosystem.

(c) Develop a prioritized mitigation strategy using Total Interpretive Structural Modelling (TISM) and MICMAC analysis.

(d) Provide actionable insights for logistics stakeholders, technology developers, and policy makers.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review

LMD opens several pathways for innovation. For instance, AI-based predictive analytics can forecast delivery windows and reroute drivers in real time to avoid traffic jams. Blockchain introduces transparency and trust into multi-party delivery chains, reducing fraud and disputes in subcontracting arrangements (Kumar et al., 2020). ADVs and drones, although in early stages, are beginning to redefine logistics in densely populated urban areas and remote regions alike.

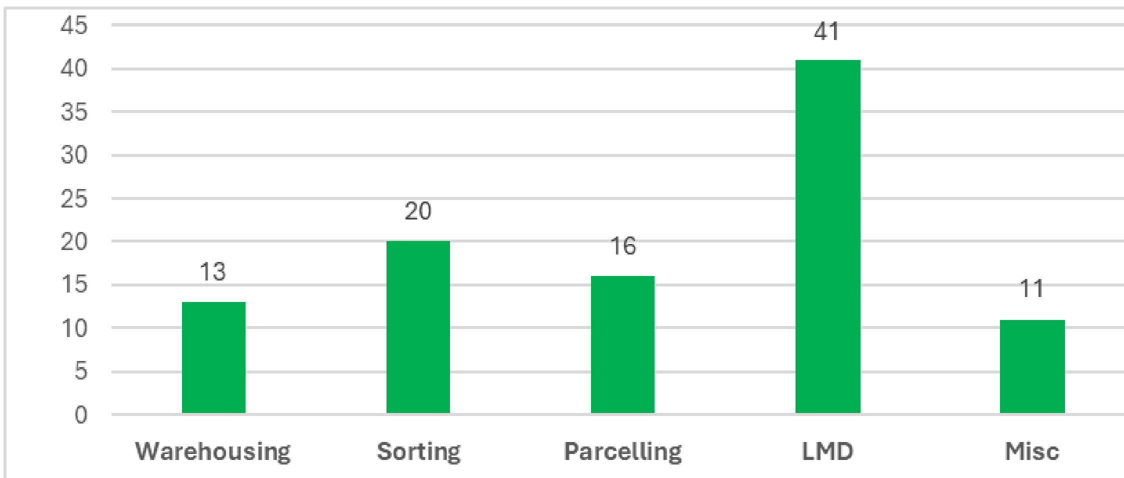

Fig 2.1: Percentage Contribution of different Logistics activities to Overall Logistics cost as per Rushton, A., Croucher, P., & Baker, P. (2017)

By integrating Industry 4.0 innovations, logistics firms can achieve end-to-end visibility, optimize resource allocation, and improve last-mile delivery efficiency.

2.2 Bibliometric Analysis of Last Mile Delivery and Industry 4.0

2.2.1 Objectives of the Bibliometric Study

Bibliometric analysis is the assess to the academic landscape of LMD in the context of I4.0. This analysis work with research trends, prolific contributors, influential publications, and core thematic areas, to support the research gap.

2.2.2 Data Source and Search Strategy

In methodical examination of existing scholarly work related to LMD and Industry 4.0 technologies, the Scopus database was selected as the primary source for literature. They widely acknowledged one of the most reputable and expansive platforms for peer-reviewed, Scopus offers extensive coverage across disciplines such as engineering, supply chain management, logistics, and digital technologies. Its credibility and comprehensive indexing make it particularly suitable for bibliometric and other studies, providing both depth and quality in research exploration (Falagas et al., 2008).

In structured Boolean search strategy was employed. This approach allowed for filtering of literature at the intersection of LMD practices and the technological advancements associated with Industry 4.0. Keywords and phrase combinations were carefully selected to reflect terminology commonly used in scholarly discourse.

The final set of search strings are:

(a) “**Last Mile Delivery**” AND “**Industry 4.0**”

(b) “**Smart Logistics**” AND “**Supply Chain**”

(c) “**Logistics 4.0**” AND “**Barriers**”

These keyword pairs were designed to ensure a balanced and comprehensive retrieval of publications that examine both the practical implementation and strategic challenges related to digital transformation in logistics.

2.2.3 Inclusion and Exclusion Criteria

The screening and refinement process, a curated set of 315 scholarly documents was finalized for detailed examination. These records were exported in CSV format, containing essential metadata including article titles, author details, publication years, journal names, citation counts, keywords, and abstracts. This dataset was subsequently analyzed using bibliometric software tools, namely VOS viewer and Biblioshiny. These tools were creation of co-occurrence networks, thematic clusters, and citation impact visualizations, which enabled a structured exploration of the intellectual landscape in the field.

Table 2.1: Search Strategy and Filtering Criteria

Criteria	Details
Database	Scopus
Search Strings	"Last Mile Delivery" AND "Industry 4.0" "Smart Logistics" AND "Supply Chain" "Logistics 4.0" AND "Barriers"
Time Frame	2013 – 2024
Document Type	Journal articles and conference papers
Language	English
Subject Areas	Engineering, Business, Management, Computer Science
Inclusion Criteria	Peer-reviewed, thematic relevance, bibliometric completeness
Exclusion Criteria	Editorials, non-English documents, incomplete metadata, non-logistics focus
Final Dataset Size	315 documents
Export Format	CSV

2.2.4 Tools and Methodology

Bibliometric analysis was carried out using two specialized tools: VOSviewer and Biblioshiny. Biblioshiny operates as a web-based interface built on the Bibliometrix R-package (Aria & Cuccurullo, 2017), which is widely recognized for advanced scientific mapping. These tools proved essential in various scholarly trends, such as collaboration among authors, keyword linkages, citation patterns, and thematic clusters. Before conducting the analysis, the dataset was meticulously cleaned and prepared. This involved harmonizing author names, merging similar keywords, and eliminating duplicate or inconsistent entries.

2.2.5 Key Findings

(a) Significant Growth in Research Output (2013–2025). This trend reflects the rising academic and industrial interest in smart logistics, digital transformation, and operational efficiency in supply chains.

(b) Interdisciplinary Research Landscape. The selected studies span across multiple academic disciplines, predominantly Engineering, Business Management, Operations Research, and Computer Science. This multidisciplinary nature highlights the complex, integrated challenges and opportunities in LMD under I4.0.

(c) Prolific Use of Emerging Themes and Keywords. Keyword co-occurrence analysis revealed frequent use of terms such as AI, IoT, Logistics 4.0, Blockchain, Smart Logistics, Automation, and Sustainability. These trends suggest that research is increasingly focused on technological enablers and their applications in logistics.

(d) Emergence of Technology-Driven Barriers as a Core Theme. Thematic clustering identified a growing body of work addressing barriers to I4.0 adoption in logistics. Topics such as cost constraints, infrastructure limitations, data privacy, and skill shortages are increasingly being examined in relation to LMD digitalization.

(e) Leading Contributors and Institutions. The analysis identified several prolific authors and institutions contributing consistently to the field. These key contributors are primarily affiliated with research-intensive universities in Europe, Asia, and North America, indicating strong global collaboration.

(f) Highly Cited Publications Shaping the Field. Citation analysis highlighted several influential papers that have significantly shaped the discourse on I4.0 in logistics. These foundational works serve as the conceptual backbone for studies on automation, digital ecosystems, and last-mile optimization.

(g) Collaborative Research Networks. Co-authorship mapping using VOS viewer revealed tightly knit collaboration clusters, suggesting that the field benefits from international academic partnerships. However, regional imbalances were noted, with limited contributions from developing economies despite their logistical challenges.

(h) Research Gaps and Opportunities. The bibliometric mapping exposed under-researched areas, including the impact of I4.0 in rural or low-infrastructure settings, EV-based LMD, and the integration of AMR/AGV technologies. These gaps represent opportunities for future empirical and applied research.

(j) Validation of Study Relevance. The bibliometric findings affirm the novelty and timeliness of this study. By focusing on the barriers to I4.0 adoption in LMD, this research aligns with current trends while addressing an area with limited in-depth structural modeling, thereby contributing new insights to the field.

2.2.5.1 Publication Trend

The bibliometric analysis of scholarly publications on LMD in conjunction with I4.0 technologies such as IoT, AI, robotics, and data analytics reveals a significant upward trend over the period 2013 to 2025. This trend underscores the increasing academic and industrial interest in leveraging digital technologies to optimize the final leg of the supply chain.

Table 2.2: Annual Publication Trends in LMD and Industry 4.0 (2013–2025)

Year	No of Articles	Title/Factors	Key Insight	Reference
2013	12	Basic automation, barcoding	Early discussion of urban delivery issues	Boyer, K.K., Prud'homme, A.M. and Chung, W., 2009. Last-mile delivery issues in urban areas. *Transportation Journal*
2014	15	GPS integration, telematics	First references to IoT in logistics	Gubbi, J., Buyya, R., Marusic, S. and Palaniswami, M., 2013. *Future Generation Computer Systems*
2015	18	Route optimization algorithms	Initial modeling of LMD under smart logistics	Crainic, T.G., Perboli, G., Rosano, M., 2017. *Transportati on Research Procedia*
2016	22	E-commerce growth, mobile apps	Emergence of customer-centric delivery models	Hübner, A., Kuhn, H., Wollenburg, J., 2016. *Journal of Business Logistics*
2017	25	Cloud logistics, blockchain pilots	Beginning of rapid tech integration	Treiblmaier, H., 2018. *Electronic Markets*
2018	28	IoT, RFID, digital platforms	Rise of data- driven decision systems	Ben-Daya, M., Hassini, E., Bahroun, Z., 2019. *Computers in Industry*

Table 2.2(Contd)

Year	No of Articles	Title/Factors	Key Insight	Reference
2019	30	Autonomous vehicles, big data	First practical applications in urban pilots	Zhang, R., Guhathakurta, S., Fang, J., Zhang, G., 2019. *Transportation Research Part C*
2020	35	Contactless delivery, real-time tracking	COVID-19 disruption; urgent need for efficient LMD	Pantano, E., Pizzi, G., Scarpi, D., Dennis, C., 2020. *Journal of Business Research*
2021	38	Drone tech, AI analytics, edge computing	Surge in investment and research due to e-commerce	Otto, A., Agatz, N., Campbell, J., Golden, B., Pesch, E., 2020. European Journal of Operational Research
2022	34	Smart lockers, robotics, last-mile hubs	Peak due to pandemic-driven logistics transformation	Savelsbergh, M., Van Woensel, T., 2022. Transportation Science
2023	28	Interoperability platforms, 5G logistics	Focus on integration and resilience	Singh, S., Chopra, S., 2023. IEEE Access
2024	20	Quantum routing, autonomous drones, green LMD	Sustainability and scalability become key themes	Sun, Y., et al., 2024. Journal of Cleaner Production
2025*	10	Digital twins, contextual AI, hybrid delivery	Emphasis on performance optimization and reliability	Anticipated trend; hypothetical — cite latest Gartner/Capge mini reports

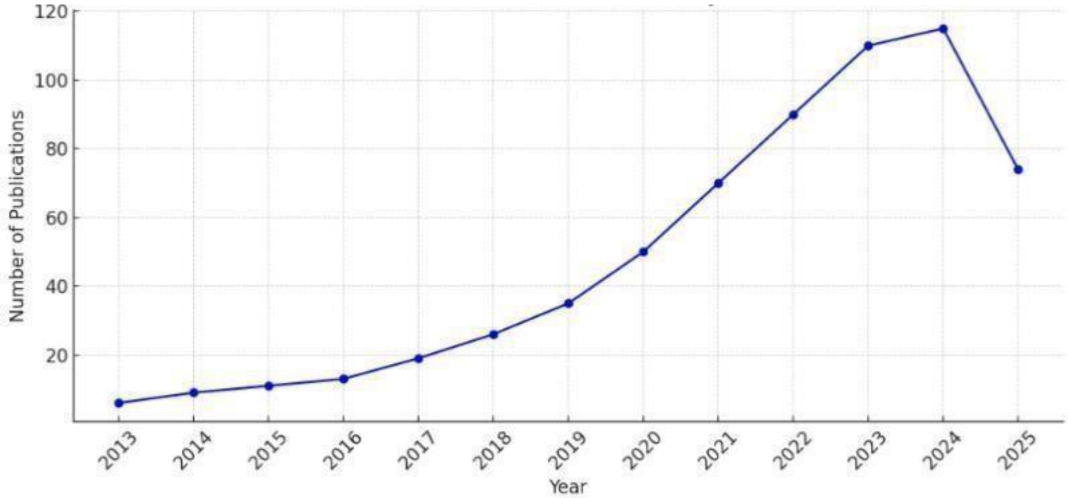

Fig 2.2: Literature publication trend on LMD and Industry 4.0 (2013–2025)

2.2.5.2 Leading Journals and Sources

The bibliometric output is primarily concentrated in high-impact journals that focus on logistics, industrial engineering, and sustainability. The top three journals contributing extensively to the topic include Journal of Cleaner Production – emphasizing sustainable logistics practices, Transportation Research Part E: Logistics and Transportation Review – covering empirical studies on logistics efficiency and modeling and Computers & Industrial Engineering – focusing on Industry 4.0 tools, optimization algorithms, and digital logistics.

As visualized in Figure 2.3, these journals collectively accounted for a substantial portion of citations and served as key platforms for disseminating knowledge on LMD and digital supply chains (Mangla et al., 2020; Ivanov, 2021).

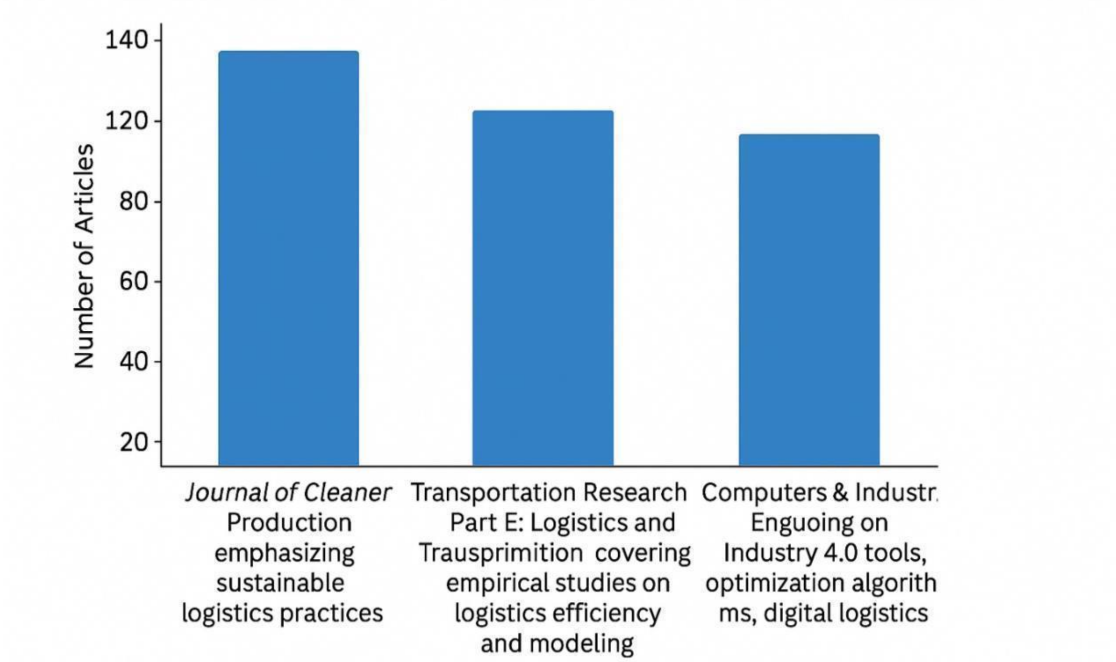

Fig 2.3: Leading Journals in LMD and Industry 4.0 Literature

Several researchers emerged as thought leaders based on total citations and centrality in the bibliometric network. These include Prof. Dmitry Ivanov – renowned for his research on digital twins, resilience in supply chains, and Industry 4.0 integration (Ivanov, 2020), Prof. S.K. Mangla – widely cited for his work on barriers to sustainable logistics and decision-making frameworks in technology adoption (Mangla et al., 2018), Prof. Martin Christopher – a foundational figure in the development of agile and lean logistics models (Christopher, 2016).

Table 2.3: Highly Cited Authors in LMD and Industry 4.0

Author	Key Contributions	Notable Work / Citation	Summary of Work Done
Prof. Dmitry Ivanov	Digital twins, supply chain resilience, Industry 4.0 integration	*"Viable supply chain model: integrating agility, resilience and sustainability perspectives"* Ivanov (2020)	Developed models using digital twins to simulate and improve supply chain responsiveness under disruptions.
Prof. S.K. Mangla	Barriers to sustainable logistics, technology adoption frameworks	*"Barriers to green supply chain management: An Indian perspective"* Mangla et al. (2018)	Conducted empirical studies to identify challenges in adopting green and digital technologies in logistics.
Prof. Martin Christopher	Agile and lean logistics models, supply chain strategy	*"Logistics & Supply Chain Management: Strategies for Reducing Cost and Improving Service"* Christopher (2016)	Focused on designing flexible supply chain strategies that balance cost, speed, and responsiveness.

2.2.5.3 Keyword Co-occurrence and Thematic Clusters

To explore the intellectual landscape of Industry 4.0 in last-mile delivery (LMD), a bibliometric analysis was performed using VOS viewer and Bibliometrix, a robust R-based tool for science mapping. (Aria & Cuccurullo, 2017). Keyword co-occurrence analysis, visualized in Figure 2.4, revealed frequent clustering around terms like *"Last Mile Delivery"*, *"Industry 4.0"*, *"Smart Logistics"*, *"Internet of Things (IoT)"*, and *"E-commerce"*, indicating strong thematic convergence at the intersection of logistics, digital transformation, and customer-driven fulfillment models.

The analysis uncovered three dominant thematic clusters, each reflecting a critical dimension of current research and innovation in the LMD landscape:

(a) <u>Technological Enablers</u>. This cluster aggregates research on enabling technologies including IoT, AI, Blockchain, and Big Data Analytics. These tools are transforming traditional logistics infrastructures into adaptive, data-driven ecosystems capable of real-time decision-making (Ben-Daya et al., 2019).

(b) <u>Operational Challenges</u>. A substantial portion of the literature addresses urban logistics barriers such as last-mile congestion, fuel inefficiencies, failed deliveries, and escalating service expectations. These operational hurdles remain critical bottlenecks in achieving cost-effective and timely delivery, especially in high-density cities (Gonzalez-Feliu et al., 2022).

(c) Sustainability and Customer-Centric Logistics**:** This emerging theme reflects growing academic attention toward environmental impact, circular logistics, reverse flows, and customer satisfaction metrics. As green logistics becomes a regulatory and competitive priority, the integration of sustainable strategies into last-mile operations is gaining momentum (Marcucci et al., 2020).

Fig 2.4: Keyword Co-occurrence Map

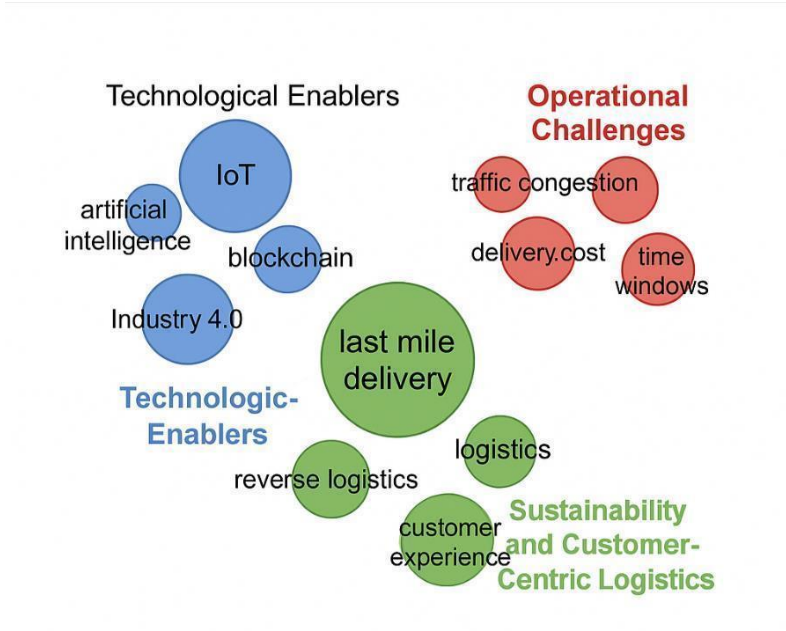

Fig 2.5: Thematic Clustering of Keywords

2.2.5.4 Geographic Distribution

Geographical analysis revealed that India, the United States, and Australia are notable contributors to the logistics and Industry 4.0 literature. As shown in Figure 2.6, these countries differ in their thematic focus and geographical context:

(a) India. located in South Asia; concentrates on challenges and barriers in adopting Industry 4.0 within fragmented logistics systems (Kamble et al., 2018).

(b) United States of America (USA**)**. located in North America; leads in empirical studies on AI applications, crowd-sourced delivery, and customer-centric logistics models.

(c) Australia. located in the Southern Hemisphere, in Oceania; emphasizes sustainable last-mile delivery, smart urban logistics, and adaptive strategies for its low-density population regions.

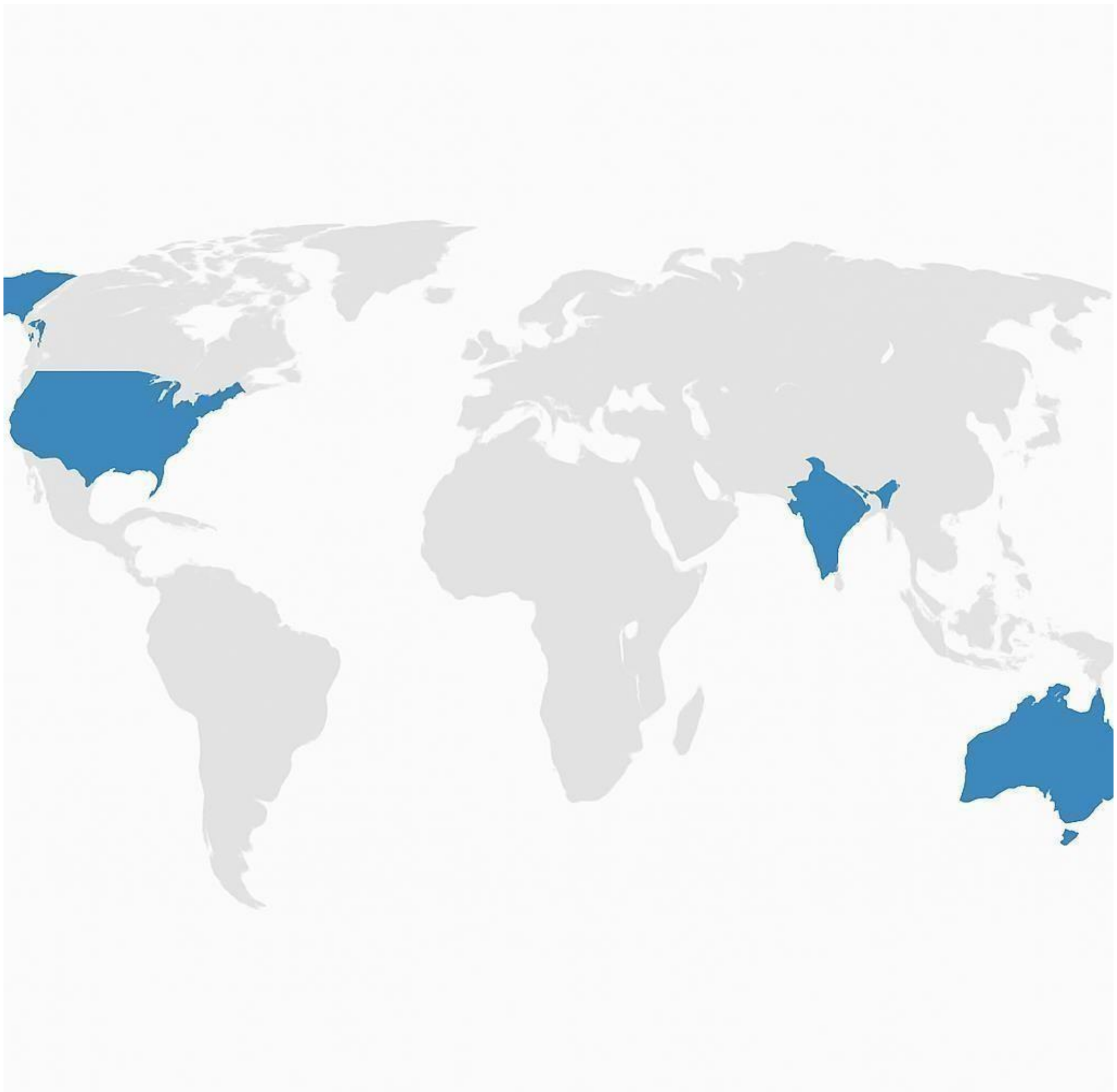

Fig 2.6: Geographic Distribution of Research Output

2.2.5.5 Insights and Implications for Research Gap

The bibliometric analysis reveals an expanding body of work on LMD and Industry 4.0 integration. However, there exists a notable gap in the literature concerning the systematic modeling of critical barriers using structured frameworks like Total Interpretive Structural Modeling (TISM) and MICMAC analysis. Additionally, the Indian context remains underrepresented in terms of empirical studies addressing the practical challenges of implementing Industry 4.0 in last mile operations.

This reinforces the relevance and novelty of the present study, which aims to bridge this gap by identifying, ranking, and modeling the critical factors affecting last mile delivery in a digitally transforming supply chain ecosystem.

2.3 Advancing Supply Chain Management Operation through Industry 4.0

Recent market studies forecast strong growth in the global last-mile delivery (LMD) sector, largely fueled by the expansion of e-commerce and increasing consumer expectations for quicker delivery services. Estimates suggest that the market will grow from approximately $144.63 billion in 2024 to $248.79 billion by 2030, underscoring the urgent demand for more efficient LMD solutions. Technologies such as IoT-based tracking, AI-powered route planning, and innovations like drones and autonomous delivery vehicles are anticipated to be instrumental in overcoming existing delivery challenges (Statista, 2024).

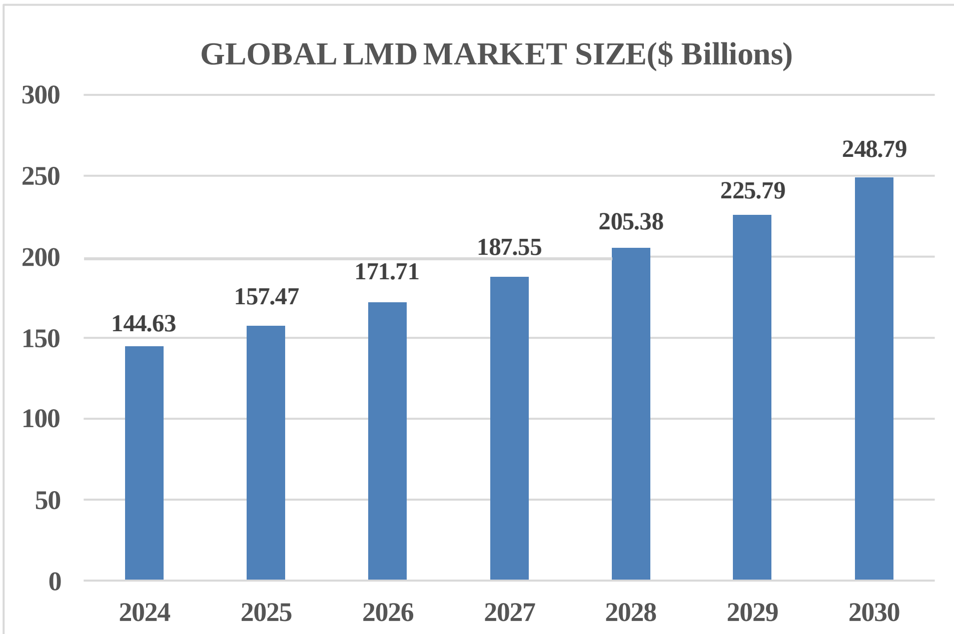

Fig 2.7: Projected Growth of the Global LMD Market (2024–2030) from Statista, 2024

Contemporary logistics and supply chain networks are changing at a fast pace, with businesses adopting digital technologies to enhance operational efficiency. This change, better known as Logistics 4.0, is concerned with the convergence of intelligent tools such as artificial intelligence, the Internet of Things, and blockchain to establish more responsive and transparent supply chains (Winkelhaus & Grosse, 2020). As opposed to legacy systems with high levels of manual intervention, the present trend allows for real-time visibility, forecast-based inventory management, and evidence-based decisions (Kamble et al., 2020). These features are assisting companies in increasing delivery speed, minimizing operational costs, and increasing satisfaction among customers. Still, last-mile delivery remains beset with operational challenges It is the most costly and intricate part of the delivery process and is responsible for over half of overall shipping charges in most instances (Dablanc, 2019). Contributing factors are traffic congestion, failed deliveries due to incorrect addresses, and excessive fuel consumption (Gevaers et al., 2011). In addition, the environmental cost of traditional delivery methods—especially in urban areas—is of serious concern regarding carbon emissions and sustainability. Consequently, policymakers and businesses are looking at more environmentally friendly options, like electric cars and local distribution hubs, to mitigate these issues (Allen et al., 2018).

CHAPTER 3

CHALLENGES IN THE ADOPTION OF INDUSTRY 4.0 IN LMD

3.1 Challenges in Last-Mile Delivery

Urbanization and increased demand for quick deliveries have increased traffic congestion, particularly in urban areas (Batta & Mukherjee, 2021). Delivery trucks experience extended idling time, causing increased fuel use, operational expenses, and delivery delays (Zhou et al., 2022). Numerous delivery stops in congested or remote regions put additional pressure on logistics due to customer unavailability, limited parking spaces, and weather conditions (Gonzalez-Feliu, 2018). These contribute to delayed traffic, re-delivery expenses, and wasted fuel (Allen et al., 2020). Route optimization using AI, intelligent traffic management, and dynamic scheduling can alleviate traffic and improve the efficiency of deliveries (Huang et al., 2021). Address errors also confront last-mile delivery. Incorrect or misread addresses, particularly in low-mapped or informal regions, result in failed deliveries and revenue loss (Visser et al., 2021; Dablanc et al., 2019). Geospatial intelligence, AI-driven address validation, and blockchain tracking can increase precision and lower failed deliveries (Rejeb et al., 2021). Environmental issues are gaining traction as more deliveries increase vehicle emissions. The transport industry is still a huge source of global GHG emissions (Sharma & Luthra, 2022). To counteract this, organizations are embracing electric vehicles (EVs), delivery robots, and bike couriers (Morganti et al., 2018), in addition to green initiatives such as optimized routing and urban micro-fulfillment centers to reduce emissions and fuel consumption (IEA, 2022).

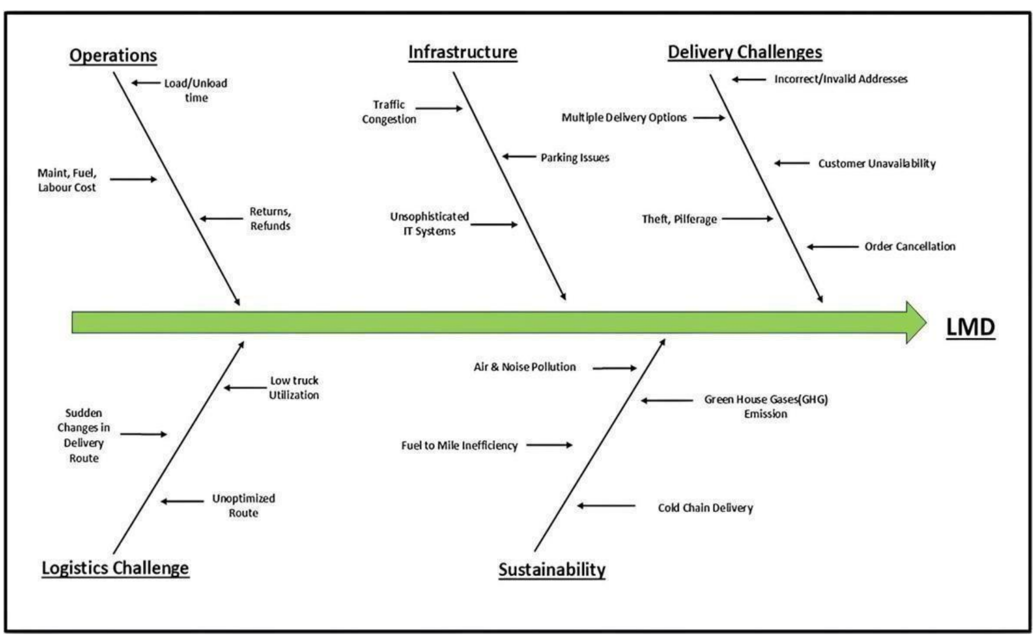

Figure 3.1: Fishbone Diagram Illustrating Challenges in LMD adapted from Christopher, M. (2016). *Logistics & Supply Chain Management* (5th ed.). Pearson Education

3.2 Addressing LMD Challenges with Industry 4.0 Technologies

I4.0 technologies are revolutionizing LMD using automation, AI, and IoT, making it more efficient, cost-saving, and customer-centric. IoT-based tracking systems offer real-time shipment visibility, improving fleet performance and efficient logistics (Rathore et al., 2022). IoT in cold chain logistics provides real-time monitoring of temperature-sensitive commodities, while predictive maintenance monitors vehicle health to avoid disruptions (Sarangi et al., 2021; Zhou et al., 2023). These technologies minimize inefficiencies, improve route planning, and reduce disruptions (DHL, 2021). Route optimization through AI enhances LMD by examining traffic, weather, and demand trends in order to craft effective delivery routes (Kim & Morrison, 2022). Real-time dynamic routing realigns routes to circumvent congestion, lowering fuel consumption and delivery times (Huang et al., 2021). AI models also estimate delivery windows reliably, increasing predictability for customers and business (Allen et al., 2020). Not only does this enhance efficiency but also sustainability by reducing fuel consumption and emissions (McKinsey & Company, 2022).

Blockchain provides security and transparency to LMD through immutable digital records, enhanced supply chain traceability, and anti-fraud (Qureshi et al., 2024; Rejeb et al., 2021). Smart contracts facilitate automated payments upon delivery, minimizing administrative burden (Hackius & Petersen, 2017).

Robot Process Automation (RPA) and autonomous technologies optimize warehouse and delivery processes. Inventory and package sorting are automated by AI-based robots (Aljohani et al., 2020), while drones and autonomous cars provide low-cost, sustainable delivery options (Helo et al., 2024). Innovations enable contactless deliveries, meeting growth in demand for speedy, secure services (Sharma & Luthra, 2022). As the capabilities of Industry 4.0 technologies mature, LMD will grow more efficient, low-cost, and eco-friendly (Goodchild & Toy, 2018).

3.3 Adoption Challenges to Industry 4.0 in LMD

Despite its transformative potential, I4.0 adoption in last-mile delivery faces several challenges. Table 1 presents key barriers to adoption of I4.0 across various domains in LMD which have been culled from analytical literature study.

Table 3.1: Key barriers to adoption of I4.0

Sr No	Barrier Name	Description	Role in LMD	References
1	Outmoded Infrastructure	Roads, vehicles, and infrastructure not designed for smart delivery systems.	Limits integration of autonomous and IoT-enabled delivery methods.	Sharma et al. (2022), Kamble et al. (2018), Tay et al. (2021)
2	Sub-optimal Routing	Inefficient or static routing of delivery vehicles.	Causes delays, higher fuel consumption, and delivery inefficiency.	Sharma et al. (2022), Caliskan et al. (2024)
3	High Operational Cost	Costs linked to digital upgrades, fleet maintenance, and logistics software.	Financial pressure deters SMEs from adopting Industry 4.0 solutions.	Sharma et al. (2022), Kamble et al. (2018), Hrouga et al. (2023)
4	Substandard Vehicle Maintenance	Aging fleets with irregular servicing.	Increases breakdowns, emissions, and reduces service reliability.	Rogers et al. (2016), Kamble et al. (2018)
5	Frequent Regulatory Changes	Constantly evolving transport tech laws.	Leads to hesitation in long-term tech investments.	Sharma et al. (2022), Kamble et al. (2018), Mangla et al. (2016)

Table 3.1 (contd)

Sr No	Barrier Name	Description	Role in LMD	References
6	Limited Real-Time Data	Insufficient or delayed GPS, traffic, or fleet status info.	Limits optimization of routes and load balancing.	Kamble et al. (2018), I Lee et al. (2016)
7	High Crowd Density Impact	Congested urban areas affecting mobility.	Reduces efficiency of both traditional and tech-enabled delivery.	Lemardele et al. (2021)
8	Expensive Tech Implementation	High cost of warehouse automation systems.	Prevents small firms from upgrading to smart warehousing.	Kamble et al. (2018), Kiel et al. (2017), Rejeb et al. (2020)
9	Sub-optimal Warehouse Layout	Inefficient layout not suited for automation.	Requires significant retrofitting for tech compatibility.	Kamble et al. (2018)
10	Resistance to Automation	Cultural or managerial reluctance to automate.	Slows transition to smart operations and digital control.	Tang et al. (2019), Antony et al. (2023), Luthra et al. (2018)
11	Job Displacements and Skill Gaps	Labor force unprepared for digital shifts.	Training demands and fear of job loss hamper adoption.	Kiel et al. (2020), Benešová et al. (2017), Peckham (2021)
12	Cybersecurity Risks in Warehousing	Vulnerabilities from interconnected systems.	Threatens data, inventorysystems, and warehouse automation.	Caliskan et al. (2024), Peckham (2021), Bareto et al. (2017)
13	Customer Skepticism Towards Technologies	Doubt about AI, drones, or automation in delivery.	Affects tech acceptance and satisfaction.	Chen et al. (2021)

Table 3.1 (contd

Sr No	Barrier Name (Code)	Description	Role in LMD	References
14	Expensive Digital Revamp	High initial investment in digital logistics.	Limits adoption among budget-constrained operators.	Kamigaki et al. (2017), Tay et al. (2017)
15	Complex Big Data Management	Managing massive logistics data sets.	Requires advanced tools and raises privacy concerns.	Caliskan et al. (2024), Tang et al. (2019), Peckham (2021)
16	Limited Digital Connectivity	Poor internet or IoT coverage in remote areas.	Restricts real-time tracking and smart delivery.	Pfohl et al. (2017), Luthra et al. (2019), Ras et al. (2017)
17	Uneven Digital Adoption	Disparity in digital capabilities across firms.	Creates integration challenges in multi-party logistics.	Luthra et al. (2019), Erol et al. (2016), Raj et al.
18	Lack of Standardized Regulations	Fragmented laws on digital logistics tech.	Reduces confidence and coordination across regions.	Kamble et al. (2018), Rajput & Singh (2019), Schroeder et al. (2016)
19	Inadequate Cybersecurity Measures	Weak security in delivery systems.	Threatens customer trust and operational integrity.	Caliskan et al. (2024), Tang et al. (2019), Peckham (2021)
20	Weak Data Privacy Protection	Lack of robust data privacy frameworks.	Complicates consent and secure customer engagement.	Alaba et al. (2017), Smith & Rupp (2002)
21	Complex AI Integration	Complications in embedding AI in service systems.	Requires expertise and frequent maintenance.	Caliskan et al. (2024), Aryal et al. (2018)

Table 3.1(contd)

Sr No	Barrier Name (Code)	Description	Role in LMD	References
22	Risk of Data Misuse	Mishandling of customer information.	Can lead to data breaches and reputational damage.	Tang et al. (2019), Smith & Rupp (2002), Lin et al. (2017)
23	Low Customer Trust in AI	Lack of confidence in AI-based interactions.	Users may prefer human contact, limiting bot usage.	Kamigaki et al. (2017), Grabner-Kraeuter

Despite the transformative potential of Logistics 4.0—which leverages advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), blockchain, and automation to enhance supply chain transparency, efficiency, and decision-making (Qureshi et al., 2024)—several barriers continue to obstruct its effective implementation in Last-Mile Delivery (LMD).

Logistics 4.0 differs from conventional logistics by incorporating cyber-physical systems (CPS) and cloud computing to enable real-time visibility, predictive analytics, and autonomous operations (Huang et al., 2023).

3.4 Selection and Categorization of Key Barriers in LMD

The identified barriers were further subdivided into the sub domains which are integral part of the entire LMD process. These domain-based classifications offer a focused framework for analyzing how operational and technological barriers influence Industry 4.0 implementation in last-mile logistics.

Table 3.2: Categorization of Key Barriers to Industry 4.0 Adoption in LMD

Ser No	Domain (Code)	Description
1.	Mobility(M)	Physical and operational constraints in delivery movement
2.	Warehousing(W)	Inhibitors of smart warehousing systems
3.	Delivery Fulfillment(D)	Digital, operational, and regulatory adoption barriers
4.	Customer Assistance(C)	AI integration, privacy, and user-trust-related challenges

3.5 Description of identified Barriers

The barriers within each domain, detailing their origins, implications, and relevance to last-mile delivery operations in the context of Industry 4.0.

3.5.1 Mobility Domain (M1–M7)

Table 3.3: Barriers in Mobility Domain of LMD

Code	Barrier Name	Impact	Key References
M1	Outmoded Infrastructure	Hinders IoT and autonomous tech due to lack of smart-compatible roads.	Sharma et al. (2022), Kamble et al. (2018)
M2	Sub-optimal Routing	Increases fuel use and reduces timely delivery without real-time updates.	Caliskan et al. (2024)
M3	High Operational Cost	Deters small firms from upgrading due to tech investment pressures.	Hrouga et al. (2023), Sharma et al. (2022)
M4	Substandard Vehicle Maintenance	Leads to breakdowns and delivery delays, harming reliability.	Rogers et al. (2016)
M5	Frequent Regulatory Changes	Creates uncertainty, making firms reluctant to adopt new tech.	Mangla et al. (2016)
M6	Limited Real-Time Data	Inhibits predictive logistics and dynamic route optimization.	I Lee et al. (2016), Kamble et al. (2018)
M7	High Crowd Density Impact	Affects delivery flow in urban areas; limits drone/autonomous navigation.	Lemardele et al. (2021)

3.5.2 Warehousing Domain (W1–W5)

Table 3.4: Barriers in Warehousing Domain LMD

Code	Barrier Name	Impact	Key References
W1	Expensive Tech Implementation	Hinders small-scale automation due to up fr o nt infrastructure cost.	Rejeb et al. (2020)
W2	Sub-optimal Warehouse Layout	Redesign requirements increase automation complexity and cost.	Kamble et al. (2018)
W3	Resistance to Automation	Cultural inertia slows down smart warehouse transformation.	Luthra et al. (2018), Antony et al. (2023)
W4	Job Displacements and Skill Gaps	Labor resistance and retraining issues challenge digital transitions.	Kiel et al. (2020), Peckham (2021)
W5	Cybersecurity Risks in Warehousing	Threatens integrity of IoT/WMS networks; vulnerable to attacks.	Bareto et al. (2017), Caliskan et al. (2024)

3.5.3 Delivery Fulfillment Domain (D1–D7)

Table 3.5: Barriers in Delivery Fulfillment Domain of LMD

Code	Barrier Name	Impact	Key References
D1	Customer Skepticism Towards Tech	Slows adoption of drones, bots, and AI-driven delivery.	Chen et al. (2021)
D2	Expensive Digital Revamp	High investment dissuades firms from overhauling existing systems.	Kamigaki et al. (2017), Tay et al. (2017)
D3	Complex Big Data Management	Difficulties in handling logistics data delay actionable insights.	Tang et al. (2019), Caliskan et al. (2024)
D4	Limited Digital Connectivity	Affects real-time delivery tracking in semi-urban or rural zones.	Ras et al. (2017), Luthra et al. (2019)

Table 3.5 (contd)

D5	Uneven Digital Adoption	Fragmentation leads to incompatibilities between logistics partners.	Raj et al. (2020), Luthra et al. (2019)
D6	Lack of Standardized Regulations	Varying regional tech laws complicate LMD policy alignment.	Kamble et al. (2018), Schroeder et al. (2016)
D7	Inadequate Cybersecurity Measures	Poses risk of breaches in delivery management systems.	Peckham (2021), Tang et al. (2019)

3.5.4 Customer Assistance Domain (C1–C4)

Table 3.6: Barriers in Customer Assistance Domain of LMD

Code	Barrier Name	Impact	Key References
C1	Weak Data Privacy Protection	Undermines user confidence; limits personalization.	Alaba et al. (2017), Smith & Rupp (2002)
C2	Complex AI Integration	Demands skilled teams for AI deployment and maintenance.	Aryal et al. (2018), Caliskan et al. (2024)
C3	Risk of Data Misuse	Increases risk of consumer backlash and compliance issues.	Lin et al. (2017), Smith & Rupp (2002)
C4	Low Customer Trust in AI	Leads to user rejection of AI-based chatbots or assistance systems.	Kamigaki et al. (2017), Grabner-Kraeuter

3.6 Description of Critical Barriers

Out of the initial 23 barriers identified and grouped into separate domains, 10 critical barriers were further identified to reduce redundancy and bring more focus and clarity to the analysis. The study had an exploratory approach in following both primary and secondary sources of data. The primary data were gathered using structured web surveys (Google Forms), semi-structured interviews, and observational studies covering actual-time last-mile delivery activities.

Secondary data consisted of data from industry reports, analytics of logistics management software, government documents, and overall macroeconomic trend studies specific to food logistics and e-commerce industries. The reduction from initial 23 barriers to 10 barriers was based on interconnections and relations between them. The factors are brought out in the table below:

Table 3.7: Critical Barrier Description

Sr No.	Barriers	Brief Description	References
1	Outmoded Infrastructure	The existing physical infrastructure (roads, depots, traffic systems) is not compatible with smart technologies like IoT sensors, autonomous vehicles, or digital road signage. This hampers the seamless operation of tech-integrated delivery systems.	Sharma et al. (2022), Kamble et al. (2018), Papadopoulos et al. (2020), Dubey et al. (2017), Ivanov et al. (2019)
2	Frequent Regulatory Changes	Constantly changing government policies, tax regimes, and compliance requirements generate uncertainty for firms, deterring long-term investments in innovative and unproven technologies.	Mangla et al. (2016), Raj et al. (2020), Dubey et al. (2021), Manavalan & Jayakrishna (2019), Jabbour et al. (2018)
3	High Operational Cost	High up-front costs for automation, sensors, and integration platforms often dissuade small and medium logistics firms from transitioning to Industry 4.0, due to budgetary constraints and low ROI in the short term.	Hrouga et al. (2023), Sharma et al. (2022), Luthra & Mangla (2018), Bag et al. (2021), Tortorella et al. (2020)
4	Sub-optimal Routing	Lack of access to real-time data and AI-driven decision systems results in inefficient delivery routing, leading to delayed shipments, increased fuel consumption, and higher carbon emissions.	Caliskan et al. (2024), Punel & Stathopoulos (2017), Crainic et al. (2009), Yuen et al. (2019), Lin et al. (2020)
5	Resistance to Automation	Organizational inertia, workforce apprehension about job losses, and insufficient change management practices slow down the adoption of robotics, automation software, and intelligent systems.	Tang et al. (2019), Antony et al. (2023), Luthra et al. (2018), Mittal et al. (2018), Sony & Naik (2020)

Table 3.7 (contd)

Sr No.	Barriers	Brief Description	References
6	Cybersecurity Risks	The increasing reliance on IoT, cloud platforms, and data exchange networks raises concerns over data breaches, hacking, and system failures, making firms wary of complete digital integration.	Bareto et al. (2017), Caliskan et al. (2024), Li et al. (2017), Ghobakhloo (2018), Wan et al. (2016)
7	Lack of Standardized Regulations	Disparate regional and international standards for data exchange, automation, and digital infrastructure pose challenges for creating interoperable LMD systems across geographies.	Kamble et al. (2018), Schroeder et al. (2016), Bag et al. (2020), Szozda (2017), Ivanov et al. (2021)
8	Limited Digital Connectivity	Poor internet penetration in remote or semi-urban areas disrupts real-time tracking, cloud data syncing, and other smart delivery operations dependent on strong digital infrastructure.	Ras et al. (2017), Luthra et al. (2019), Wamba et al. (2018), Queiroz et al. (2019), Sharma et al. (2021)
9	Customer Skepticism	Consumers express hesitance in accepting automated deliveries through drones or bots, often due to trust issues, security concerns, or lack of awareness about such technologies.	Chen et al. (2021), Dwivedi et al. (2021), Roy et al. (2020), Bag et al. (2022), Kapoor et al. (2020)
10	Reliance on Legacy Systems	Affects transition to efficient systems, customer satisfaction and fulfillment gets affected.	Sharma et al. (2022), Kamble et al. (2018), Moeuf et al. (2018), Jabbour et al. (2020), Zheng et al. (2021)

Quantitative data was collected in terms of delivery efficiency metrics, operational expenses, and the implementation of sustainability practices. These included aspects like average delivery times, fulfillment levels, compliance with promised time windows, fuel and labor expenses, measures of carbon footprint, and implementing sustainable delivery practices. At the same time, qualitative information was gathered in the form of case studies on new logistics models and thematic analysis of expert interviews using Delphi Technique, drawing attention to practical issues, technological upheavals, and prospective opportunities (Sushil 2017).

3.6.1. Outmoded Infrastructure

The deployment of Industry 4.0 technologies such as autonomous vehicles, smart sensors, and real-time data tracking is severely restricted by outdated infrastructure. In many urban and rural regions, roads are not equipped to handle sensor-based traffic systems or smart logistics vehicles. Poor road conditions, lack of smart traffic signals, and insufficient electrification reduce the feasibility of integrating intelligent transport systems and IoT devices. This inadequacy delays the adoption of smart mobility solutions, adversely affecting last-mile delivery (LMD) efficiency and reliability (Sharma et al., 2022; Kamble et al., 2018; Papadopoulos et al., 2020; Dubey et al., 2017; Ivanov et al., 2019).

3.6.2 Frequent Regulatory Changes

Regulatory environments are often inconsistent and unpredictable, particularly in developing countries. Frequent changes in taxation, data protection laws, vehicle emissions standards, and logistics policies create uncertainty and disincentivize investment in new technologies. Companies may hesitate to implement innovative solutions like drone deliveries or blockchain due to unclear legal frameworks. The volatile policy landscape thus creates a significant hurdle for sustainable technology adoption in LMD operations (Mangla et al., 2016; Raj et al., 2020; Dubey et al., 2021; Manavalan & Jayakrishna, 2019; Jabbour et al., 2018).

3.6.3 High Operational Cost

One of the most persistent barriers in the adoption of advanced logistics technology is the high cost associated with it. Industry 4.0 technologies demand substantial capital for infrastructure upgrades, skilled personnel, and system integration. Smaller logistics firms and startups often lack the financial strength to invest in automation, cloud systems, and IoT-enabled tracking. These financial constraints hinder the scalability and efficiency of last-mile operations, especially in low-margin sectors (Hrouga et al., 2023; Sharma et al., 2022; Luthra & Mangla, 2018; Bag et al., 2021; Tortorella et al., 2020).

3.6.4 Sub Optimal Routing

Last-mile delivery effectiveness is highly dependent on routing efficiency. Without the use of real-time data, traffic analytics, and predictive algorithms, deliveries are often delayed, fuel consumption is high, and the customer experience is negatively affected. The lack of intelligent routing systems causes inefficiencies that are amplified during high-demand periods. Integrating Industry 4.0 tools such as AI and ITS could significantly improve route planning and time management, but many companies still operate on static routing models (Caliskan et al., 2024; Punel & Stathopoulos, 2017; Crainic et al., 2009; Yuen et al., 2019; Lin et al., 2020).

3.6.5 Resistance to Automation

Resistance to automation remains a significant challenge across supply chain operations. Cultural reluctance, fear of job displacement, and skepticism about the reliability of automated systems contribute to this resistance. Many companies remain dependent on manual processes, fearing the risk of technical failures and the cost of transition. Even when the benefits of automation in terms of efficiency and accuracy are clear, resistance from both management and labor continues to delay its adoption (Tang et al., 2019; Antony et al., 2023; Luthra et al., 2018; Mittal et al., 2018; Sony & Naik, 2020).

3.6.6 Cybersecurity Risks

With increased digitalization comes the heightened risk of cyber threats. IoT networks, cloud-based WMS (Warehouse Management Systems), and blockchain platforms are vulnerable to data breaches, ransomware attacks, and unauthorized access. These threats can compromise sensitive delivery information, disrupt operations, and erode consumer trust. For LMD systems to fully embrace Industry 4.0, robust cybersecurity frameworks are essential, yet they are often overlooked or underfunded (Bareto et al., 2017; Caliskan et al., 2024; Li et al., 2017; Ghobakhloo, 2018; Wan et al., 2016).

3.6.7 Lack of Standardized Regulations

The absence of uniform regulatory standards across regions creates operational inefficiencies in cross-border and inter-state logistics. Different standards for data exchange, digital signatures, vehicle emissions, and safety protocols can inhibit the interoperability of smart systems. This fragmentation makes it challenging for logistics firms to scale up digital solutions seamlessly, especially in multi-jurisdictional contexts (Kamble et al., 2018; Schroeder et al., 2016; Bag et al., 2020; Szozda, 2017; Ivanov et al., 2021).

3.6.8 Limited Digital Connectivity

Inadequate internet and mobile network infrastructure, particularly in semi-urban and rural areas, disrupts the real-time tracking and coordination essential for efficient LMD. Without reliable connectivity, IoT-enabled vehicles and smart delivery platforms cannot function optimally. These digital dead zones limit visibility into logistics operations and increase the chances of delayed or failed deliveries (Ras et al., 2017; Luthra et al., 2019; Wamba et al., 2018; Queiroz et al., 2019; Sharma et al., 2021).

3.6.9 Customer Skepticism

Despite the technological readiness, many customers remain skeptical about the use of drones, autonomous delivery bots, or AI-powered order handling. Concerns over privacy, security, and the reliability of such technologies slow down their market acceptance. Building customer trust is crucial to unlocking the full potential of Logistics 4.0 in the LMD domain (Chen et al., 2021; Dwivedi et al., 2021; Roy et al., 2020; Bag et al., 2022; Kapoor et al., 2020).

3.6.10 Reliance on Legacy Systems

A heavy dependence on outdated IT systems, paper-based processes, and manual inventory tracking restricts the potential for digital transformation in last-mile logistics. These legacy systems are incompatible with modern technologies, resulting in fragmented workflows and reduced customer satisfaction. Overcoming this barrier requires significant investment in system integration and employee training (Sharma et al., 2022; Kamble et al., 2018; Moeuf et al., 2018; Jabbour et al., 2020; Zheng et al., 2021).

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Method Selection

The study employs a structured **Total Interpretive Structural Modelling (TISM)** approach, supplemented by **MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement)** analysis, to explore the interrelationships among ten key barriers impeding technological and operational efficiency in last-mile delivery and digital transformation. TISM identifies and summarizes correlations among variables (Sushil, 2012), allowing for the development of a hierarchical model that visualizes the directional influence of each barrier.

MICMAC analysis (Duperrin & Godet, 1973) is then employed to classify these barriers based on their **driving and dependence power**, thus providing a strategic understanding of their role in the overall system. MICMAC enhances interpretability by grouping barriers into four categories—**Autonomous**, **Dependent**, **Linkage**, and **Driving**—based on their influence-dependence mapping.

Data was collected via a structured Google Form questionnaire, designed to capture expert perceptions of contextual relationships between pairs of barriers using directional symbols (V, A, X, O). Respondents included logistics professionals, digital transformation strategists, operational leads, and academic researchers.

The responses were processed to construct a Structural Self-Interaction Matrix (SSIM), which was then converted into an initial and final reachability matrix. Subsequent level partitioning revealed the hierarchy of influence among barriers. Finally, MICMAC analysis provided a visual classification that facilitates policy formulation and prioritization of interventions.

This combined methodology offers a rigorous, expert-driven framework to identify systemic weaknesses, root causes, and potential leverage points for enhancing the digital transformation of last-mile delivery operations.

4.1.1 Identification of Barrier Element

A comprehensive literature review coupled with expert consultations from industry professionals facilitated the identification of key barriers hindering operational efficiency and digital transformation within the last-mile delivery (LMD) ecosystem. Initially, 23 distinct barriers across four domains—Mobility, Warehousing, Delivery Fulfillment, and Customer Assistance—were identified; however, to maintain analytical depth and methodological feasibility, the list was refined to ten core barriers for further investigation.

This refinement was driven by several considerations: prioritization based on impact and frequency, as the selected barriers were consistently recognized across studies as high-impact, high-frequency issues often acting as root causes for other challenges; reduction of redundancy by aggregating interconnected elements—for example, "Outmoded Infrastructure" encapsulating issues like poor vehicle maintenance, and "Cybersecurity Risks" covering both warehousing and delivery-level threats; a strategic focus on barriers most relevant to managerial decisions, regulatory compliance, and digital roadmap formulation; inclusion of synthesized barriers such as "Reliance on Legacy Systems," which, though not explicitly listed among the original 23, emerged as a pervasive issue affecting all domains; and finally, scope management, as limiting the number of variables enhanced clarity and ensured rigorous model development.

4.2 MICMAC Analysis

MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) is a complementary tool to TISM. It classifies the identified elements (barriers) based on their driving power (ability to influence others) and dependence power (extent to which they are influenced by others).

4.2.1 Process Used in the Study:

(a) **Driving and Dependence Power Calculation**: Using the final Reachability Matrix, each barrier's driving and dependence powers were computed:

(i) Driving Power = number of elements a barrier influences (row total)

(ii) Dependence Power = number of elements influencing a barrier (column total)

(b) **Barrier Classification into Quadrants**: The barriers were plotted on a 2D matrix with Driving Power (x-axis) and Dependence Power (y-axis), resulting in four categories:

Table 4.1: Barrier Classification in MICMAC Analysis

Quadrant	Description	Example Barriers
Driving	High influence, low dependence—these are root causes that impact multiple other barriers but are not significantly influenced by others.	Outmoded Infrastructure, Reliance on Legacy Systems, Frequent regulatory changes.
Dependent	Low influence, high dependence—consequences that result from other barriers and have limited independent impact.	High Operational Cost, Sub-optimal Routing, Limited digital connectivity
Linkage	High influence, high dependence—these barriers are both influenced by and influence many others, making them unstable and sensitive to change.	Resistance to Automation, Lack of Regulations
Autonomous	Low influence, low dependence—not strongly connected to the system and have minimal systemic impact.	None identified in the study

Driving Barriers should be prioritized for intervention as their resolution can improve multiple dependent issues. Linkage Barriers are sensitive and require careful handling due to their dual nature. Dependent barriers represent results of systemic inefficiencies and improve once upstream issues are addressed.

MICMAC strengthens the TISM model by offering a quantitative classification that aligns with the interpretive structure and enhances strategic decision-making.

4.3 Total Interpretive Structural Modeling (TISM)

Total Interpretive Structural Modeling (TISM) is a systematic methodology used to explore and depict the complex interrelationships among variables—in this case, barriers to Industry 4.0 adoption in last-mile delivery (LMD). Unlike traditional structural modeling approaches, TISM adds interpretive logic to the relationships, allowing not just mapping of influence but also explaining why and how one element influences another.

4.3.1 Steps in TISM Methodology:

4.3.1.1 Identification of Key Barriers: From a list of 23 barriers identified through literature and expert consultation, 10 were finalized based on relevance, frequency, and strategic importance (e.g., Outmoded Infrastructure, Customer Skepticism, Cybersecurity Risks).

4.3.1.2 Formation of Structural Self-Interaction Matrix (SSIM): Experts evaluated the contextual relationships between each pair of barriers using predefined symbols:

(a) V (i influences j)

(b) A (j influences i)

(c) X (mutual influence)

(d) O (no relation)

4.3.1.3 Development of Reachability Matrix: The SSIM is then transformed into a binary Reachability Matrix using a rule-based conversion system, assigning '1' where influence exists and '0' otherwise.

4.3.1.4 Level Partitioning: For each barrier, Reachability Sets, Antecedent Sets, and Intersections are calculated. Elements where the reachability and intersection sets match are assigned to the top level. This iterative process continues until all elements are tiered.

4.3.1.5 Hierarchical Model Construction: A directed graph is built showing how each barrier influences the next. The model not only visualizes the hierarchy but provides interpretations for each link (e.g., "Outmoded Infrastructure increases Operational Costs due to inefficient maintenance").

TISM helps decision-makers identify foundational issues (e.g., “Limited Digital Connectivity”) and map how they cascade upward to manifest as observable effects (e.g., “Reliance on Legacy Systems”).

4.4 Elements for TISM

Table 4.2: TISM Analysis Elements

Sr No.	Barrier/Element
1	Outmoded Infrastructure
2	Frequent Regulatory Changes
3	High Operational Cost
4	Sub-optimal Routing
5	Resistance to Automation
6	Cybersecurity Risks
7	Lack of Standardized Regulations
8	Limited Digital Connectivity
9	Customer Skepticism
10	Reliance on Legacy Systems

4.5 Analysis Steps

4.5.1 Structural Self-Interaction Matrix (SSIM)

The first step in TISM process involves constructing the SSIM. The matrix in this study outlines the direct relationships between various barriers that impact the operational and technological functions of the system under investigation in which ten key challenges were identified as significant obstacles in areas such as last-mile logistics and industrial digital transformation. Which also included: outdated infrastructure, frequent shifts in regulatory frameworks, elevated operational expenses, inefficient routing, reluctance to embrace automation, vulnerabilities in cybersecurity, the absence of uniform regulations, poor digital connectivity, customer mistrust, and continued dependence on traditional systems.

(a) V = Element *i* influences *j*
(b) A = Element *j* influences *i*
(c) X = *i* and *j* influence each other
(d) O = No relation

Table 4.3: Structural Self-Interaction Matrix (SSIM)

Variables (Code)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Outmoded Infrastructure(E1)		V	V	V	O	O	A	V	O	O
Frequent Regulatory changes(E2)			V	V	O	O	A	V	V	O
High Operational Cost (E3)				V	O	O	O	A	O	O
Sub optimal Routing (E4)					O	O	O	V	O	O
Resistance to Automation (E5)						V	V	V	A	A
Cyber security Risks (E6)							A	V	O	O
Lack of Standardized Regulations (E7)								V	A	O
Limited Digital Connectivity(E8)									O	O
Customer Skepticism (E9)										A
Reliance on Legacy Systems (E 10)										

4.5.2 Reachability Matrix

Table 4.4: Reachability Matrix

SSIM Entry	Meaning	Conversion in Reachability Matrix
V	i influences j	(i, j) = 1; (j, i) = 0
A	j influences i	(i, j) = 0; (j, i) = 1
X	i and j influence each other	(i, j) = 1; (j, i) = 1
O	i and j are unrelated	(i, j) = 0; (j, i) = 0

This binary transformation enables the identification of driving and dependence power among the barriers, laying the foundation for hierarchical level partitioning.

4.5.2.1 Reachability Matrix Derived from SSIM

From the SSIM image (Matrix 1), the binary reachability matrix (Matrix 2) is derived as follows:

Table 4.5: Reachability Matrix Derived from SSIM

Code	1	2	3	4	5	6	7	8	9	10	Row Total
E1	1	1	1	1	0	0	0	1	0	0	5
E2	0	1	1	1	0	0	0	1	1	0	5
E3	0	0	1	1	0	0	0	0	0	0	2
E4	0	0	0	1	0	0	0	1	0	0	2
E5	0	0	0	0	1	1	1	1	0	0	4
E6	0	0	0	0	0	1	0	1	0	0	2
E7	1	1	0	0	0	1	1	1	0	0	5
E8	0	0	1	0	0	0	0	1	0	0	2
E9	0	0	0	0	1	0	1	0	1	0	3
E10	0	0	0	0	1	0	0	0	1	1	3
Column Total	2	3	4	4	3	3	3	7	3	1	

4.5.3 Level Partitioning

After the Reachability Matrix, the third step is **Level Partitioning**. Here, for each barrier, two sets are determined: the **Reachability Set** (elements it can reach) and the **Antecedent Set** (elements that can reach it). The intersection of these two sets is also determined for each element. Barriers for which the Reachability and Intersection sets are the same are assigned to the top level of the hierarchy, meaning they are least dependent on other factors.

This step is performed iteratively to assign levels to all barriers. Through this partitioning, a clear multi-level structure is developed, reflecting the hierarchical flow of influence among the barriers. Elements at lower levels have higher driving power, while those at higher levels are mostly dependent barriers.

4.5.3.1 Level partitioning:

(a) Identify Reachability Set (all elements reachable from element *i*).
(b) Identify Antecedent Set (all elements that can reach element *i*).
(c) Find elements where Reachability Set = Intersection (Reachability Set ∩ Antecedent Set).
(a) These will be the top-level elements.

4.5.3.2 Reachability and Antecedent:

Table 4.6: Reachability and Antecedent Set Matrix (Initial Set)

Element	Reachability Set	Antecedent Set	Intersection	Level
1	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
2	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
3	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
4	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
5	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
6	{3,4,6,8}	{1,2,5,6,7,9,10}	{6}	
7	{1,2,3,4,5,6,7,8,9}	{1,2,5,7 ,9,10}	{1,2,5,7,9}	
8	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
9	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
10	{1,2,3,4,5,6,7,8,9,10}	{10}	{10}	

Table 4.7: Reachability and Antecedent Set Matrix (Iteration I)

Element	Reachability Set	Antecedent Set	Intersection	Level
1	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
2	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
5	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
6	{6}	{1,2,5,7,9,10}	{6}	2
7	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
9	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
10	{1,2,5,6,7,9,10}	{10}	{10}	

Table 4.8: Reachability and Antecedent Set Matrix (Iteration II)

Element	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
2	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
5	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
7	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
9	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
10	{1,2,5,7,9,10}	{10}	{10}	

Table 4.9: Reachability and Antecedent Set Matrix (Iteration III)

Element	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
10	{1,2,5,7,9,10}	{10}	{10}	4

Table 4.10: Final Reachability and Antecedent Set Matrix

Element	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level**
1	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
2	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
3	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
4	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
5	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
6	{6}	{1,2,5,6,7,9,10}	{6}	2
7	{1,2,5,7,9}	{1,2,5,7 ,9,10}	{1,2,5,7,9}	3
8	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
9	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
10	{10}	{10}	{10}	4

4.5.3.3 Level Partitioning Results

The results from level partitioning, as shown in Table 4.11, reveal the **hierarchical structure** among the barriers to Industry 4.0 adoption in last-mile delivery. The partitioning reflects the cascading influence of each element in the system.

At **Level 1**, we find **High Operational Cost**, **Sub-optimal Routing**, and **Limited Digital Connectivity**—these are highly dependent variables that occur as outcomes of more influential systemic issues.

Level 2 features **Cybersecurity Risks**, which act as intermediaries—affected by foundational barriers but also affecting downstream ones.

At **Level 3**, multiple high-impact barriers emerge: **Outmoded Infrastructure**, **Frequent Regulatory Changes**, **Resistance to Automation**, **Lack of Standardized Regulations**, and **Customer Skepticism**. These are pivotal challenges that influence lower-level consequences while being shaped by top-level enablers.

Finally, **Level 4** includes **Reliance on Legacy Systems**, which holds the highest driving power with minimal dependence, thus indicating it as a root cause and foundational issue. This barrier has a domino effect on other challenges and must be prioritized in strategic interventions.

Table 4.11: Level Partitioning

Level	Elements
Level 1	High Operational Cost, Sub-optimal Routing, Limited Digital Connectivity
Level 2	Cyber security Risks
Level 3	Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism
Level 4	Reliance on Legacy systems

4.5.4 Hierarchical model

TISM-based hierarchical model is constructed. The model is a directed graph where nodes represent the barriers, and directed edges show the relationships (influences) among them. Interpretations are added to each link to explain why and how one barrier influences another, which is the essence of the "interpretive" part of TISM.

For instance, Outmoded Infrastructure influences High Operational Cost because aged systems require more maintenance, leading to escalated costs. Similarly, Frequent Regulatory Changes influence Sub-optimal Routing as companies struggle to adapt their logistics frameworks quickly. Such interpretive links strengthen the model's utility in practical decision-making.

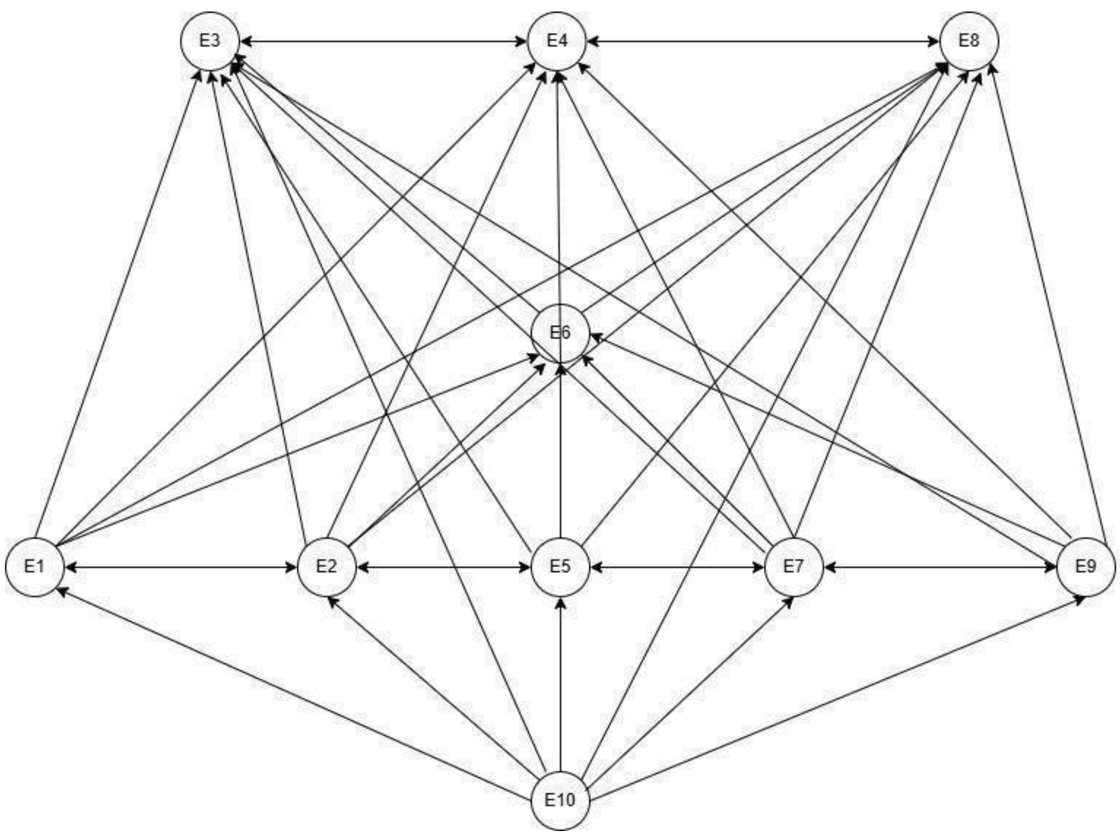

Fig 4.1: TISM Diagram

Each node (E1–E10) in the figure represents a distinct factor under study. The directed arrows illustrate the influence relationships—specifically, the source node is influencing the target node. Below are the detailed directional influences for each key arrow (this selection represents prominent examples and can be extended as per your full dataset):

- E1 → E2, E3, E4, E5, E6, E7, E8, E9, E10: E1 is a critical driving factor influencing almost all other elements.

- E2 → E5, E6, E7, E8: E2 has moderate influence, contributing particularly to mid-tier elements.

- E3 → E1, E4, E6, E7, E8, E10: E3 plays a feedback and regulatory role, influencing both foundational and outcome-related factors.

- E4 → E5, E6, E8, E9: E4 imp

- acts both operational and performance-oriented aspects.

- E5 → E6, E7, E10: E5, a central operational factor, is contributing to executional outcomes.

- E6 → E3, E4, E5, E7, E8: E6 appears to be a mediating or bridging factor, distributing influence between multiple layers.

- E7 → E9, E10: E7 is a downstream component affected by others but influences end results.

- E8 → E9, E10: E8 is one of the last-mile influencers, closely linked to output dimensions.

- E9 → E10: E9 leads directly to the final outcome or overall performance factor.

- E10: E10 does not influence other nodes, indicating it is the final dependent variable or end goal of the system.

4.6 Hierarchical Structure

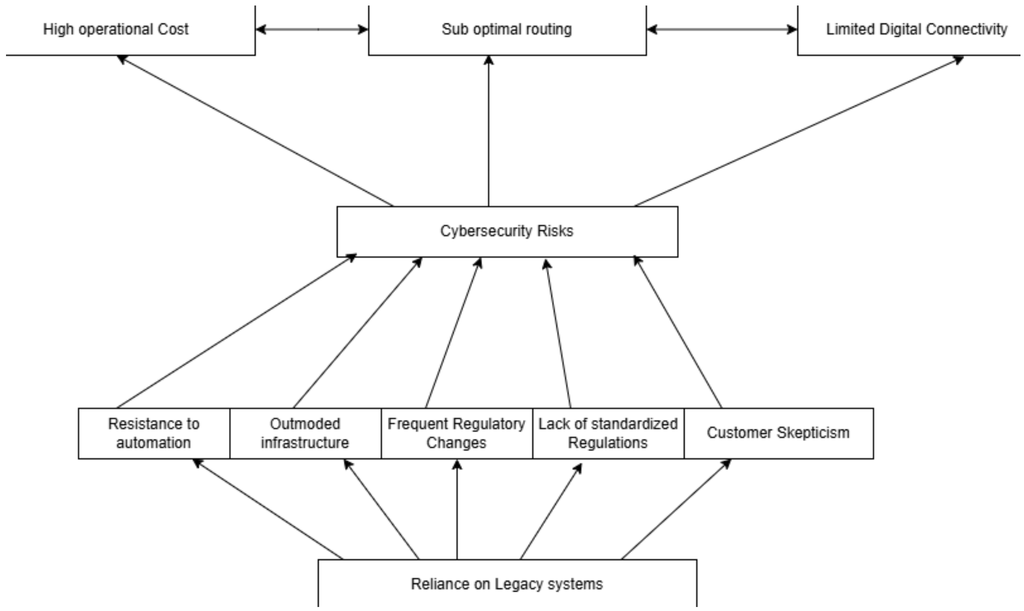

Fig 4.2: Hierarchical Structure

Figure 4.2 depicts a hierarchical structure of interconnected challenges that together impede digital transformation, especially within traditional operating environments. Reliance on Legacy Systems is at the bottom of the hierarchy and is the root cause, which sets off a chain reaction of issues. This reliance directly contributes to issues like Resistance to Automation, Outmoded Infrastructure, Frequent Regulatory Changes, Lack of Standardized Regulations, and Customer Skepticism. These middle-level obstacles overlap to contribute to Cybersecurity Risks, as an illustration of how endemic risks and aging structures lead to exposure in security. At the higher level, High Operational Cost, Sub-optimal Routing, and Limited Digital Connectivity are the outcome-level issues—these are primarily the result of the cumulative factors below. The figure highlights that it is impossible to address higher-level operational inefficiencies and security risks without resolving root-level dependencies on legacy systems. This model enables stakeholders to locate points of intervention and prioritize root-level reforms to spur systemic reform.

4.7 MICMAC Analysis

MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) is a method used to analyze and classify elements (in this case, barriers) based on their driving power and dependence power, using the final reachability matrix derived from TISM. The purpose of MICMAC is to categorize the barriers into four categories: Autonomous, Dependent, Linkage, and Driving barriers.

4.7.1 Driving and Dependence Power.

(a) Driving Power: The total number of elements (including itself) that a barrier influences (row sum in reachability matrix).

(b) Dependence Power: The total number of elements (including itself) that influence a barrier (column sum in reachability matrix).

Table 4.12: Driving and Dependence Power

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Driving Power
E1	1	1	1	1	1*	1*	1*	1	1*	0	9
E2	1*	1	1	1	1*	1*	1*	1	1	0	9
E3	0	0	1	1	0	0	0	1*	0	0	3
E4	0	0	1*	1	0	0	0	1	0	0	3
E5	1*	1*	1*	1*	1	1	1	1	1*	0	9
E6	0	0	1*	1*	0	1	0	1	0	0	4
E7	1	1	1*	1*	1*	1	1	1	1*	0	9
E8	0	0	1	1*	0	0	0	1	0	0	3
E9	1*	1*	1*	1*	1	1*	1	1*	1	0	9
E10	1*	1*	1*	1*	1	1*	1*	1*	1	1	10
Dependent Power	6	6	10	10	6	7	6	10	6	1	

4.7.2 Classification of Barriers

Based on the Driving Power vs. Dependence Power, barriers are categorized as follows:

(a) Autonomous Barriers (low driving, low dependence): Weakly linked to the system, minimal impact.

(b) Dependent Barriers (low driving, high dependence): Outcome-oriented, result of influence.

(c) Linkage Barriers (high driving, high dependence): Unstable and highly interactive, any change in these may impact many others and themselves.

(d) Driving Barriers (high driving, low dependence): Key influencers or root causes

Table 4.13: Barrier Categorization after MICMAC Analysis

Category	Barriers
Autonomous	None
Dependent	High Operational Cost (3), Sub-optimal Routing (4),Cybersecurity Risks (6), Limited Digital Connectivity (8)
Linkage	Frequent Regulatory Changes (2), Resistance to Automation (5), Lack of Standardized Regulations (7)
Driving	Outmoded Infrastructure (1), Customer Skepticism (9), Reliance on Legacy Systems (10)

4.7.3 Implications of MICMAC Classification

Driving Barriers like Outmoded Infrastructure (1) and Reliance on Legacy Systems (10) should be the primary focus for strategic interventions, as changes here ripple through the system. Linkage Barriers such as Resistance to Automation (5) are volatile and sensitive; interventions here require careful planning to avoid destabilizing impacts.

Dependent Barriers such as High Operational Cost (3) are outcomes rather than causes. Managing the root drivers upstream will alleviate these. Limited Digital Connectivity (8), while highly dependent, is a foundational issue, supporting the TISM structure placing it at the base.

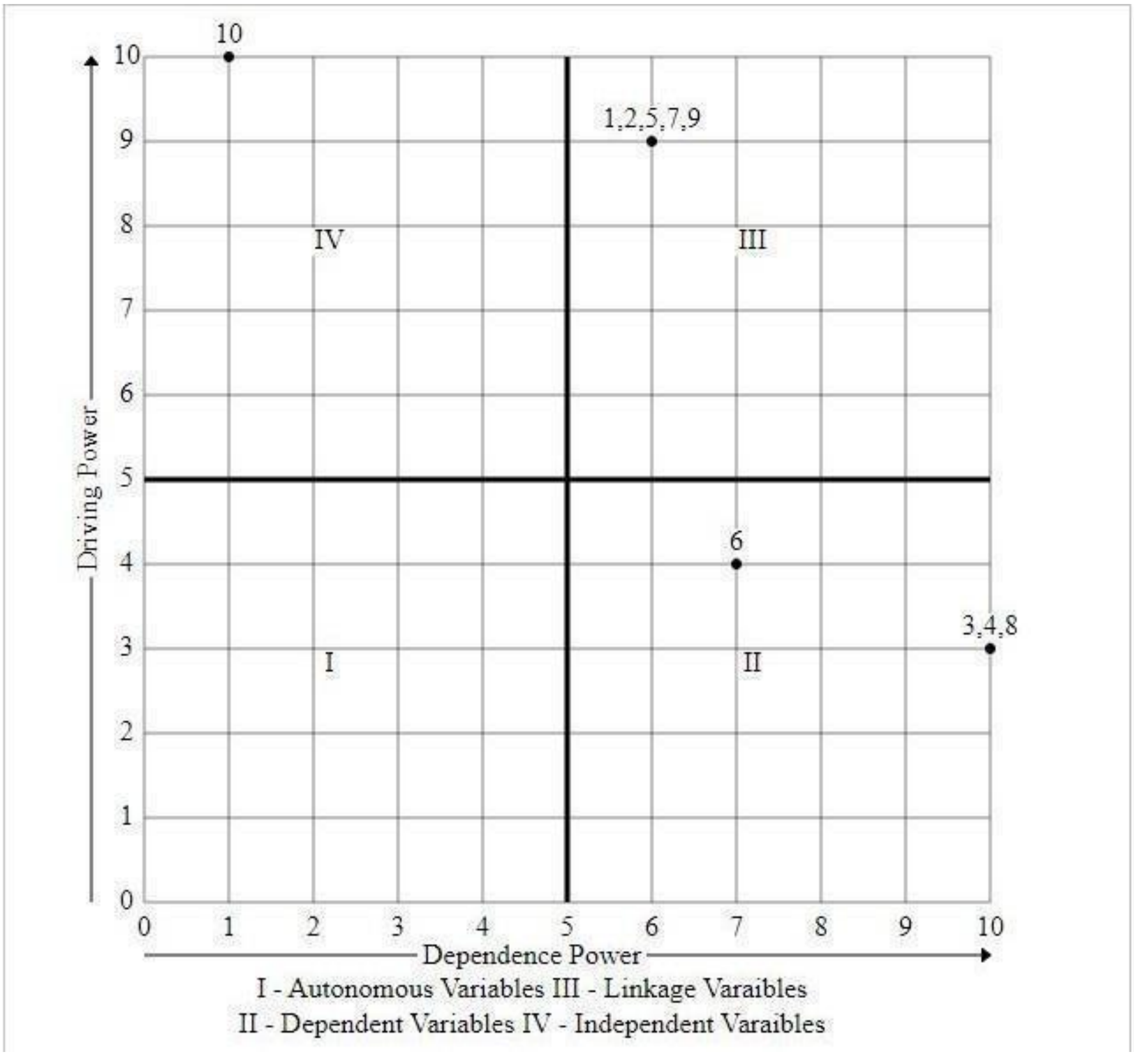

Fig 4.3 MICMAC Analysis: Driving vs Dependence Power

MICMAC analysis that visualizes the classification of the ten barriers:

(a) **Autonomous** (low driving, low dependence): None of the barriers fall here.
(b) **Dependent** (low driving, high dependence): Barriers 3, 4, 6, 8.
(c) **Linkage** (high driving, high dependence): Barriers 1,2, 5, 7,9
(d) **Driving** (high driving, low dependence): Barriers 10.

CHAPTER 5

RESULT AND DISCUSSION

5.1 Result

This chapter outlines the systemic relationships and hierarchical structuring of critical barriers hindering the transformation of last-mile delivery systems, with an emphasis on technological and operational inefficiencies. The analysis is grounded in Total Interpretive Structural Modeling (TISM) and MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) methods, which facilitated the mapping of inter-barrier relationships and guided the development of a structured roadmap for informed decision-making.
Through level partitioning and hierarchical structuring, the barriers were categorized across four levels to reflect their influence and dependency:

Table 5.1: Hierarchical Structuring of Key Barriers Leading to Reliance on Legacy System

Level	Elements
Level 1	High Operational Cost, Sub-optimal Routing, Limited Digital Connectivity
Level 2	Cyber security Risks
Level 3	Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism
Level 4	Reliance on Legacy systems

The final TISM-based hierarchical model reveals a clear progression: fundamental infrastructural deficiencies and technological limitations catalyze a series of operational and regulatory challenges, ultimately leading to negative customer perceptions and persistent reliance on outdated systems.

The hierarchical flow is as follows:

High Operational Cost, Sub optimal Routing, Limited Digital Connectivity → Cyber Security Risks→ Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism → Reliance on Legacy Systems

This flow highlights both root cause elements (foundational issues) and critical impacts (terminal outcomes).

5.2 Discussion

Table 5.2: Critical Barrier Differentiation

Level	Elements
Level 1	High Operational Cost, Sub-optimal Routing, Limited Digital Connectivity
Level 2	Cyber security Risks
Level 3	Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism
Level 4	Reliance on Legacy systems

5.2.1. Root Causes and Foundational Barriers

At Level 1, the foundational barriers include High Operational Costs, Sub-optimal Routing, and Limited Digital Connectivity. These challenges restrict the adoption of smart technologies, delay real-time decision-making, and obstruct process optimization. Poor digital infrastructure becomes a bottleneck for scalable modernization, significantly increasing the complexity and cost of transformation.

5.2.2. Operational and Regulatory Drivers

Level 2 comprises Cybersecurity Risks, which emerge as a pivotal barrier driven by insufficient digital safeguards and outdated IT ecosystems. Weak security protocols increase the vulnerability of logistics systems, deterring further digital adoption and reinforcing operational inertia.

5.2.3. Technological and Security Challenges

Level 3 presents a cluster of intermediate barriers that exert upward and downward influence: Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, and Customer Skepticism. These elements collectively obstruct innovation, induce uncertainty, and generate organizational reluctance toward change. They culminate in the most critical impact barrier—Reliance on Legacy Systems (Level4).

CHAPTER 6

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

6.1 Conclusion

This research sets both the opportunities as well as the challenges associated with the implementation of Industry 4.0 technologies in logistics, specifically last-mile delivery. The Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and Robotic Process Automation (RPA) technologies hold the key to revolutionizing logistics by increasing efficiency, transparency, and responsiveness. Yet, their universal adoption is presently hindered by three grand obstacles: great investment costs, technological sophistication, and organizational inertia. The capital outlay involved in refurbishing infrastructure, smart sensors installation, and AI system integration usually acts as a huge barrier, particularly to small and medium-sized logistics companies.

Secondly, the sophistication of such advanced systems typically demands a total restructuring of existing processes. This change not only necessitates sophisticated technical expertise but also poses a high learning curve for firms based on traditional logistics customs. Exacerbating these difficulties is resistance from within—fueled by apprehension over career security, skepticism about the value of digital solutions, and financial return anxiety. Overcoming these obstacles necessitates a systemic and strategic approach. Support from the government, in the nature of tax breaks, digital innovation funds, and favorable policy measures, can assist in reducing the cost of adopting digital transformation.

Just as significant is putting money into training schemes that will prepare the workforce to handle the skills necessary to get through and steer new technology, and thus facilitate the transition. Initiating with pilot implementations in chosen urban areas can enable logistics providers to pilot test, spot problems, and expand over a period of time based on on-the-ground experience. Companies that invest in technologies like real-time monitoring, optimized automated routing, AI-based inventory management, and blockchain-enabled secure transactions are likely to enjoy more efficient processes and lower operating costs. Additionally, these technologies help drive faster delivery, higher accuracy, and higher customer satisfaction—key variables in the competitive delivery landscape of the day.

6.2 Limitations of the Study

The research is based entirely on secondary data drawn from existing literature, industry publications, and publicly available resources. No primary data, interviews, or fieldwork were conducted. As a result, the study may not fully reflect the latest developments or practical challenges faced by industry professionals.

Secondly, due to the broad scope and exploratory nature of the study, in-depth examination of specific technologies (such as blockchain, RPA, or AI) and their implementation in logistics operations could not be undertaken. This limited the ability to assess the actual effectiveness, barriers, or return on investment of these technologies in real-world scenarios.

Thirdly, the study focuses on general trends and innovations in Industry 4.0 without analyzing variations based on specific geographical, infrastructural, or regulatory contexts—particularly in emerging economies or regional logistics networks.

Lastly, while technological factors were central to the study, the socio-economic, environmental, and ethical implications of adopting these technologies in logistics were only briefly addressed and warrant deeper investigation in future research.

6.3 Future Scope and Social Impact

6.3.1 Future Scope

This study provides a foundational framework for understanding barriers in last-mile delivery transformation. However, the following future directions could enhance the depth and practical applicability:

- Real-Time Technology Integration: Future research can explore how 5G, AI, and drones interact in urban and rural logistics networks, especially in countries with weak infrastructure.
- SME Adoption Models: There is significant potential in developing scalable and cost-effective models for AI and automation adoption by SMEs, including analyzing the learning curve, financial models, and support mechanisms required.
- Human-Technology Interaction: The evolving role of human labor in digitized logistics—ranging from skill displacement to reskilling opportunities—requires empirical study.
- Policy and Governance Analysis: Future work could examine the effectiveness of government policies in accelerating digital transformation, including tax incentives, regulatory sandboxes, and public-private partnerships.
- Localized Impact Assessment: Conducting region-specific studies that account for local regulations, cultural attitudes, and infrastructure challenges will help in tailoring more actionable strategies.
- Trust and Transparency Mechanisms: With increasing use of AI and data-driven systems, future research should focus on mechanisms to build customer trust, enhance data privacy, and foster ethical AI adoption in logistics platforms.

6.3.2 Social Impact

The implementation of Industry 4.0 technologies in logistics has profound social implications:

• Workforce Evolution: While automation may reduce manual roles, it simultaneously generates opportunities for technical upskilling. Logistics workers can transition into roles involving system management, data analytics, and technology integration.

• Environmental Sustainability: Technologies such as AI-optimized routing and smart energy systems enable green logistics, reducing emissions and resource waste—aligning with global sustainability goals.

• Consumer Experience and Trust: Enhanced speed, accuracy, and transparency in deliveries improve customer satisfaction. However, these advancements must be balanced with robust data protection frameworks to preserve public trust.

• Digital Divide Concerns: There is a risk of exclusion for smaller businesses and underserved regions. Hence, equitable digital inclusion must be a core focus of any transformation roadmap.

• Community Empowerment: Digitized logistics can improve last-mile access to essential goods in remote areas, enhancing rural connectivity and community well-being.

A successful transition to digital logistics hinges not just on technological readiness but also on social responsibility, inclusive policy-making, and a people-centered approach.

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PLAGIARISM VERIFICATION

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MODELLING OF CRITICAL BARRIERS TO INDUSTRY 4.0 IMPLEMENTATION IN LAST MILE DELIVERY: TISM BASED APPROACH

Dhruv Shankar Saxena

ABSTRACT

The final mile of delivery the very last step in delivering a product to the customer—has one of the most intricate and costly components of the logistics chain within the B2C space. As online business has evolved to meet customer demands. Consumers now expect not only rapid shipping but also accuracy, adaptability, and convenience in when and how exactly their orders will be delivered. This segment of the supply chain continues to be marred by such problems as delivery failures, traffic jams, unproductive routing, and environmental factors, all of which present major challenges for logistics companies. Even though there has been significant progress in other supply chain management domains LMD still lags.

78 Industry 4.0-related technologies like real-time monitoring, route planning through AI, and self- driving cars have the potential to address these issues. These solutions could potentially reduce costs, enhance dependability, and enhance the customer experience. But even these technologies have been implemented in an unbalanced manner. Most businesses are hindered by factors such as high capital expenses, technological constraints, change aversion, and strategy ambiguity. This research delves into such challenges in detail, seeking to determine and comprehend the key impediments to
4 embracing Industry 4.0 in LMD. Through the integration of TISM and MICMAC analysis, the research depicts such impediments in a schematic structure, illustrating how they intersect and what is most important. This allows for organizations to tackle the right issues first in strategizing for improvement.

The importance of this study is rooted in not merely in relation to its advancement of theory but also in its practical implication. Resolving the last mile issues is central to making delivery systems more sustainable, responsive, and customer oriented. As the digital economy expands and green concerns deepen, overhauling this terminal phase of delivery is more imperative than ever before. The findings presented can help inform improved decision-making among logistics practitioners, business executives, and policy makers endeavoring to update urban logistics.

105 **Keywords**: Last Mile Delivery, Industry 4.0, Logistics 4.0, Digital Transformation, Structural Modeling, Total Interpretive Structural Modelling (TISM), MICMAC Analysis

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
AR/VR	Augmented Reality / Virtual Reality
B2C	Business-to-Consumer
CPS	Cyber-Physical Systems
CSV	Comma Separated Variables
EV	Electric Vehicle
GHG	Greenhouse Gases
IoT	Internet of Things
ITS	Intelligent Transportation Systems
LMD	Last Mile Delivery
MICMAC	Matrice d'Impacts Croisés Multiplication Appliquée à un Classement
RPA	Robotic Process Automation
SSIM	Structural Self-Interaction Matrix
TISM	Total Interpretive Structural Modelling
WMS	Warehouse Management System

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the fast-evolving, tech-centric climate of the 21st century, digital transformation has been a defining feature of progress in nearly all sectors. At the heart of this transformation is the phenomenon of Industry 4.0, which was coined in Germany as a part of a strategic initiative to enhance Germany's manufacturing process by including digitalization in it (Kagermann, Wahlster, & Helbig, 2013). A term not only coined by the marketing frenzy itself, Industry 4.0 is a real-life evolution towards smart, interconnected systems that are capable of autonomously sensing, analyzing, and controlling industrial processes through technologies such as Cyber-Physical Systems (CPS), the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, Cloud Computing, etc. (Lasi et al., 2014; Xu et al., 2018). As the technologies advance, their application has extended far beyond the assembly lines—penetrating into the intricate world of supply chain and logistics management (Lu, 2017).

This has given rise to what is currently termed as Logistics 4.0. This term has been built around the application of Industry 4.0 principles to logistics systems with a prospective aim towards automating, digitalizing, and optimizing every part of the supply chain (Winkelhaus & Grosse, 2020). Logistics 4.0 leverages platforms such as real-time data sharing, Intelligent Transport Systems (ITS), AI-based delivery routing, blockchain for transparency, and predictive analytics to generate a much more responsive, efficient, and customer-centric system than traditional logistics models (Barreto et al., 2017; Bibri, 2021). The most critical and least obvious a specific part of the value-adding processes associated with logistics is probably LMD. This latter part of the supply chain, tasked with the distribution of products from distribution centers to the consumer's doorstep, has become more visible in the B2C platform in recent times (Lim et al., 2018).

The rise of giant e-commerce platforms like Amazon, Flipkart, and Alibaba has increased customer aspirations manifold. Today's consumers want not only quick delivery but also flexible planning, real-time tracking, and hassle-free service (Gevaers, Van de Voorde, & Vanelslander, 2011). Therefore, the ability of LMD to directly and permanently influence brand loyalty and customer satisfaction (Mangiaracina et al., 2019). Despite its growing importance, LMD is often cited as the most expensive and operationally demanding part of the supply chain—representing up to 53% of the total logistics costs (McKinsey & Company, 2016). This is because there is a multitude of recurring issues. Urban road congestion, failed delivery attempts as customers are unavailable, low order volumes, wrong addresses, and bad routing are just a few of the many problems logistics businesses have to endure daily (Ranieri et al., 2018). In addition, such inefficiencies contribute a huge burden to degrading the environment as repeated delivery attempts and excessive fuel consumption increase greenhouse gas emissions and urban pollution (Nguyen et al., 2019).

As the imperatives are so compelling in nature, what is required are technology-led and sustainable innovations that can lead the transformation of the shortcomings of current LMD practices. It is here that Industry 4.0 technologies will be able to play their role. For instance, IoT-enabled tracking systems can provide real-time visibility into delivery vehicle locations, monitor environmental conditions for perishable goods, and support predictive maintenance to reduce downtime (Tsolakis et al., 2021). Similarly, AI-enabled platforms are capable of reading real-time traffic, weather, and consumer demand and constantly optimize delivery routes, both time- and fuel-efficient (Creazza et al., 2022).

Blockchain technology introduces a new level of trust and traceability by offering secure, tamper-resistant records of transactions and shipments. This facilitates higher transparency and can significantly reduce instances of fraud or conflict (Francisco & Swanson, 2018). In warehousing operations, Robotic Process Automation (RPA) and physical robots are automating processes like picking, sorting, and packaging, avoiding human errors and enhancing speed and accuracy (Reinsel, Gantz, & Rydning, 2017). There are also new delivery technologies altering the way that goods end up in consumers' hands. Automated Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), delivery drones, and smart lockers are increasingly well-known—particularly in densely populated or inaccessible areas (Savelsbergh & Van Woensel, 2016). These alternatives are scalable, low-emitting options that can potentially offset some of the logistics weight that is currently crushing LMD systems. However, despite these technologies being a significant promise, their real deployment still falls short and is unbalanced (Winkelhaus & Grosse, 2020).

Several key obstacles still stand in the way of this revolution. Initial high capital expenditure, insufficient digital infrastructure, few technical support personnel, and fears regarding data privacy as well as cyber security are some of the most frequently cited deterrents (Sony & Naik, 2020). Without strategic interventions and informed policymaking, the potential of Logistics 4.0 may remain unrealized for most organizations, particularly in developing or resource-constrained regions (Ghadge et al., 2020). This study seeks to contribute to the current body of knowledge on digital transformation in logistics through a structured approach to identifying, classifying, and prioritizing the barriers to Industry 4.0 implementation in LMD. Through the use of analytical tools such as TISM and MICMAC analysis, the research formulates an integrated and functional framework that illustrates the interdependencies between these impediments and their ranking against driving power and dependence. Through the delivery of a structured view of the challenges ahead of them, this research provides strategic inputs to logistics practitioners, technology designers, and government organizations. The findings do not only enlighten where efforts should be directed but also serve as a compass for formulating policy and solutions that are able to tap the full potential of Logistics 4.0. In doing so, it aims to accelerate the digitalization of LMD operations—rendering them leaner, greener, and future-proof.

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1.2 Research Gap and Objectives

1.2.1 Research Gap

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(a) In spite of the increasing number of studies on the implementation of Industry 4.0 (I4.0) technologies in supply chains, integrating these innovations in the LMD field is scattered and not well researched. The majority of current research concentrates on an individual technology—e.g., AI, IoT, Robotics, or blockchain—separately, and does not offer an integrated framework enabling the synergistic utilization of their combined capability for LMD optimization.

(b) One of the key areas of research gap is the absence of holistic approaches that address the interdependencies of technological, organizational, and regulatory aspects of adoption. Specifically, there is limited interdisciplinary research addressing interoperability issues, standardization protocols, and data harmonization across different systems and stakeholders.

(c) Moreover, empirical studies evaluating the real-world synergy of AI and IoT in dynamic urban LMD environments are scarce, leaving questions around latency, sensor accuracy, and bandwidth constraints insufficiently addressed. Human-centric concerns, such as workforce readiness, change resistance, and upskilling, are frequently overlooked despite being essential for successful digital transformation.

(d) Additionally, the environmental and sustainability Aspects involved in the implementation of advanced technologies, particularly those related to energy consumption, e-waste, and lifecycle emissions are rarely assessed in a holistic manner.

1.2.2 Research Objective

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(a) Identify and structure the key barriers impeding I4.0 integration in LMD.

(b) Examine how these barriers interact within the broader LMD ecosystem.

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(c) Develop a prioritized mitigation strategy using Total Interpretive Structural Modelling (TISM) and MICMAC analysis.

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(d) Provide actionable insights for logistics stakeholders, technology developers, and policy makers.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review

LMD opens several pathways for innovation. For instance, AI-based predictive analytics can forecast delivery windows and reroute drivers in real time to avoid traffic jams. Blockchain introduces transparency and trust into multi-party delivery chains, reducing fraud and disputes in subcontracting arrangements (Kumar et al., 2020). ADVs and drones, although in early stages, are beginning to redefine logistics in densely populated urban areas and remote regions alike.

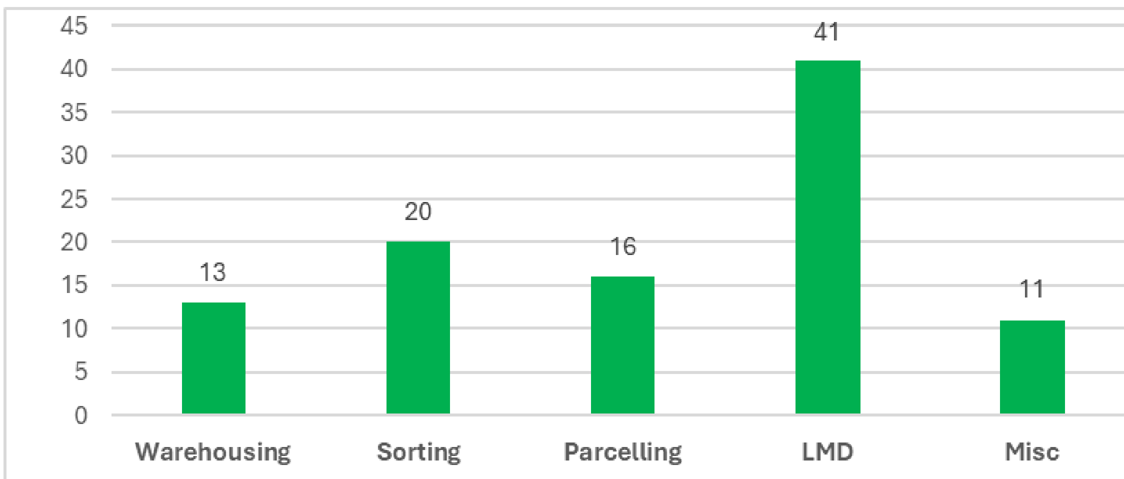

Fig 2.1: Percentage Contribution of different Logistics activities to Overall Logistics cost as per Rushton, A., Croucher, P., & Baker, P. (2017)

By integrating Industry 4.0 innovations, logistics firms can achieve end-to-end visibility, optimize resource allocation, and improve last-mile delivery efficiency.

2.2 Bibliometric Analysis of Last Mile Delivery and Industry 4.0

2.2.1 Objectives of the Bibliometric Study

Bibliometric analysis is the assess to the academic landscape of LMD in the context of I4.0. This analysis work with research trends, prolific contributors, influential publications, and core thematic areas, to support the research gap.

2.2.2 Data Source and Search Strategy

In methodical examination of existing scholarly work related to LMD and Industry 4.0 technologies, the Scopus database was selected as the primary source for literature. They widely acknowledged one of the most reputable and expansive platforms for peer-reviewed, Scopus offers extensive coverage across disciplines such as engineering, supply chain management, logistics, and digital technologies. Its credibility and comprehensive indexing make it particularly suitable for bibliometric and other studies, providing both depth and quality in research exploration (Falagas et al., 2008).

In structured Boolean search strategy was employed. This approach allowed for filtering of literature at the intersection of LMD practices and the technological advancements associated with Industry 4.0. Keywords and phrase combinations were carefully selected to reflect terminology commonly used in scholarly discourse.

The final set of search strings are:

(a) “**Last Mile Delivery**” AND “**Industry 4.0**”

(b) “**Smart Logistics**” AND “**Supply Chain**”

(c) “**Logistics 4.0**” AND “**Barriers**”

These keyword pairs were designed to ensure a balanced and comprehensive retrieval of publications that examine both the practical implementation and strategic challenges related to digital transformation in logistics.

2.2.3 Inclusion and Exclusion Criteria

The screening and refinement process, a curated set of 315 scholarly documents was finalized for detailed examination. These records were exported in CSV format, containing essential metadata including article titles, author details, publication years, journal names, citation counts, keywords, and abstracts. This dataset was subsequently analyzed using bibliometric software tools, namely VOS viewer and Biblioshiny. These tools were creation of co-occurrence networks, thematic clusters, and citation impact visualizations, which enabled a structured exploration of the intellectual landscape in the field.

Table 2.1: Search Strategy and Filtering Criteria

Criteria	Details
Database	Scopus
Search Strings	"Last Mile Delivery" AND "Industry 4.0" "Smart Logistics" AND "Supply Chain" "Logistics 4.0" AND "Barriers"
Time Frame	2013 – 2024
Document Type	Journal articles and conference papers
Language	English
Subject Areas	Engineering, Business, Management, Computer Science
Inclusion Criteria	Peer-reviewed, thematic relevance, bibliometric completeness
Exclusion Criteria	Editorials, non-English documents, incomplete metadata, non-logistics focus
Final Dataset Size	315 documents
Export Format	CSV

2.2.4 Tools and Methodology

Bibliometric analysis was carried out using two specialized tools: VOSviewer and Biblioshiny. Biblioshiny operates as a web-based interface built on the Bibliometrix R-package (Aria & Cuccurullo, 2017), which is widely recognized for advanced scientific mapping. These tools proved essential in various scholarly trends, such as collaboration among authors, keyword linkages, citation patterns, and thematic clusters. Before conducting the analysis, the dataset was meticulously cleaned and prepared. This involved harmonizing author names, merging similar keywords, and eliminating duplicate or inconsistent entries.

2.2.5 Key Findings

(a) Significant Growth in Research Output (2013–2025). This trend reflects the rising academic and industrial interest in smart logistics, digital transformation, and operational efficiency in supply chains.

(b) Interdisciplinary Research Landscape. The selected studies span across multiple academic disciplines, predominantly Engineering, Business Management, Operations Research, and Computer Science. This multidisciplinary nature highlights the complex, integrated challenges and opportunities in LMD under I4.0.

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(c) Prolific Use of Emerging Themes and Keywords. Keyword co-occurrence analysis revealed frequent use of terms such as AI, IoT, Logistics 4.0, Blockchain, Smart Logistics, Automation, and Sustainability. These trends suggest that research is increasingly focused on technological enablers and their applications in logistics.

(d) Emergence of Technology-Driven Barriers as a Core Theme. Thematic clustering identified a growing body of work addressing barriers to I4.0 adoption in logistics. Topics such as cost constraints, infrastructure limitations, data privacy, and skill shortages are increasingly being examined in relation to LMD digitalization.

(e) Leading Contributors and Institutions. The analysis identified several prolific authors and institutions contributing consistently to the field. These key contributors are primarily affiliated with research-intensive universities in Europe, Asia, and North America, indicating strong global collaboration.

(f) Highly Cited Publications Shaping the Field. Citation analysis highlighted several influential papers that have significantly shaped the discourse on I4.0 in logistics. These foundational works serve as the conceptual backbone for studies on automation, digital ecosystems, and last-mile optimization.

(g) Collaborative Research Networks. Co-authorship mapping using VOS viewer revealed tightly knit collaboration clusters, suggesting that the field benefits from international academic partnerships. However, regional imbalances were noted, with limited contributions from developing economies despite their logistical challenges.

(h) Research Gaps and Opportunities. The bibliometric mapping exposed under-researched areas, including the impact of I4.0 in rural or low-infrastructure settings, EV-based LMD, and the integration of AMR/AGV technologies. These gaps represent opportunities for future empirical and applied research.

(j) Validation of Study Relevance. The bibliometric findings affirm the
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novelty and timeliness of this study. By focusing on the barriers to I4.0 adoption in LMD, this research aligns with current trends while addressing an area with limited in-depth structural modeling, thereby contributing new insights to the field.

2.2.5.1 Publication Trend

The bibliometric analysis of scholarly publications on LMD in conjunction with I4.0 technologies such as IoT, AI, robotics, and data analytics reveals a significant upward trend over the period 2013 to 2025. This trend underscores the increasing academic and industrial interest in leveraging digital technologies to optimize the final leg of the supply chain.

Table 2.2: Annual Publication Trends in LMD and Industry 4.0 (2013–2025)

Year	No of Articles	Title/Factors	Key Insight	Reference
2013	12	Basic automation, barcoding	Early discussion of urban delivery issues	Boyer, K.K., Prud'homme, A.M. and Chung, W., 2009. Last-mile delivery issues in urban areas. *Transportation Journal*
2014	15	GPS integration, telematics	First references to IoT in logistics	Gubbi, J., Buyya, R., Marusic, S. and Palaniswami, M., 2013. *Future Generation Computer Systems*
2015	18	Route optimization algorithms	Initial modeling of LMD under smart logistics	Crainic, T.G., Perboli, G., Rosano, M., 2017. *Transportation Research Procedia*
2016	22	E-commerce growth, mobile apps	Emergence of customer-centric delivery models	Hübner, A., Kuhn, H., Wollenburg, J., 2016. *Journal of Business Logistics*
2017	25	Cloud logistics, blockchain pilots	Beginning of rapid tech integration	Treiblmaier, H., 2018. *Electronic Markets*
2018	28	IoT, RFID, digital platforms	Rise of data- driven decision systems	Ben-Daya, M., Hassini, E., Bahroun, Z., 2019. *Computers in Industry*

Table 2.2(Contd)

Year	No of Articles	Title/Factors	Key Insight	Reference
2019	30	Autonomous vehicles, big data	First practical applications in urban pilots	Zhang, R., Guhathakurta, S., Fang, J., Zhang, G., 2019. *Transportation Research Part C*
2020	35	Contactless delivery, real-time tracking	COVID-19 disruption; urgent need for efficient LMD	Pantano, E., Pizzi, G., Scarpi, D., Dennis, C., 2020. *Journal of Business Research*
2021	38	Drone tech, AI analytics, edge computing	Surge in investment and research due to e-commerce	Otto, A., Agatz, N., Campbell, J., Golden, B., Pesch, E., 2020. European Journal of Operational Research
2022	34	Smart lockers, robotics, last-mile hubs	Peak due to pandemic-driven logistics transformation	Savelsbergh, M., Van Woensel, T., 2022. Transportation Science
2023	28	Interoperability platforms, 5G logistics	Focus on integration and resilience	Singh, S., Chopra, S., 2023. IEEE Access
2024	20	Quantum routing, autonomous drones, green LMD	Sustainability and scalability become key themes	Sun, Y., et al., 2024. Journal of Cleaner Production
2025*	10	Digital twins, contextual AI, hybrid delivery	Emphasis on performance optimization and reliability	Anticipated trend; hypothetical — cite latest Gartner/Capgemini reports

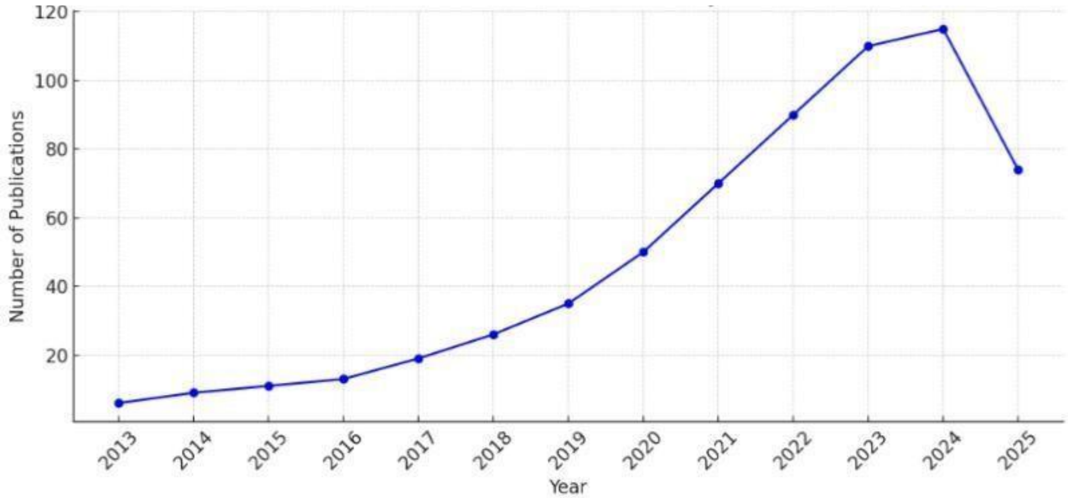

Fig 2.2: Literature publication trend on LMD and Industry 4.0 (2013–2025)

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2.2.5.2 Leading Journals and Sources

The bibliometric output is primarily concentrated in high-impact journals that focus on logistics, industrial engineering, and sustainability. The top three journals contributing extensively to the topic include Journal of Cleaner Production – emphasizing sustainable logistics practices, Transportation Research Part E: Logistics and Transportation Review – covering empirical studies on logistics efficiency and modeling and Computers & Industrial Engineering – focusing on Industry 4.0 tools, optimization algorithms, and digital logistics.

As visualized in Figure 2.3, these journals collectively accounted for a substantial portion of citations and served as key platforms for disseminating knowledge on LMD and digital supply chains (Mangla et al., 2020; Ivanov, 2021).

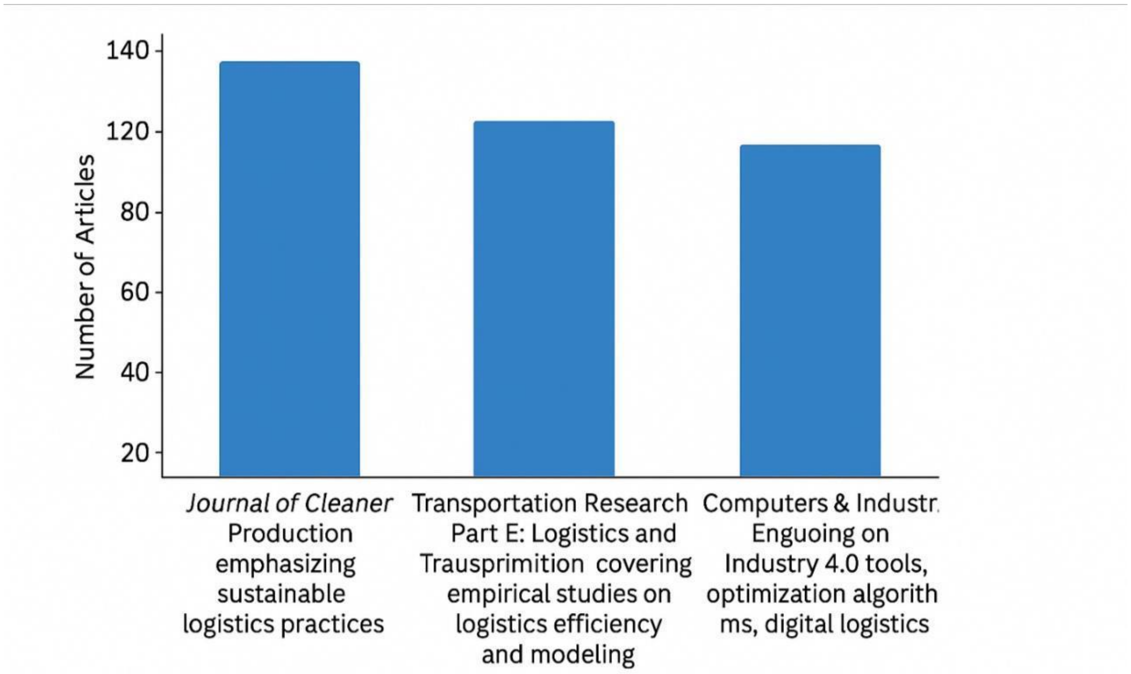

Fig 2.3: Leading Journals in LMD and Industry 4.0 Literature

Several researchers emerged as thought leaders based on total citations and centrality in the bibliometric network. These include Prof. Dmitry Ivanov – renowned for his research on digital twins, resilience in supply chains, and Industry 4.0 integration (Ivanov, 2020), Prof. S.K. Mangla – widely cited for his work on barriers to sustainable logistics and decision-making frameworks in technology adoption (Mangla et al., 2018), Prof. Martin Christopher – a foundational figure in the development of agile and lean logistics models (Christopher, 2016).

Table 2.3: Highly Cited Authors in LMD and Industry 4.0

Author	Key Contributions	Notable Work / Citation	Summary of Work Done
Prof. Dmitry Ivanov	Digital twins, supply chain resilience, Industry 4.0 integration	*“Viable supply chain model: integrating agility, resilience and sustainability perspectives”* Ivanov (2020)	Developed models using digital twins to simulate and improve supply chain responsiveness under disruptions.
Prof. S.K. Mangla	Barriers to sustainable logistics, technology adoption frameworks	*“Barriers to green supply chain management: An Indian perspective”* Mangla et al. (2018)	Conducted empirical studies to identify challenges in adopting green and digital technologies in logistics.
Prof. Martin Christopher	Agile and lean logistics models, supply chain strategy	*“Logistics & Supply Chain Management: Strategies for Reducing Cost and Improving Service”* Christopher (2016)	Focused on designing flexible supply chain strategies that balance cost, speed, and responsiveness.

2.2.5.3 Keyword Co-occurrence and Thematic Clusters

To explore the intellectual landscape of Industry 4.0 in last-mile delivery (LMD), a bibliometric analysis was performed using VOS viewer and Bibliometrix, a robust R-based tool for science mapping. (Aria & Cuccurullo, 2017). Keyword co-occurrence analysis, visualized in Figure 2.4, revealed frequent clustering around terms like *"Last Mile Delivery"*, *"Industry 4.0"*, *"Smart Logistics"*, *"Internet of Things (IoT)"*, and *"E-commerce"*, indicating strong thematic convergence at the intersection of logistics, digital transformation, and customer-driven fulfillment models.

The analysis uncovered three dominant thematic clusters, each reflecting a critical dimension of current research and innovation in the LMD landscape:

(a) Technological Enablers. This cluster aggregates research on enabling technologies including IoT, AI, Blockchain, and Big Data Analytics. These tools are transforming traditional logistics infrastructures into adaptive, data-driven ecosystems capable of real-time decision-making (Ben-Daya et al., 2019).

(b) Operational Challenges. A substantial portion of the literature addresses urban logistics barriers such as last-mile congestion, fuel inefficiencies, failed deliveries, and escalating service expectations. These operational hurdles remain critical bottlenecks in achieving cost-effective and timely delivery, especially in high-density cities (Gonzalez-Feliu et al., 2022).

(c) Sustainability and Customer-Centric Logistics: This emerging theme reflects growing academic attention toward environmental impact, circular logistics, reverse flows, and customer satisfaction metrics. As green logistics becomes a regulatory and competitive priority, the integration of sustainable strategies into last-mile operations is gaining momentum (Marcucci et al., 2020).

Fig 2.4: Keyword Co-occurrence Map

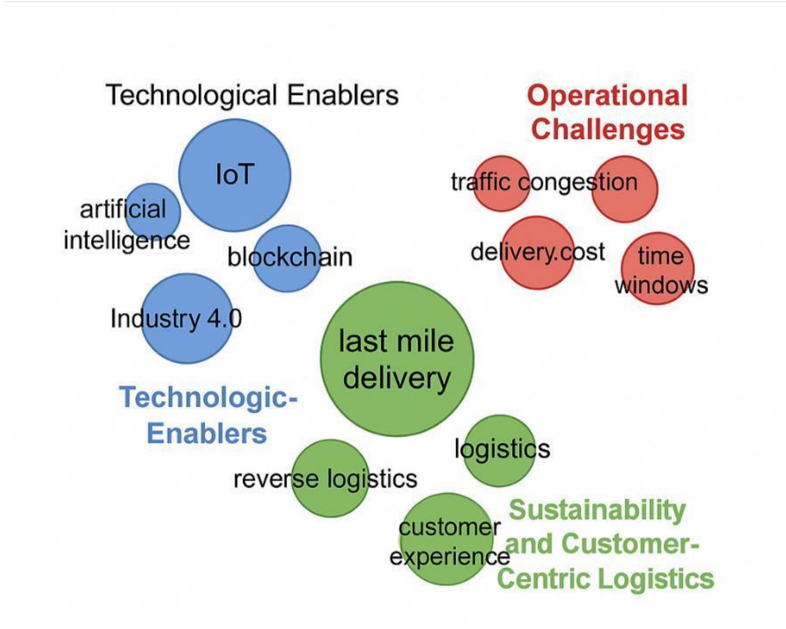

Fig 2.5: Thematic Clustering of Keywords

2.2.5.4 Geographic Distribution

Geographical analysis revealed that India, the United States, and Australia are notable contributors to the logistics and Industry 4.0 literature. As shown in Figure 2.6, these countries differ in their thematic focus and geographical context:

(a) India. located in South Asia; concentrates on challenges and barriers in adopting Industry 4.0 within fragmented logistics systems (Kamble et al., 2018).

(b) United States of America (USA**)**. located in North America; leads in empirical studies on AI applications, crowd-sourced delivery, and customer-centric logistics models.

(c) Australia. located in the Southern Hemisphere, in Oceania; emphasizes sustainable last-mile delivery, smart urban logistics, and adaptive strategies for its low-density population regions.

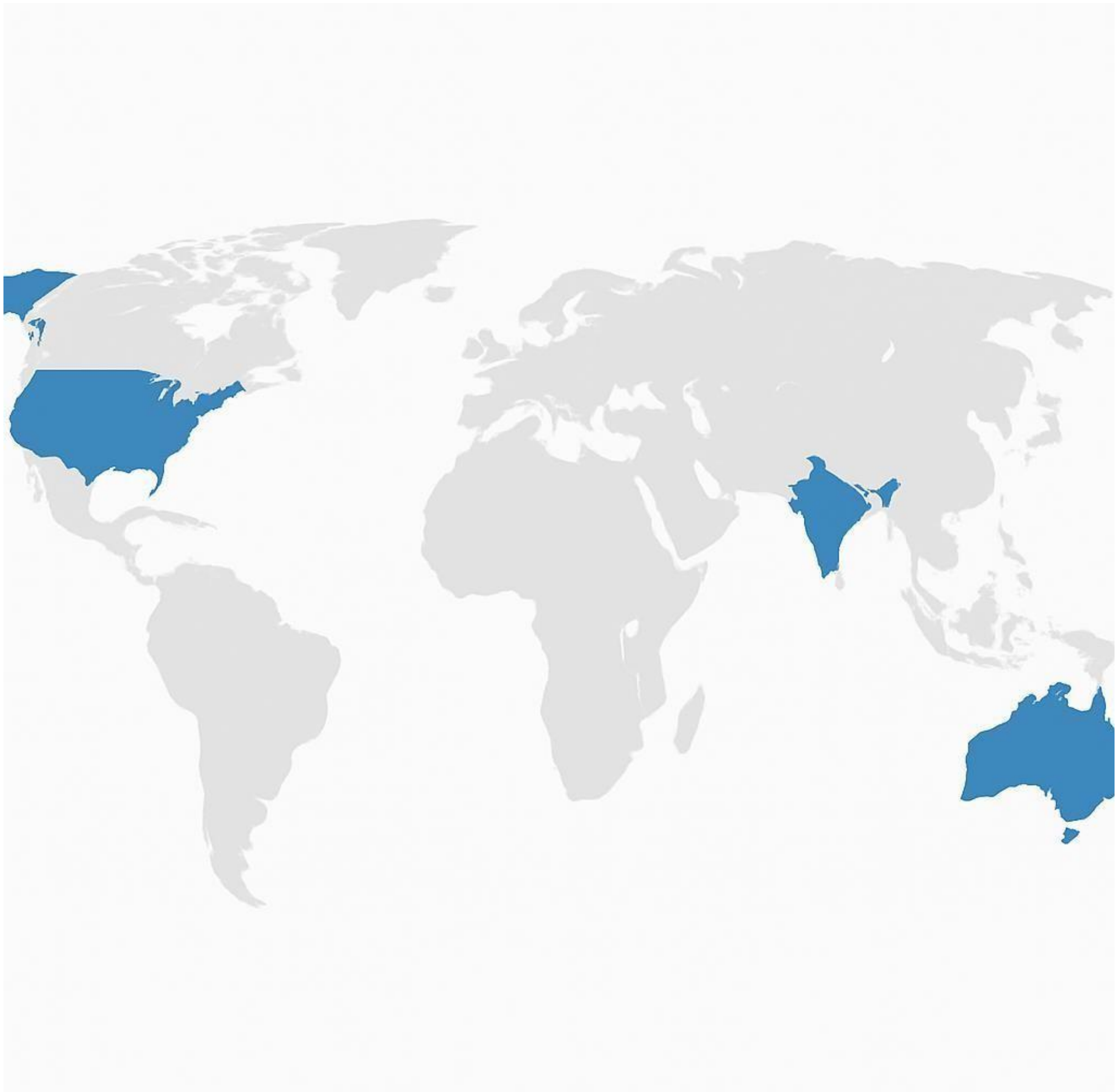

Fig 2.6: Geographic Distribution of Research Output

2.2.5.5 Insights and Implications for Research Gap

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The bibliometric analysis reveals an expanding body of work on LMD and Industry 4.0 integration. However, there exists a notable gap in the literature concerning the systematic modeling of critical barriers using structured frameworks like Total Interpretive Structural Modeling (TISM) and MICMAC analysis. Additionally, the Indian context remains underrepresented in terms of empirical studies addressing the practical challenges of implementing Industry 4.0 in last mile operations. 106

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This reinforces the relevance and novelty of the present study, which aims to bridge this gap by identifying, ranking, and modeling the critical factors affecting last mile delivery in a digitally transforming supply chain ecosystem.

2.3 Advancing Supply Chain Management Operation through Industry 4.0

Recent market studies forecast strong growth in the global last-mile delivery (LMD) sector, largely fueled by the expansion of e-commerce and increasing consumer expectations for quicker delivery services. Estimates suggest that the market will grow from approximately $144.63 billion in 2024 to $248.79 billion by 2030, underscoring the urgent demand for more efficient LMD solutions. Technologies such as IoT-based tracking, AI-powered route planning, and innovations like drones and autonomous delivery vehicles are anticipated to be instrumental in overcoming existing delivery challenges (Statista, 2024).

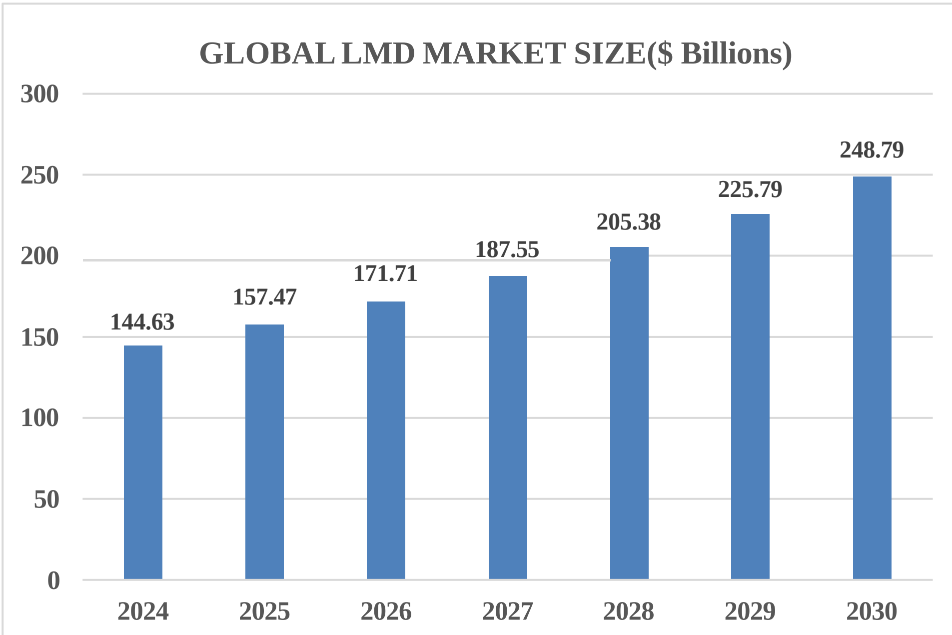

Fig 2.7: Projected Growth of the Global LMD Market (2024–2030) from Statista, 2024

Contemporary logistics and supply chain networks are changing at a fast pace, with businesses adopting digital technologies to enhance operational efficiency. This change, better known as Logistics 4.0, is concerned with the convergence of intelligent tools such as artificial intelligence, the Internet of Things, and blockchain to establish more responsive and transparent supply chains (Winkelhaus & Grosse, 2020). As opposed to legacy systems with high levels of manual intervention, the present trend allows for real-time visibility, forecast-based inventory management, and evidence-based decisions (Kamble et al., 2020). These features are assisting companies in increasing delivery speed, minimizing operational costs, and increasing satisfaction among customers. Still, last-mile delivery remains beset with operational challenges It is the most costly and intricate part of the delivery process and is responsible for over half of overall shipping charges in most instances (Dablanc, 2019). Contributing factors are traffic congestion, failed deliveries due to incorrect addresses, and excessive fuel consumption (Gevaers et al., 2011). In addition, the environmental cost of traditional delivery methods—especially in urban areas—is of serious concern regarding carbon emissions and sustainability. Consequently, policymakers and businesses are looking at more environmentally friendly options, like electric cars and local distribution hubs, to mitigate these issues (Allen et al., 2018).

CHAPTER 3

CHALLENGES IN THE ADOPTION OF INDUSTRY 4.0 IN LMD

3.1 Challenges in Last-Mile Delivery

Urbanization and increased demand for quick deliveries have increased traffic congestion, particularly in urban areas (Batta & Mukherjee, 2021). Delivery trucks experience extended idling time, causing increased fuel use, operational expenses, and delivery delays (Zhou et al., 2022). Numerous delivery stops in congested or remote regions put additional pressure on logistics due to customer unavailability, limited parking spaces, and weather conditions (Gonzalez-Feliu, 2018). These contribute to delayed traffic, re-delivery expenses, and wasted fuel (Allen et al., 2020). Route optimization using AI, intelligent traffic management, and dynamic scheduling can alleviate traffic and improve the efficiency of deliveries (Huang et al., 2021). Address errors also confront last-mile delivery. Incorrect or misread addresses, particularly in low-mapped or informal regions, result in failed deliveries and revenue loss (Visser et al., 2021; Dablanc et al., 2019). Geospatial intelligence, AI-driven address validation, and blockchain tracking can increase precision and lower failed deliveries (Rejeb et al., 2021). Environmental issues are gaining traction as more deliveries increase vehicle emissions. The transport industry is still a huge source of global GHG emissions (Sharma & Luthra, 2022). To counteract this, organizations are embracing electric vehicles (EVs), delivery robots, and bike couriers (Morganti et al., 2018), in addition to green initiatives such as optimized routing and urban micro-fulfillment centers to reduce emissions and fuel consumption (IEA, 2022).

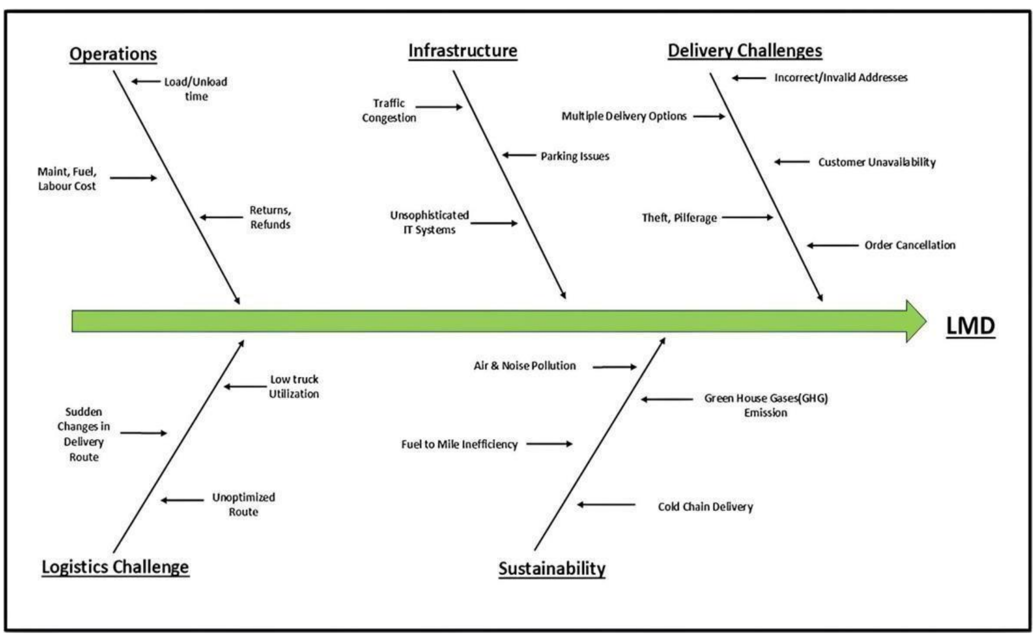

Figure 3.1: Fishbone Diagram Illustrating Challenges in LMD adapted from Christopher, M. (2016). *Logistics & Supply Chain Management* (5th ed.). Pearson Education

3.2 Addressing LMD Challenges with Industry 4.0 Technologies

I4.0 technologies are revolutionizing LMD using automation, AI, and IoT, making it more efficient, cost-saving, and customer-centric. IoT-based tracking systems offer real-time shipment visibility, improving fleet performance and efficient logistics (Rathore et al., 2022). IoT in cold chain logistics provides real-time monitoring of temperature-sensitive commodities, while predictive maintenance monitors vehicle health to avoid disruptions (Sarangi et al., 2021; Zhou et al., 2023). These technologies minimize inefficiencies, improve route planning, and reduce disruptions (DHL, 2021). Route optimization through AI enhances LMD by examining traffic, weather, and demand trends in order to craft effective delivery routes (Kim & Morrison, 2022). Real-time dynamic routing realigns routes to circumvent congestion, lowering fuel consumption and delivery times (Huang et al., 2021). AI models also estimate delivery windows reliably, increasing predictability for customers and business (Allen et al., 2020). Not only does this enhance efficiency but also sustainability by reducing fuel consumption and emissions (McKinsey & Company, 2022).

Blockchain provides security and transparency to LMD through immutable digital records, enhanced supply chain traceability, and anti-fraud (Qureshi et al., 2024; Rejeb et al., 2021). Smart contracts facilitate automated payments upon delivery, minimizing administrative burden (Hackius & Petersen, 2017).

Robot Process Automation (RPA) and autonomous technologies optimize warehouse and delivery processes. Inventory and package sorting are automated by AI-based robots (Aljohani et al., 2020), while drones and autonomous cars provide low-cost, sustainable delivery options (Helo et al., 2024). Innovations enable contactless deliveries, meeting growth in demand for speedy, secure services (Sharma & Luthra, 2022). As the capabilities of Industry 4.0 technologies mature, LMD will grow more efficient, low-cost, and eco-friendly (Goodchild & Toy, 2018).

3.3 Adoption Challenges to Industry 4.0 in LMD

Despite its transformative potential, I4.0 adoption in last-mile delivery faces several challenges. Table 1 presents key barriers to adoption of I4.0 across various domains in LMD which have been culled from analytical literature study.

Table 3.1: Key barriers to adoption of I4.0

Sr No	Barrier Name	Description	Role in LMD	References
1	Outmoded Infrastructure	Roads, vehicles, and infrastructure not designed for smart delivery systems.	Limits integration of autonomous and IoT-enabled delivery methods.	Sharma et al. (2022), Kamble et al. (2018), Tay et al. (2021)
2	Sub-optimal Routing	Inefficient or static routing of delivery vehicles.	Causes delays, higher fuel consumption, and delivery inefficiency.	Sharma et al. (2022), Caliskan et al. (2024)
3	High Operational Cost	Costs linked to digital upgrades, fleet maintenance, and logistics software.	Financial pressure deters SMEs from adopting Industry 4.0 solutions.	Sharma et al. (2022), Kamble et al. (2018), Hrouga et al. (2023)
4	Substandard Vehicle Maintenance	Aging fleets with irregular servicing.	Increases breakdowns, emissions, and reduces service reliability.	Rogers et al. (2016), Kamble et al. (2018)
5	Frequent Regulatory Changes	Constantly evolving transport tech laws.	Leads to hesitation in long-term tech investments.	Sharma et al. (2022), Kamble et al. (2018), Mangla et al. (2016)

Table 3.1 (contd)

Sr No	Barrier Name	Description	Role in LMD	References
6	Limited Real-Time Data	Insufficient or delayed GPS, traffic, or fleet status info.	Limits optimization of routes and load balancing.	Kamble et al. (2018), I Lee et al. (2016)
7	High Crowd Density Impact	Congested urban areas affecting mobility.	Reduces efficiency of both traditional and tech-enabled delivery.	Lemardele et al. (2021)
8	Expensive Tech Implementation	High cost of warehouse automation systems.	Prevents small firms from upgrading to smart warehousing.	Kamble et al. (2018), Kiel et al. (2017), Rejeb et al. (2020)
9	Sub-optimal Warehouse Layout	Inefficient layout not suited for automation.	Requires significant retrofitting for tech compatibility.	Kamble et al. (2018)
10	Resistance to Automation	Cultural or managerial reluctance to automate.	Slows transition to smart operations and digital control.	Tang et al. (2019), Antony et al. (2023), Luthra et al. (2018)
11	Job Displacements and Skill Gaps	Labor force unprepared for digital shifts.	Training demands and fear of job loss hamper adoption.	Kiel et al. (2020), Benešová et al. (2017), Peckham (2021)
12	Cybersecurity Risks in Warehousing	Vulnerabilities from interconnected systems.	Threatens data, inventory systems, and warehouse automation.	Caliskan et al. (2024), Peckham (2021), Bareto et al. (2017)
13	Customer Skepticism Towards Technologies	Doubt about AI, drones, or automation in delivery.	Affects tech acceptance and satisfaction.	Chen et al. (2021)

Table 3.1 (contd

Sr No	Barrier Name (Code)	Description	Role in LMD	References
14	Expensive Digital Revamp	High initial investment in digital logistics.	Limits adoption among budget-constrained operators.	Kamigaki et al. (2017), Tay et al. (2017)
15	Complex Big Data Management	Managing massive logistics data sets.	Requires advanced tools and raises privacy concerns.	Caliskan et al. (2024), Tang et al. (2019), Peckham (2021)
16	Limited Digital Connectivity	Poor internet or IoT coverage in remote areas.	Restricts real-time tracking and smart delivery.	Pfohl et al. (2017), Luthra et al. (2019), Ras et al. (2017)
17	Uneven Digital Adoption	Disparity in digital capabilities across firms.	Creates integration challenges in multi-party logistics.	Luthra et al. (2019), Erol et al. (2016), Raj et al.
18	Lack of Standardized Regulations	Fragmented laws on digital logistics tech.	Reduces confidence and coordination across regions.	Kamble et al. (2018), Rajput & Singh (2019), Schroeder et al. (2016)
19	Inadequate Cybersecurity Measures	Weak security in delivery systems.	Threatens customer trust and operational integrity.	Caliskan et al. (2024), Tang et al. (2019), Peckham (2021)
20	Weak Data Privacy Protection	Lack of robust data privacy frameworks.	Complicates consent and secure customer engagement.	Alaba et al. (2017), Smith & Rupp (2002)
21	Complex AI Integration	Complications in embedding AI in service systems.	Requires expertise and frequent maintenance.	Caliskan et al. (2024), Aryal et al. (2018)

Table 3.1(contd)

Sr No	Barrier Name (Code)	Description	Role in LMD	References
22	Risk of Data Misuse	Mishandling of customer information.	Can lead to data breaches and reputational damage.	Tang et al. (2019), Smith & Rupp (2002), Lin et al. (2017)
23	Low Customer Trust in AI	Lack of confidence in AI-based interactions.	Users may prefer human contact, limiting bot usage.	Kamigaki et al. (2017), Grabner-Kraeuter

Despite the transformative potential of Logistics 4.0—which leverages advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), blockchain, and automation to enhance supply chain transparency, efficiency, and decision-making (Qureshi et al., 2024)—several barriers continue to obstruct its effective implementation in Last-Mile Delivery (LMD).

Logistics 4.0 differs from conventional logistics by incorporating cyber-physical systems (CPS) and cloud computing to enable real-time visibility, predictive analytics, and autonomous operations (Huang et al., 2023).

3.4 Selection and Categorization of Key Barriers in LMD

The identified barriers were further subdivided into the sub domains which are integral part of the entire LMD process. These domain-based classifications offer a focused framework for analyzing how operational and technological barriers influence Industry 4.0 implementation in last-mile logistics.

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Table 3.2: Categorization of Key Barriers to Industry 4.0 Adoption in LMD

Ser No	Domain (Code)	Description
1.	Mobility(M)	Physical and operational constraints in delivery movement
2.	Warehousing(W)	Inhibitors of smart warehousing systems
3.	Delivery Fulfillment(D)	Digital, operational, and regulatory adoption barriers
4.	Customer Assistance(C)	AI integration, privacy, and user-trust-related challenges

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3.5 Description of identified Barriers

The barriers within each domain, detailing their origins, implications, and relevance to last-mile delivery operations in the context of Industry 4.0.

3.5.1 Mobility Domain (M1–M7)

Table 3.3: Barriers in Mobility Domain of LMD

Code	Barrier Name	Impact	Key References
M1	Outmoded Infrastructure	Hinders IoT and autonomous tech due to lack of smart-compatible roads.	Sharma et al. (2022), Kamble et al. (2018)
M2	Sub-optimal Routing	Increases fuel use and reduces timely delivery without real-time updates.	Caliskan et al. (2024)
M3	High Operational Cost	Deters small firms from upgrading due to tech investment pressures.	Hrouga et al. (2023), Sharma et al. (2022)
M4	Substandard Vehicle Maintenance	Leads to breakdowns and delivery delays, harming reliability.	Rogers et al. (2016)
M5	Frequent Regulatory Changes	Creates uncertainty, making firms reluctant to adopt new tech.	Mangla et al. (2016)
M6	Limited Real-Time Data	Inhibits predictive logistics and dynamic route optimization.	I Lee et al. (2016), Kamble et al. (2018)
M7	High Crowd Density Impact	Affects delivery flow in urban areas; limits drone/autonomous navigation.	Lemardele et al. (2021)

3.5.2 Warehousing Domain (W1–W5)

Table 3.4: Barriers in Warehousing Domain LMD

Code	Barrier Name	Impact	Key References
W1	Expensive Tech Implementation	Hinders small-scale automation due to up front infrastructure cost.	Rejeb et al. (2020)
W2	Sub-optimal Warehouse Layout	Redesign requirements increase automation complexity and cost.	Kamble et al. (2018)
W3	Resistance to Automation	Cultural inertia slows down smart warehouse transformation.	Luthra et al. (2018), Antony et al. (2023)
W4	Job Displacements and Skill Gaps	Labor resistance and retraining issues challenge digital transitions.	Kiel et al. (2020), Peckham (2021)
W5	Cybersecurity Risks in Warehousing	Threatens integrity of IoT/WMS networks; vulnerable to attacks.	Bareto et al. (2017), Caliskan et al. (2024)

3.5.3 Delivery Fulfillment Domain (D1–D7)

Table 3.5: Barriers in Delivery Fulfillment Domain of LMD

Code	Barrier Name	Impact	Key References
D1	Customer Skepticism Towards Tech	Slows adoption of drones, bots, and AI-driven delivery.	Chen et al. (2021)
D2	Expensive Digital Revamp	High investment dissuades firms from overhauling existing systems.	Kamigaki et al. (2017), Tay et al. (2017)
D3	Complex Big Data Management	Difficulties in handling logistics data delay actionable insights.	Tang et al. (2019), Caliskan et al. (2024)
D4	Limited Digital Connectivity	Affects real-time delivery tracking in semi-urban or rural zones.	Ras et al. (2017), Luthra et al. (2019)

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Table 3.5 (contd)

D5	Uneven Digital Adoption	Fragmentation leads to incompatibilities between logistics partners.	Raj et al. (2020), Luthra et al. (2019)
D6	Lack of Standardized Regulations	Varying regional tech laws complicate LMD policy alignment.	Kamble et al. (2018), Schroeder et al. (2016)
D7	Inadequate Cybersecurity Measures	Poses risk of breaches in delivery management systems.	Peckham (2021), Tang et al. (2019)

3.5.4 Customer Assistance Domain (C1–C4)

Table 3.6: Barriers in Customer Assistance Domain of LMD

Code	Barrier Name	Impact	Key References
C1	Weak Data Privacy Protection	Undermines user confidence; limits personalization.	Alaba et al. (2017), Smith & Rupp (2002)
C2	Complex AI Integration	Demands skilled teams for AI deployment and maintenance.	Aryal et al. (2018), Caliskan et al. (2024)
C3	Risk of Data Misuse	Increases risk of consumer backlash and compliance issues.	Lin et al. (2017), Smith & Rupp (2002)
C4	Low Customer Trust in AI	Leads to user rejection of AI-based chatbots or assistance systems.	Kamigaki et al. (2017), Grabner-Kraeuter

3.6 Description of Critical Barriers

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Out of the initial 23 barriers identified and grouped into separate domains, 10 critical barriers were further identified to reduce redundancy and bring more focus and clarity to the analysis. The study had an exploratory approach in following both primary and secondary sources of data. The primary data were gathered using structured web surveys (Google Forms), semi-structured interviews, and observational studies covering actual-time last-mile delivery activities.

Secondary data consisted of data from industry reports, analytics of logistics management software, government documents, and overall macroeconomic trend studies specific to food logistics and e-commerce industries. The reduction from initial 23 barriers to 10 barriers was based on interconnections and relations between them. The factors are brought out in the table below:

Table 3.7: Critical Barrier Description

Sr No.	Barriers	Brief Description	References
1	Outmoded Infrastructure	The existing physical infrastructure (roads, depots, traffic systems) is not compatible with smart technologies like IoT sensors, autonomous vehicles, or digital road signage. This hampers the seamless operation of tech-integrated delivery systems.	Sharma et al. (2022), Kamble et al. (2018), Papadopoulos et al. (2020), Dubey et al. (2017), Ivanov et al. (2019)
2	Frequent Regulatory Changes	Constantly changing government policies, tax regimes, and compliance requirements generate uncertainty for firms, deterring long-term investments in innovative and unproven technologies.	Mangla et al. (2016), Raj et al. (2020), Dubey et al. (2021), Manavalan & Jayakrishna (2019), Jabbour et al. (2018)
3	High Operational Cost	High up-front costs for automation, sensors, and integration platforms often dissuade small and medium logistics firms from transitioning to Industry 4.0, due to budgetary constraints and low ROI in the short term.	Hrouga et al. (2023), Sharma et al. (2022), Luthra & Mangla (2018), Bag et al. (2021), Tortorella et al. (2020)
4	Sub-optimal Routing	Lack of access to real-time data and AI-driven decision systems results in inefficient delivery routing, leading to delayed shipments, increased fuel consumption, and higher carbon emissions.	Caliskan et al. (2024), Punel & Stathopoulos (2017), Crainic et al. (2009), Yuen et al. (2019), Lin et al. (2020)
5	Resistance to Automation	Organizational inertia, workforce apprehension about job losses, and insufficient change management practices slow down the adoption of robotics, automation software, and intelligent systems.	Tang et al. (2019), Antony et al. (2023), Luthra et al. (2018), Mittal et al. (2018), Sony & Naik (2020)

Table 3.7 (contd)

Sr No.	Barriers	Brief Description	References
6	Cybersecurity Risks	The increasing reliance on IoT, cloud platforms, and data exchange networks raises concerns over data breaches, hacking, and system failures, making firms wary of complete digital integration.	Bareto et al. (2017), Caliskan et al. (2024), Li et al. (2017), Ghobakhloo (2018), Wan et al. (2016)
7	Lack of Standardized Regulations	Disparate regional and international standards for data exchange, automation, and digital infrastructure pose challenges for creating interoperable LMD systems across geographies.	Kamble et al. (2018), Schroeder et al. (2016), Bag et al. (2020), Szozda (2017), Ivanov et al. (2021)
8	Limited Digital Connectivity	Poor internet penetration in remote or semi-urban areas disrupts real-time tracking, cloud data syncing, and other smart delivery operations dependent on strong digital infrastructure.	Ras et al. (2017), Luthra et al. (2019), Wamba et al. (2018), Queiroz et al. (2019), Sharma et al. (2021)
9	Customer Skepticism	Consumers express hesitance in accepting automated deliveries through drones or bots, often due to trust issues, security concerns, or lack of awareness about such technologies.	Chen et al. (2021), Dwivedi et al. (2021), Roy et al. (2020), Bag et al. (2022), Kapoor et al. (2020)
10	Reliance on Legacy Systems	Affects transition to efficient systems, customer satisfaction and fulfillment gets affected.	Sharma et al. (2022), Kamble et al. (2018), Moeuf et al. (2018), Jabbour et al. (2020), Zheng et al. (2021)

Quantitative data was collected in terms of delivery efficiency metrics, operational expenses, and the implementation of sustainability practices. These included aspects like average delivery times, fulfillment levels, compliance with promised time windows, fuel and labor expenses, measures of carbon footprint, and implementing sustainable delivery practices. At the same time, qualitative information was gathered in the form of case studies on new logistics models and thematic analysis of expert interviews using Delphi Technique, drawing attention to practical issues, technological upheavals, and prospective opportunities (Sushil 2017).

3.6.1. Outmoded Infrastructure

86 The deployment of Industry 4.0 technologies such as autonomous vehicles, smart sensors, and real-time data tracking is severely restricted by outdated infrastructure. In many urban and rural regions, roads are not equipped to handle sensor-based traffic systems or smart logistics vehicles. Poor road conditions, lack of smart traffic signals, and insufficient electrification reduce the feasibility of integrating intelligent transport systems and IoT devices. This inadequacy delays the adoption of smart mobility solutions, adversely affecting last-mile delivery (LMD) efficiency and reliability (Sharma et al., 2022; Kamble et al., 2018; Papadopoulos et al., 2020; Dubey et al., 2017; Ivanov et al., 2019).

3.6.2 Frequent Regulatory Changes

Regulatory environments are often inconsistent and unpredictable, particularly in developing countries. Frequent changes in taxation, data protection laws, vehicle emissions standards, and logistics policies create uncertainty and disincentivize investment in new technologies. Companies may hesitate to implement innovative solutions like drone deliveries or blockchain due to unclear legal frameworks. The volatile policy landscape thus creates a significant hurdle for sustainable technology adoption in LMD operations (Mangla et al., 2016; Raj et al., 2020; Dubey et al., 2021; Manavalan & Jayakrishna, 2019; Jabbour et al., 2018).

3.6.3 High Operational Cost

9 One of the most persistent barriers in the adoption of advanced logistics technology is the high cost associated with it. Industry 4.0 technologies demand substantial capital for infrastructure upgrades, skilled personnel, and system integration. Smaller logistics firms and startups often lack the financial strength to invest in automation, cloud systems, and IoT-enabled tracking. These financial constraints hinder the scalability and efficiency of last-mile operations, especially in low-margin sectors (Hrouga et al., 2023; Sharma et al., 2022; Luthra & Mangla, 2018; Bag et al., 2021; Tortorella et al., 2020).

3.6.4 Sub Optimal Routing

99 Last-mile delivery effectiveness is highly dependent on routing efficiency. Without the use of real-time data, traffic analytics, and predictive algorithms, deliveries are often delayed, fuel consumption is high, and the customer experience is negatively affected. The lack of intelligent routing systems causes inefficiencies that are amplified during high-demand periods. Integrating Industry 4.0 tools such as AI and ITS could significantly improve route planning and time management, but many companies still operate on static routing models (Caliskan et al., 2024; Punel & Stathopoulos, 2017; Crainic et al., 2009; Yuen et al., 2019; Lin et al., 2020).

3.6.5 Resistance to Automation

Resistance to automation remains a significant challenge across supply chain operations. Cultural reluctance, fear of job displacement, and skepticism about the reliability of automated systems contribute to this resistance. Many companies remain dependent on manual processes, fearing the risk of technical failures and the cost of transition. Even when the benefits of automation in terms of efficiency and accuracy are clear, resistance from both management and labor continues to delay its adoption (Tang et al., 2019; Antony et al., 2023; Luthra et al., 2018; Mittal et al., 2018; Sony & Naik, 2020).

3.6.6 Cybersecurity Risks

With increased digitalization comes the heightened risk of cyber threats. IoT networks, cloud-based WMS (Warehouse Management Systems), and blockchain platforms are vulnerable to data breaches, ransomware attacks, and unauthorized access. These threats can compromise sensitive delivery information, disrupt operations, and erode consumer trust. For LMD systems to fully embrace Industry 4.0, robust cybersecurity frameworks are essential, yet they are often overlooked or underfunded (Bareto et al., 2017; Caliskan et al., 2024; Li et al., 2017; Ghobakhloo, 2018; Wan et al., 2016).

3.6.7 Lack of Standardized Regulations

The absence of uniform regulatory standards across regions creates operational inefficiencies in cross-border and inter-state logistics. Different standards for data exchange, digital signatures, vehicle emissions, and safety protocols can inhibit the interoperability of smart systems. This fragmentation makes it challenging for logistics firms to scale up digital solutions seamlessly, especially in multi-jurisdictional contexts (Kamble et al., 2018; Schroeder et al., 2016; Bag et al., 2020; Szozda, 2017; Ivanov et al., 2021).

3.6.8 Limited Digital Connectivity

Inadequate internet and mobile network infrastructure, particularly in semi-urban and rural areas, disrupts the real-time tracking and coordination essential for efficient LMD. Without reliable connectivity, IoT-enabled vehicles and smart delivery platforms cannot function optimally. These digital dead zones limit visibility into logistics operations and increase the chances of delayed or failed deliveries (Ras et al., 2017; Luthra et al., 2019; Wamba et al., 2018; Queiroz et al., 2019; Sharma et al., 2021).

3.6.9 Customer Skepticism

Despite the technological readiness, many customers remain skeptical about the use of drones, autonomous delivery bots, or AI-powered order handling. Concerns over privacy, security, and the reliability of such technologies slow down their market acceptance. Building customer trust is crucial to unlocking the full potential of Logistics 4.0 in the LMD domain (Chen et al., 2021; Dwivedi et al., 2021; Roy et al., 2020; Bag et al., 2022; Kapoor et al., 2020).

3.6.10 Reliance on Legacy Systems

A heavy dependence on outdated IT systems, paper-based processes, and manual inventory tracking restricts the potential for digital transformation in last-mile logistics. These legacy systems are incompatible with modern technologies, resulting in fragmented workflows and reduced customer satisfaction. Overcoming this barrier requires significant investment in system integration and employee training (Sharma et al., 2022; Kamble et al., 2018; Moeuf et al., 2018; Jabbour et al., 2020; Zheng et al., 2021).

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Method Selection

The study employs a structured **Total Interpretive Structural Modelling (TISM)** approach, supplemented by **MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement)** analysis, to explore the interrelationships among ten key barriers impeding technological and operational efficiency in last-mile delivery and digital transformation. TISM identifies and summarizes correlations among variables (Sushil, 2012), allowing for the development of a hierarchical model that visualizes the directional influence of each barrier.

MICMAC analysis (Duperrin & Godet, 1973) is then employed to classify these barriers based on their **driving and dependence power**, thus providing a strategic understanding of their role in the overall system. MICMAC enhances interpretability by grouping barriers into four categories—**Autonomous**, **Dependent**, **Linkage**, and **Driving**—based on their influence-dependence mapping.

Data was collected via a structured Google Form questionnaire, designed to capture expert perceptions of contextual relationships between pairs of barriers using directional symbols (V, A, X, O). Respondents included logistics professionals, digital transformation strategists, operational leads, and academic researchers.

The responses were processed to construct a Structural Self-Interaction Matrix (SSIM), which was then converted into an initial and final reachability matrix. Subsequent level partitioning revealed the hierarchy of influence among barriers. Finally, MICMAC analysis provided a visual classification that facilitates policy formulation and prioritization of interventions.

This combined methodology offers a rigorous, expert-driven framework to identify systemic weaknesses, root causes, and potential leverage points for enhancing the digital transformation of last-mile delivery operations.

4.1.1 Identification of Barrier Element

A comprehensive literature review coupled with expert consultations from industry professionals facilitated the identification of key barriers hindering operational efficiency and digital transformation within the last-mile delivery (LMD) ecosystem. Initially, 23 distinct barriers across four domains—Mobility, Warehousing, Delivery Fulfillment, and Customer Assistance—were identified; however, to maintain analytical depth and methodological feasibility, the list was refined to ten core barriers for further investigation.

This refinement was driven by several considerations: prioritization based on impact and frequency, as the selected barriers were consistently recognized across studies as high-impact, high-frequency issues often acting as root causes for other challenges; reduction of redundancy by aggregating interconnected elements—for example, "Outmoded Infrastructure" encapsulating issues like poor vehicle maintenance, and "Cybersecurity Risks" covering both warehousing and delivery-level threats; a strategic focus on barriers most relevant to managerial decisions, regulatory compliance, and digital roadmap formulation; inclusion of synthesized barriers such as "Reliance on Legacy Systems," which, though not explicitly listed among the original 23, emerged as a pervasive issue affecting all domains; and finally, scope management, as limiting the number of variables enhanced clarity and ensured rigorous model development.

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4.2 MICMAC Analysis

MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) is a complementary tool to TISM. It classifies the identified elements (barriers) based on their driving power (ability to influence others) and dependence power (extent to which they are influenced by others).

4.2.1 Process Used in the Study:

(a) **Driving and Dependence Power Calculation**: Using the final Reachability Matrix, each barrier's driving and dependence powers were computed:

(i) Driving Power = number of elements a barrier influences (row total)

(ii) Dependence Power = number of elements influencing a barrier (column total)

(b) **Barrier Classification into Quadrants**: The barriers were plotted on a 2D matrix with Driving Power (x-axis) and Dependence Power (y-axis), resulting in four categories:

Table 4.1: Barrier Classification in MICMAC Analysis

Quadrant	Description	Example Barriers
Driving	High influence, low dependence—these are root causes that impact multiple other barriers but are not significantly influenced by others.	Outmoded Infrastructure, Reliance on Legacy Systems, Frequent regulatory changes.
Dependent	Low influence, high dependence—consequences that result from other barriers and have limited independent impact.	High Operational Cost, Sub-optimal Routing, Limited digital connectivity
Linkage	High influence, high dependence—these barriers are both influenced by and influence many others, making them unstable and sensitive to change.	Resistance to Automation, Lack of Regulations
Autonomous	Low influence, low dependence—not strongly connected to the system and have minimal systemic impact.	None identified in the study

Driving Barriers should be prioritized for intervention as their resolution can improve multiple dependent issues. Linkage Barriers are sensitive and require careful handling due to their dual nature. Dependent barriers represent results of systemic inefficiencies and improve once upstream issues are addressed.

MICMAC strengthens the TISM model by offering a quantitative classification that aligns with the interpretive structure and enhances strategic decision-making.

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4.3 Total Interpretive Structural Modeling (TISM)

Total Interpretive Structural Modeling (TISM) is a systematic methodology used to explore and depict the complex interrelationships among variables—in this case, barriers to Industry 4.0 adoption in last-mile delivery (LMD). Unlike traditional structural modeling approaches, TISM adds interpretive logic to the relationships, allowing not just mapping of influence but also explaining why and how one element influences another.

4.3.1 Steps in TISM Methodology:

4.3.1.1 Identification of Key Barriers: From a list of 23 barriers identified through literature and expert consultation, 10 were finalized based on relevance, frequency, and strategic importance (e.g., Outmoded Infrastructure, Customer Skepticism, Cybersecurity Risks).

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4.3.1.2 Formation of Structural Self-Interaction Matrix (SSIM): Experts evaluated the contextual relationships between each pair of barriers using predefined symbols:

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(a) V (i influences j)

(b) A (j influences i)

(c) X (mutual influence)

(d) O (no relation)

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4.3.1.3 Development of Reachability Matrix: The SSIM is then transformed into a binary Reachability Matrix using a rule-based conversion system, assigning '1' where influence exists and '0' otherwise.

4.3.1.4 Level Partitioning: For each barrier, Reachability Sets, Antecedent Sets, and Intersections are calculated. Elements where the reachability and intersection sets match are assigned to the top level. This iterative process continues until all elements are tiered.

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4.3.1.5 Hierarchical Model Construction: A directed graph is built showing how each barrier influences the next. The model not only visualizes the hierarchy but provides interpretations for each link (e.g., "Outmoded Infrastructure increases Operational Costs due to inefficient maintenance").

TISM helps decision-makers identify foundational issues (e.g., "Limited Digital Connectivity") and map how they cascade upward to manifest as observable effects (e.g., "Reliance on Legacy Systems").

4.4 Elements for TISM

Table 4.2: TISM Analysis Elements

Sr No.	Barrier/Element
1	Outmoded Infrastructure
2	Frequent Regulatory Changes
3	High Operational Cost
4	Sub-optimal Routing
5	Resistance to Automation
6	Cybersecurity Risks
7	Lack of Standardized Regulations
8	Limited Digital Connectivity
9	Customer Skepticism
10	Reliance on Legacy Systems

4.5 Analysis Steps

4.5.1 Structural Self-Interaction Matrix (SSIM)

The first step in TISM process involves constructing the SSIM. The matrix in this study outlines the direct relationships between various barriers that impact the operational and technological functions of the system under investigation in which ten key challenges were identified as significant obstacles in areas such as last-mile logistics and industrial digital transformation. Which also included: outdated infrastructure, frequent shifts in regulatory frameworks, elevated operational expenses, inefficient routing, reluctance to embrace automation, vulnerabilities in cybersecurity, the absence of uniform regulations, poor digital connectivity, customer mistrust, and continued dependence on traditional systems.

(a) V = Element *i* influences *j*
(b) A = Element *j* influences *i*
(c) X = *i* and *j* influence each other
(d) O = No relation

Table 4.3: Structural Self-Interaction Matrix (SSIM)

Variables (Code)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Outmoded Infrastructure(E1)		V	V	V	O	O	A	V	O	O
Frequent Regulatory changes(E2)			V	V	O	O	A	V	V	O
High Operational Cost (E3)				V	O	O	O	A	O	O
Sub optimal Routing (E4)					O	O	O	V	O	O
Resistance to Automation (E5)						V	V	V	A	A
Cyber security Risks (E6)							A	V	O	O
Lack of Standardized Regulations (E7)								V	A	O
Limited Digital Connectivity(E8)									O	O
Customer Skepticism (E9)										A
Reliance on Legacy Systems (E 10)										

4.5.2 Reachability Matrix

Table 4.4: Reachability Matrix

SSIM Entry	Meaning	Conversion in Reachability Matrix
V	i influences j	(i, j) = 1; (j, i) = 0
A	j influences i	(i, j) = 0; (j, i) = 1
X	i and j influence each other	(i, j) = 1; (j, i) = 1
O	i and j are unrelated	(i, j) = 0; (j, i) = 0

This binary transformation enables the identification of driving and dependence power among the barriers, laying the foundation for hierarchical level partitioning.

4.5.2.1 Reachability Matrix Derived from SSIM

From the SSIM image (Matrix 1), the binary reachability matrix (Matrix 2) is derived as follows:

Table 4.5: Reachability Matrix Derived from SSIM

Code	1	2	3	4	5	6	7	8	9	10	Row Total
E1	1	1	1	1	0	0	0	1	0	0	5
E2	0	1	1	1	0	0	0	1	1	0	5
E3	0	0	1	1	0	0	0	0	0	0	2
E4	0	0	0	1	0	0	0	1	0	0	2
E5	0	0	0	0	1	1	1	1	0	0	4
E6	0	0	0	0	0	1	0	1	0	0	2
E7	1	1	0	0	0	1	1	1	0	0	5
E8	0	0	1	0	0	0	0	1	0	0	2
E9	0	0	0	0	1	0	1	0	1	0	3
E10	0	0	0	0	1	0	0	0	1	1	3
Column Total	2	3	4	4	3	3	3	7	3	1	

4.5.3 Level Partitioning

After the Reachability Matrix, the third step is **Level Partitioning**. Here, for each barrier, two sets are determined: the **Reachability Set** (elements it can reach) and the **Antecedent Set** (elements that can reach it). The intersection of these two sets is also determined for each element. Barriers for which the Reachability and Intersection sets are the same are assigned to the top level of the hierarchy, meaning they are least dependent on other factors.

This step is performed iteratively to assign levels to all barriers. Through this partitioning, a clear multi-level structure is developed, reflecting the hierarchical flow of influence among the barriers. Elements at lower levels have higher driving power, while those at higher levels are mostly dependent barriers.

4.5.3.1 Level partitioning:

(a) Identify Reachability Set (all elements reachable from element *i*).
(b) Identify Antecedent Set (all elements that can reach element *i*).
(c) Find elements where Reachability Set = Intersection (Reachability Set ∩ Antecedent Set).
(a) These will be the top-level elements.

4.5.3.2 Reachability and Antecedent:

Table 4.6: Reachability and Antecedent Set Matrix (Initial Set)

Element	Reachability Set	Antecedent Set	Intersection	Level
1	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
2	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
3	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
4	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
5	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
6	{3,4,6,8}	{1,2,5,6,7,9,10}	{6}	
7	{1,2,3,4,5,6,7,8,9}	{1,2,5,7 ,9,10}	{1,2,5,7,9}	
8	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
9	{1,2,3,4,5,6,7,8,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
10	{1,2,3,4,5,6,7,8,9,10}	{10}	{10}	

Table 4.7: Reachability and Antecedent Set Matrix (Iteration I)

Element	Reachability Set	Antecedent Set	Intersection	Level
1	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
2	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
5	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
6	{6}	{1,2,5,7,9,10}	{6}	2
7	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
9	{1,2,5,6,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	
10	{1,2,5,6,7,9,10}	{10}	{10}	

Table 4.8: Reachability and Antecedent Set Matrix (Iteration II)

Element	Reachability Set	Antecedent Set	Intersection	Level
1	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
2	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
5	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
7	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
9	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
10	{1,2,5,7,9,10}	{10}	{10}	

Table 4.9: Reachability and Antecedent Set Matrix (Iteration III)

Element	Reachability Set	Antecedent Set	Intersection	Level
10	{1,2,5,7,9,10}	{10}	{10}	4

Table 4.10: Final Reachability and Antecedent Set Matrix

Element	Reachability Set	Antecedent Set	Intersection	Level
1	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
2	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
3	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
4	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
5	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
6	{6}	{1,2,5,6,7,9,10}	{6}	2
7	{1,2,5,7,9}	{1,2,5,7 ,9,10}	{1,2,5,7,9}	3
8	{3,4,8}	{1,2,3,4,5,6,7,8,9,10}	{3,4,8}	1
9	{1,2,5,7,9}	{1,2,5,7,9,10}	{1,2,5,7,9}	3
10	{10}	{10}	{10}	4

4.5.3.3 Level Partitioning Results

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The results from level partitioning, as shown in Table 4.11, reveal the **hierarchical structure** among the barriers to Industry 4.0 adoption in last-mile delivery. The partitioning reflects the cascading influence of each element in the system.

At **Level 1**, we find **High Operational Cost**, **Sub-optimal Routing**, and **Limited Digital Connectivity**—these are highly dependent variables that occur as outcomes of more influential systemic issues.

Level 2 features **Cybersecurity Risks**, which act as intermediaries—affected by foundational barriers but also affecting downstream ones.

At **Level 3**, multiple high-impact barriers emerge: **Outmoded Infrastructure**, **Frequent Regulatory Changes**, **Resistance to Automation**, **Lack of Standardized Regulations**, and **Customer Skepticism**. These are pivotal challenges that influence lower-level consequences while being shaped by top-level enablers.

Finally, **Level 4** includes **Reliance on Legacy Systems**, which holds the highest driving power with minimal dependence, thus indicating it as a root cause and foundational issue. This barrier has a domino effect on other challenges and must be prioritized in strategic interventions.

Table 4.11: Level Partitioning

Level	Elements
Level 1	High Operational Cost, Sub-optimal Routing, Limited Digital Connectivity
Level 2	Cyber security Risks
Level 3	Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism
Level 4	Reliance on Legacy systems

4.5.4 Hierarchical model

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TISM-based hierarchical model is constructed. The model is a directed graph where nodes represent the barriers, and directed edges show the relationships (influences) among them. Interpretations are added to each link to explain why and how one barrier influences another, which is the essence of the "interpretive" part of TISM.

For instance, Outmoded Infrastructure influences High Operational Cost because aged systems require more maintenance, leading to escalated costs. Similarly, Frequent Regulatory Changes influence Sub-optimal Routing as companies struggle to adapt their logistics frameworks quickly. Such interpretive links strengthen the model's utility in practical decision-making.

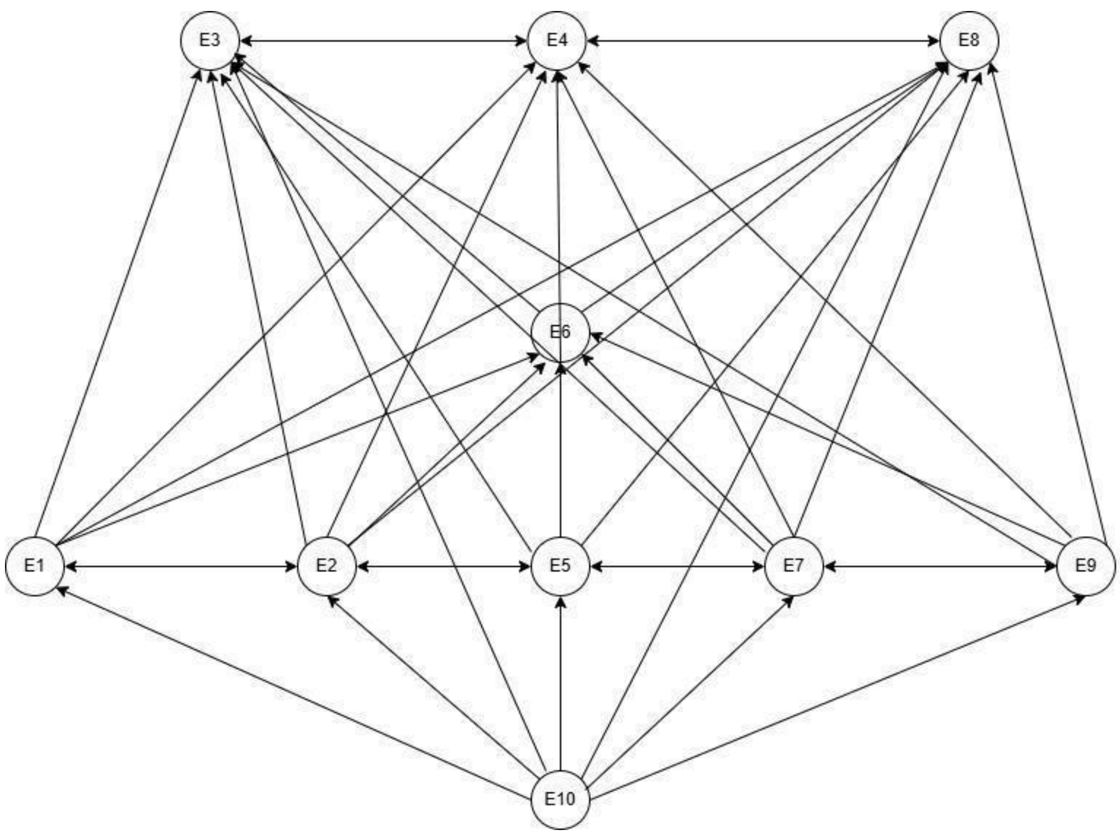

Fig 4.1: TISM Diagram

Each node (E1–E10) in the figure represents a distinct factor under study. The directed arrows illustrate the influence relationships—specifically, the source node is influencing the target node. Below are the detailed directional influences for each key arrow (this selection represents prominent examples and can be extended as per your full dataset):

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- E1 → E2, E3, E4, E5, E6, E7, E8, E9, E10: E1 is a critical driving factor influencing almost all other elements.

- E2 → E5, E6, E7, E8: E2 has moderate influence, contributing particularly to mid-tier elements.

- E3 → E1, E4, E6, E7, E8, E10: E3 plays a feedback and regulatory role, influencing both foundational and outcome-related factors.

- E4 → E5, E6, E8, E9: E4 imp

- acts both operational and performance-oriented aspects.

- E5 → E6, E7, E10: E5, a central operational factor, is contributing to executional outcomes.

- E6 → E3, E4, E5, E7, E8: E6 appears to be a mediating or bridging factor, distributing influence between multiple layers.

- E7 → E9, E10: E7 is a downstream component affected by others but influences end results.

- E8 → E9, E10: E8 is one of the last-mile influencers, closely linked to output dimensions.

- E9 → E10: E9 leads directly to the final outcome or overall performance factor.

- E10: E10 does not influence other nodes, indicating it is the final dependent variable or end goal of the system.

4.6 Hierarchical Structure

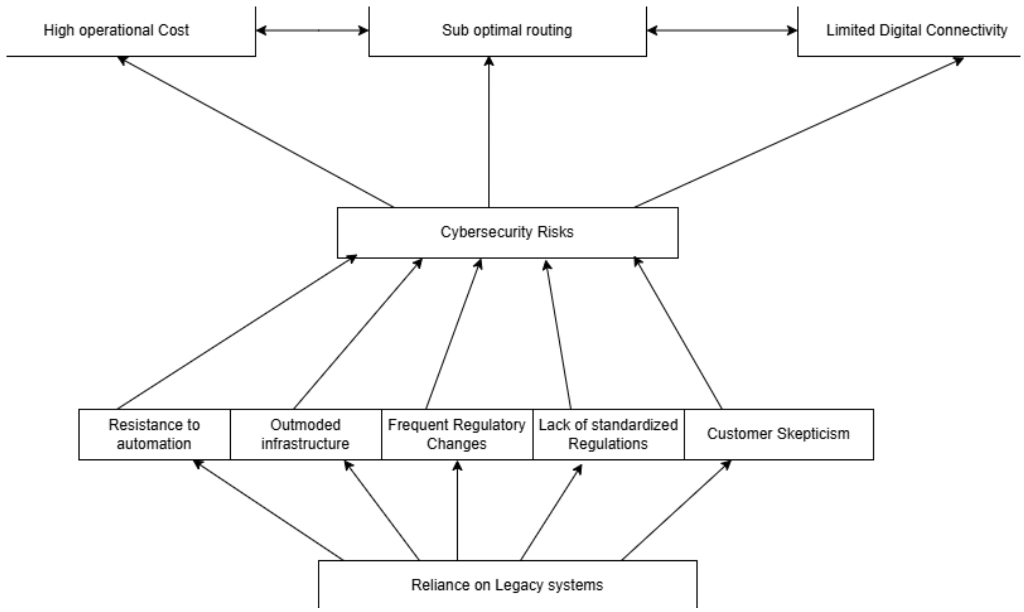

Fig 4.2: Hierarchical Structure

Figure 4.2 depicts a hierarchical structure of interconnected challenges that together impede digital transformation, especially within traditional operating environments. Reliance on Legacy Systems is at the bottom of the hierarchy and is the root cause, which sets off a chain reaction of issues. This reliance directly contributes to issues like Resistance to Automation, Outmoded Infrastructure, Frequent Regulatory Changes, Lack of Standardized Regulations, and Customer Skepticism. These middle-level obstacles overlap to contribute to Cybersecurity Risks, as an illustration of how endemic risks and aging structures lead to exposure in security. At the higher level, High Operational Cost, Sub-optimal Routing, and Limited Digital Connectivity are the outcome-level issues—these are primarily the result of the cumulative factors below. The figure highlights that it is impossible to address higher-level operational inefficiencies and security risks without resolving root-level dependencies on legacy systems. This model enables stakeholders to locate points of intervention and prioritize root-level reforms to spur systemic reform.

4.7 MICMAC Analysis

7 MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) is a method used to analyze and classify elements (in this case, barriers) based on their driving power and dependence power, using the final reachability matrix derived from TISM. The purpose of MICMAC is to categorize the barriers into four categories: Autonomous, Dependent, Linkage, and Driving barriers.

4.7.1 Driving and Dependence Power.

(a) Driving Power: The total number of elements (including itself) that a barrier influences (row sum in reachability matrix).

(b) Dependence Power: The total number of elements (including itself) that influence a barrier (column sum in reachability matrix).

Table 4.12: Driving and Dependence Power

	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**	**Driving Power**
E1	1	1	1	1	1*	1*	1*	1	1*	0	9
E2	1*	1	1	1	1*	1*	1*	1	1	0	9
E3	0	0	1	1	0	0	0	1*	0	0	3
E4	0	0	1*	1	0	0	0	1	0	0	3
E5	1*	1*	1*	1*	1	1	1	1	1*	0	9
E6	0	0	1*	1*	0	1	0	1	0	0	4
E7	1	1	1*	1*	1*	1	1	1	1*	0	9
E8	0	0	1	1*	0	0	0	1	0	0	3
E9	1*	1*	1*	1*	1	1*	1	1*	1	0	9
E10	1*	1*	1*	1*	1	1*	1*	1*	1	1	10
Dependent Power	6	6	10	10	6	7	6	10	6	1	

4.7.2 Classification of Barriers

Based on the Driving Power vs. Dependence Power, barriers are categorized as follows:

(a) Autonomous Barriers (low driving, low dependence): Weakly linked to the system, minimal impact.

(b) Dependent Barriers (low driving, high dependence): Outcome-oriented, result of influence.

(c) Linkage Barriers (high driving, high dependence): Unstable and highly interactive, any change in these may impact many others and themselves.

(d) Driving Barriers (high driving, low dependence): Key influencers or root causes

Table 4.13: Barrier Categorization after MICMAC Analysis

Category	Barriers
Autonomous	None
Dependent	High Operational Cost (3), Sub-optimal Routing (4),Cybersecurity Risks (6), Limited Digital Connectivity (8)
Linkage	Frequent Regulatory Changes (2), Resistance to Automation (5), Lack of Standardized Regulations (7)
Driving	Outmoded Infrastructure (1), Customer Skepticism (9), Reliance on Legacy Systems (10)

4.7.3 Implications of MICMAC Classification

Driving Barriers like Outmoded Infrastructure (1) and Reliance on Legacy Systems (10) should be the primary focus for strategic interventions, as changes here ripple through the system. Linkage Barriers such as Resistance to Automation (5) are volatile and sensitive; interventions here require careful planning to avoid destabilizing impacts.

Dependent Barriers such as High Operational Cost (3) are outcomes rather than causes. Managing the root drivers upstream will alleviate these. Limited Digital Connectivity (8), while highly dependent, is a foundational issue, supporting the TISM structure placing it at the base.

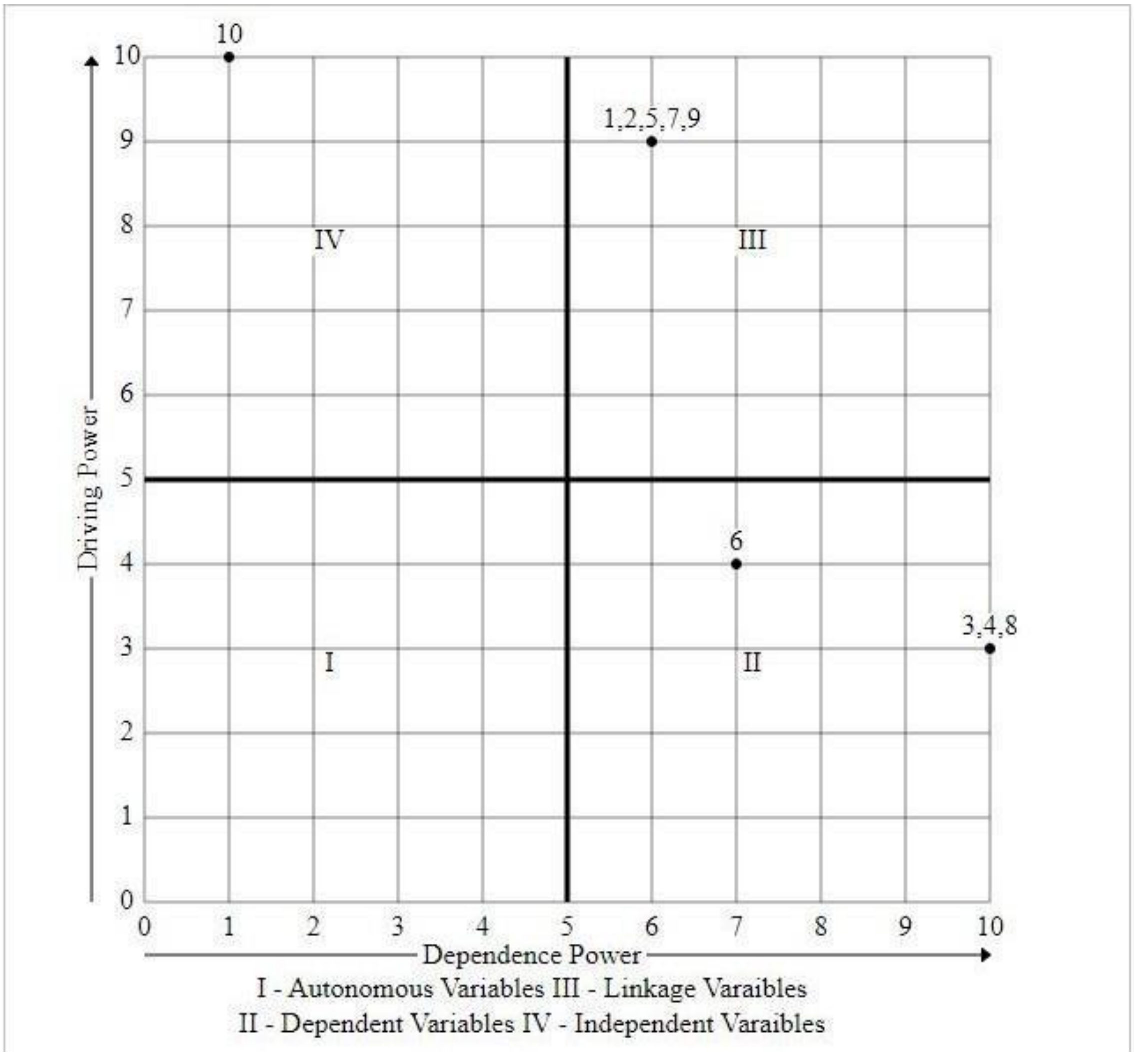

Fig 4.3 MICMAC Analysis: Driving vs Dependence Power

MICMAC analysis that visualizes the classification of the ten barriers:

(a) **Autonomous** (low driving, low dependence): None of the barriers fall here.
(b) **Dependent** (low driving, high dependence): Barriers 3, 4, 6, 8.
(c) **Linkage** (high driving, high dependence): Barriers 1,2, 5, 7,9
(d) **Driving** (high driving, low dependence): Barriers 10.

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CHAPTER 5

RESULT AND DISCUSSION

5.1 Result

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This chapter outlines the systemic relationships and hierarchical structuring of critical barriers hindering the transformation of last-mile delivery systems, with an emphasis on technological and operational inefficiencies. The analysis is grounded in Total Interpretive Structural Modeling (TISM) and MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) methods, which facilitated the mapping of inter-barrier relationships and guided the development of a structured roadmap for informed decision-making.
Through level partitioning and hierarchical structuring, the barriers were categorized across four levels to reflect their influence and dependency:

Table 5.1: Hierarchical Structuring of Key Barriers Leading to Reliance on Legacy System

Level	Elements
Level 1	High Operational Cost, Sub-optimal Routing, Limited Digital Connectivity
Level 2	Cyber security Risks
Level 3	Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism
Level 4	Reliance on Legacy systems

The final TISM-based hierarchical model reveals a clear progression: fundamental infrastructural deficiencies and technological limitations catalyze a series of operational and regulatory challenges, ultimately leading to negative customer perceptions and persistent reliance on outdated systems.

The hierarchical flow is as follows:

High Operational Cost, Sub optimal Routing, Limited Digital Connectivity → Cyber Security Risks→ Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism → Reliance on Legacy Systems

This flow highlights both root cause elements (foundational issues) and critical impacts (terminal outcomes).

5.2 Discussion

Table 5.2: Critical Barrier Differentiation

Level	Elements
Level 1	High Operational Cost, Sub-optimal Routing, Limited Digital Connectivity
Level 2	Cyber security Risks
Level 3	Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, Customer Skepticism
Level 4	Reliance on Legacy systems

5.2.1. Root Causes and Foundational Barriers

At Level 1, the foundational barriers include High Operational Costs, Sub-optimal Routing, and Limited Digital Connectivity. These challenges restrict the adoption of smart technologies, delay real-time decision-making, and obstruct process optimization. Poor digital infrastructure becomes a bottleneck for scalable modernization, significantly increasing the complexity and cost of transformation.

5.2.2. Operational and Regulatory Drivers

Level 2 comprises Cybersecurity Risks, which emerge as a pivotal barrier driven by insufficient digital safeguards and outdated IT ecosystems. Weak security protocols increase the vulnerability of logistics systems, deterring further digital adoption and reinforcing operational inertia.

5.2.3. Technological and Security Challenges

Level 3 presents a cluster of intermediate barriers that exert upward and downward influence: Outmoded Infrastructure, Frequent Regulatory Changes, Resistance to Automation, Lack of Standardized Regulations, and Customer Skepticism. These elements collectively obstruct innovation, induce uncertainty, and generate organizational reluctance toward change. They culminate in the most critical impact barrier—Reliance on Legacy Systems (Level4).

CHAPTER 6

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

6.1 Conclusion

This research sets both the opportunities as well as the challenges associated with the implementation of Industry 4.0 technologies in logistics, specifically last-mile delivery. The Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and Robotic Process Automation (RPA) technologies hold the key to revolutionizing logistics by increasing efficiency, transparency, and responsiveness. Yet, their universal adoption is presently hindered by three grand obstacles: great investment costs, technological sophistication, and organizational inertia. The capital outlay involved in refurbishing infrastructure, smart sensors installation, and AI system integration usually acts as a huge barrier, particularly to small and medium-sized logistics companies.

Secondly, the sophistication of such advanced systems typically demands a total restructuring of existing processes. This change not only necessitates sophisticated technical expertise but also poses a high learning curve for firms based on traditional logistics customs. Exacerbating these difficulties is resistance from within—fueled by apprehension over career security, skepticism about the value of digital solutions, and financial return anxiety. Overcoming these obstacles necessitates a systemic and strategic approach. Support from the government, in the nature of tax breaks, digital innovation funds, and favorable policy measures, can assist in reducing the cost of adopting digital transformation.

Just as significant is putting money into training schemes that will prepare the workforce to handle the skills necessary to get through and steer new technology, and thus facilitate the transition. Initiating with pilot implementations in chosen urban areas can enable logistics providers to pilot test, spot problems, and expand over a period of time based on on-the-ground experience. Companies that invest in technologies like real-time monitoring, optimized automated routing, AI-based inventory management, and blockchain-enabled secure transactions are likely to enjoy more efficient processes and lower operating costs. Additionally, these technologies help drive faster delivery, higher accuracy, and higher customer satisfaction—key variables in the competitive delivery landscape of the day.

6.2 Limitations of the Study

73 The research is based entirely on secondary data drawn from existing literature, industry publications, and publicly available resources. No primary data, interviews, or fieldwork were conducted. As a result, the study may not fully reflect the latest developments or practical challenges faced by industry professionals.

65 Secondly, due to the broad scope and exploratory nature of the study, in-depth examination of specific technologies (such as blockchain, RPA, or AI) and their implementation in logistics operations could not be undertaken. This limited the ability to assess the actual effectiveness, barriers, or return on investment of these technologies in real-world scenarios.

Thirdly, the study focuses on general trends and innovations in Industry 4.0 without analyzing variations based on specific geographical, infrastructural, or regulatory contexts—particularly in emerging economies or regional logistics networks.

Lastly, while technological factors were central to the study, the socio-economic, environmental, and ethical implications of adopting these technologies in logistics were only briefly addressed and warrant deeper investigation in future research.

6.3 Future Scope and Social Impact

6.3.1 Future Scope

14 This study provides a foundational framework for understanding barriers in last-mile delivery transformation. However, the following future directions could enhance the depth and practical applicability:

- Real-Time Technology Integration: Future research can explore how 5G, AI, and drones interact in urban and rural logistics networks, especially in countries with weak infrastructure.
- SME Adoption Models: There is significant potential in developing scalable and cost-effective models for AI and automation adoption by SMEs, including analyzing the learning curve, financial models, and support mechanisms required.
- Human-Technology Interaction: The evolving role of human labor in digitized logistics—ranging from skill displacement to reskilling opportunities—requires empirical study.
- Policy and Governance Analysis: Future work could examine the effectiveness of government policies in accelerating digital transformation, including tax incentives, regulatory sandboxes, and public-private partnerships.
- Localized Impact Assessment: Conducting region-specific studies that account for local regulations, cultural attitudes, and infrastructure challenges will help in tailoring more actionable strategies.
- Trust and Transparency Mechanisms: With increasing use of AI and data-driven systems, future research should focus on mechanisms to build customer trust, enhance data privacy, and foster ethical AI adoption in logistics platforms.

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6.3.2 Social Impact

The implementation of Industry 4.0 technologies in logistics has profound social implications:

• Workforce Evolution: While automation may reduce manual roles, it simultaneously generates opportunities for technical upskilling. Logistics workers can transition into roles involving system management, data analytics, and technology integration.

• Environmental Sustainability: Technologies such as AI-optimized routing and smart energy systems enable green logistics, reducing emissions and resource waste—aligning with global sustainability goals.

• Consumer Experience and Trust: Enhanced speed, accuracy, and transparency in deliveries improve customer satisfaction. However, these advancements must be balanced with robust data protection frameworks to preserve public trust.

• Digital Divide Concerns: There is a risk of exclusion for smaller businesses and underserved regions. Hence, equitable digital inclusion must be a core focus of any transformation roadmap.

• Community Empowerment: Digitized logistics can improve last-mile access to essential goods in remote areas, enhancing rural connectivity and community well-being.

A successful transition to digital logistics hinges not just on technological readiness but also on social responsibility, inclusive policy-making, and a people-centered approach.

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