



DIVYEN MAYANDI ARIVU

Micro-Fulfilment Centres (MFCs) and Industry 5.0

Cranfield School of Management
Logistic and Supply Chain Management

MSc in Logistics and Supply Chain Management
Academic Year: 2024 - 2025

Supervisor: Dr. Asefe Forghani
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This thesis is submitted in partial fulfilment of the requirements for
the degree of Master of Science

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Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

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Abstract

This study presents a systematic literature review (SLR) on the application of Industry 5.0 principles to MFCs in urban logistics. Industry 5.0, characterised by human–machine collaboration, advanced automation, and sustainability-driven operations, offers a transformative framework to meet the growing demand for rapid, flexible, and environmentally responsible last-mile delivery. While MFCs are increasingly adopted for hyperlocal distribution, their alignment with Industry 5.0 remains underexplored.

Using a structured methodology involving database searches, inclusion and exclusion criteria, and quality appraisal, this review synthesises both academic and industry studies to address three objectives: (1) to map current research on Industry 5.0 in MFC operations, (2) to identify technological and organisational benefits, and (3) to propose strategies for successful adoption.

Findings indicate that full-scale Industry 5.0 integration in MFCs is still emerging. However, enabling technologies such as digital twins for operational planning, AI-driven pick location optimisation, and customer-participatory locker-based delivery show measurable benefits. These include faster fulfilment times, improved resource efficiency, reduced operational costs, and enhanced customer convenience.

The review identifies five critical enablers for a successful transition: structured change management, phased implementation, targeted workforce reskilling, proactive customer engagement, and a post-launch hypercare phase to ensure operational stability. This study contributes to advancing the conceptual understanding of Industry 5.0 in reshaping hyperlocal fulfilment ecosystems and provides evidence-based recommendations for practitioners. Additionally, it identifies key research gaps, notably the need for longitudinal and cross-context studies on the socio-technical impacts of Industry 5.0-enabled MFCs in sustainable urban logistics.

Keywords:

Industry 5.0, MFCs, Urban Logistics, Last-Mile Delivery, Hyperlocal Distribution, Digital Twins, Artificial Intelligence in Logistics, Human–Machine Collaboration, Sustainable Supply Chains.

Acknowledgements

First of all, I am deeply grateful to my supervisor, Dr. Asefe Forghani, for her time, effort, and guidance throughout this thesis. Her valuable recommendations, constructive feedback, and continuous support have been instrumental in shaping and improving my work. I truly appreciate her patience, encouragement, and expertise during this research journey.

I would also like to express my heartfelt gratitude to my family for their unwavering support, understanding, and motivation, which have been a constant source of strength.

Lastly, I would like to thank all my professors and classmates at Cranfield University for their camaraderie, collaboration, and shared learning experiences during my studies.

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List of Abbreviations

IT	Information Technology
MFCs	Micro-Fulfilment Centres
FMCG	Fast Moving Consumer Goods
ESG	Environmental, Social and Governance
AI	Artificial Intelligence
AMRs	Autonomous Mobile Robots
DT	Digital Twin
LMD	Last-Mile Delivery
UAT	User Acceptance Testing
SLR	Systematic Literature Review
TLR	Traditional Literature Review
UCC	Urban Consolidation Centre
IoT	Internet of Things
PLS-SEM	Partial Least Squares Structural Equation Modelling
MCDM	Multi-Criteria Decision Making
SKU	Stock Keeping Unit
ADR	Autonomous Delivery Robot
AR	Augmented Reality
ERP	Enterprise Resource Planning
EV	Electric Vehicle
ICT	Information and Communication Technology
IT	Information Technology
KPI	Key Performance Indicator
VR	Virtual Reality

Key Definitions

Term	Definition
MFCs	Small, automated fulfilment hubs located within urban areas to reduce delivery times and improve efficiency. MFCs leverage technologies like robotics and AI to streamline inventory management and enhance LMD, helping meet the growing demand for fast, cost-effective e-commerce services in dense cities (Karaoulanis, 2024)
Industry 5.0	The fifth industrial revolution focusing on human-machine collaboration, sustainability, and resilience. Unlike Industry 4.0, which emphasised automation, Industry 5.0 places humans at the centre of the production process, with a focus on leveraging AI, robotics, and human skills to enhance efficiency and adaptability while promoting sustainability (Alves et al., 2023; Xu et al., 2021)
Human-Centred Logistics	Human-Centric Logistics is an approach that prioritises human needs, safety, and well-being alongside technological innovation in logistics. It focuses on human-machine collaboration, using tools like collaborative robotics and ergonomics to enhance worker empowerment, productivity, and safety, rather than replacing human labour (Brzezinski, 2022)
Last-Mile Delivery (LMD)	The final segment of the supply chain where goods are delivered to the consumer's location. LMD is often the most time-consuming and expensive part of logistics, especially in urban areas, and is increasingly being optimised through MFCs, autonomous vehicles, and innovative delivery

	models to improve efficiency and reduce costs (Engesser et al., 2023).
User Acceptance Testing (UAT)	A phase in the deployment of new systems where end-users validate that the systems or technologies meet their needs and function as intended. In MFCs, UAT ensures that technologies like digital twins, AI, and robotics are operational before full-scale deployment (Xu et al., 2021).
Omnichannel Fulfilment	Omnichannel fulfilment is an integrated approach to fulfilling customer orders across multiple sales channels, ensuring a seamless and consistent experience for customers. In MFCs, this strategy streamlines inventory management and delivery systems, allowing businesses to fulfil orders from the most efficient source whether it's a physical store, an MFC, or a distribution centre. This method significantly boosts responsiveness and efficiency, especially in urban areas where customers expect faster deliveries (Alessandro et al., 2022)
Circular Economy	A circular economy is an economic system aimed at minimising waste and maximising the reuse of materials. In logistics, it encompasses practices such as product reuse, recycling, and designing systems that reduce environmental impact. MFCs and sustainable logistics models often incorporate circular economy principles to minimise waste in packaging, energy usage, and product disposal. These approaches contribute to a more sustainable and resource-efficient supply chain (Cerqueira-Streit et al., 2023)
Key Performance Indicators (KPIs)	KPIs are quantitative metrics used to evaluate the performance of logistics operations. In MFCs, KPIs may include order fulfilment time, cost per delivery, inventory

	turnover, and customer satisfaction. These indicators are critical for assessing the efficiency and effectiveness of MFC operations, enabling businesses to identify areas for improvement and optimise their supply chain processes (Bressolles & Lang, 2020; Grewal et al., 2017).
Sustainability	Sustainability in logistics refers to the development of systems and practices that minimise the environmental impact of supply chain operations. This includes reducing emissions, optimising resource usage, and promoting the reuse and recycling of materials. In the context of MFCs, sustainability involves efficient energy usage, waste reduction, and the implementation of eco-friendly delivery models, which help to lower the carbon footprint of urban logistics (Karaoulanis, 2024).

1 INTRODUCTION

1.1 Background

The landscape of urban logistics is undergoing a profound transformation driven by rapid urbanisation, the exponential growth of e-commerce, and evolving consumer expectations for faster and more flexible deliveries. In this changing environment, Micro-Fulfilment Centres (MFCs) have emerged as a crucial innovation to address the logistical challenges associated with the last-mile delivery (LMD) which is widely regarded as the most complex, costly, and environmentally impactful component of the supply chain (Alessandro et al., 2022).

The growing requirement for MFCs is largely influenced by the increasing demand for rapid delivery services, especially in the grocery and fast-moving consumer goods (FMCG) sectors, where same-day or next-day delivery has become the new standard (Yang et al., 2024). Traditional large distribution centres, typically located on city outskirts, struggle to fulfil this demand due to longer delivery distances and urban congestion. Consequently, companies are investing in smaller, automated fulfilment hubs closer to urban consumers, enabling reduced delivery lead times and improved service equality.

The COVID-19 pandemic accelerated e-commerce growth, highlighting vulnerabilities in traditional supply chains reliant on large, centralised distribution centres. These centres struggled to meet demand due to longer delivery distances and urban congestion. In response, companies like Walmart and Amazon expanded their MFCs to shorten delivery times and reduce operational costs. MFCs, located closer to urban consumers, significantly enhance delivery speed, cost efficiency, and customer satisfaction. Research indicates that decentralised networks, such as MFCs, improve supply chain flexibility and resilience, while enabling faster deliveries. The market for MFCs is projected to grow rapidly, with significant investments in automation and robotics (Gujar &

Vishwakarma, 2024). Industry estimates indicate that the global MFC market will expand by more than USD 25 billion between 2024 and 2030, driven by e-commerce growth, omnichannel retail strategies, and advances in inventory optimisation and automation.¹

In addition to operational benefits, MFCs contribute significantly to space optimisation and sustainability objectives. Their compact footprint allows integration into underutilised urban spaces such as retail store basements or parking structures, addressing the high cost and scarcity of real estate in cities (AR Racking, 2024). Furthermore, by shortening delivery distances and enabling route consolidation, MFCs reduce greenhouse gas emissions, aligning supply chains with environmental, social, and governance (ESG) frameworks increasingly demanded by consumers and regulators (Starr, 2025).

Technological advancements play a pivotal role in enhancing the effectiveness of MFCs. The integration of robotics, artificial intelligence (AI), and real-time tracking tools enables high throughput and order accuracy within limited physical spaces (Prabu, 2022). These automation technologies streamline operations, reduce manual errors, and improve inventory management, thereby addressing labour shortages and rising costs in urban logistics (Honeywell, 2022). For instance, the deployment of autonomous mobile robots (AMRs) has significantly improved picking speed, enabling scalable and responsive fulfilment operations.²

Furthermore, the use of AI-driven systems facilitates predictive analytics and demand forecasting, which are essential for optimising inventory levels and reducing waste (Kamble, 2024). This not only enhances operational efficiency but also supports sustainability by reducing energy consumption and emissions

¹ ResearchAndMarkets.com, Micro-Fulfilment Centres (MFCs) Strategic Industry Report 2025: Global Market to Grow by Over USD 25 Billion During 2024–2030, Driven by Omnichannel Retailing, Inventory Optimisation and E-commerce (2025), available at: <https://www.researchandmarkets.com/>, accessed 11 August 2025.

² <https://inviarobotics.com/blog/revolutionizing-warehouse-automation-with-autonomous-mobile-robots-amrs/>

associated with traditional logistics. As part of Industry 5.0, such technologies align with a more human-centric approach that ensures sustainability and resilience in supply chain operations, particularly in MFCs, where the complexity of modern supply chain demands a more adaptable, ethical, and flexible model.

Technological upgrades in Industry 5.0 emphasise the integration of advanced technologies with human-centric, sustainable, and resilient systems (Breque et al., 2021). Unlike Industry 4.0, which focused on automation and operational efficiency, Industry 5.0 shifts the focus to augmenting the workforce with technology, rather than replacing it. This approach is vital for MFCs, where technological efficiency alone is no longer enough to address the growing complexity of modern supply chains. While Industry 4.0's automation and AI-driven solutions significantly improve speed and cost-efficiency, they often overlook the human factor, which is crucial for fostering adaptability, resilience, and ethical decision-making in MFCs. Industry 5.0's human-centric model enables MFCs to maintain flexibility and adaptability to meet evolving consumer demands and ensure sustainable operations. Collaborative robotics, AI, and digital twins, for example, enhance decision-making while empowering employees (Steiber, 2025). Such innovations help companies like Haier demonstrate how Industry 5.0 can successfully combine technological advancement with human empowerment. This evolution fosters greater workforce well-being, ethical design, and long-term sustainability, making Industry 5.0 more important than Industry 4.0 for future MFC operations (Atieh Ali et al., 2024; Nazarian & Khan, 2024).

Despite the increasing attention to MFCs and Industry 5.0, the existing literature remains fragmented. Studies often focus either on MFC technologies or on last-mile logistics performance, with limited integration of human-centric, sustainable, and resilience-oriented perspectives. To address this knowledge gap, the present thesis adopts a Systematic Literature Review (SLR) methodology. This approach applies a structured, transparent, and replicable process to identify, appraise, and synthesise relevant research. By consolidating dispersed evidence, the SLR will

provide a comprehensive understanding of how MFCs can be designed, implemented, and managed under Industry 5.0 principles to support efficient, sustainable, and resilient urban logistics systems.

1.2 Evolution

1.2.1 Evolution of Warehouses

Warehousing has evolved from local storage facilities such as granaries in ancient civilisations to large, centralised hubs during the Industrial Revolution, where storage capacity was prioritised over geographical proximity to customers. In medieval times, warehouses located near ports supported the rapid growth of international trade, while the 19th and 20th centuries saw the establishment of extensive storage facilities on city outskirts, enabled by the expansion of rail and road networks. These high-capacity warehouses allowed large-scale inventory management but significantly increased LMD times.

In the contemporary era, the rise of e-commerce has shifted the focus from centralised facilities to MFCs, which are small, technology-driven warehouses strategically embedded within urban areas. Unlike traditional large warehouses, MFCs balance reduced storage capacity with greater proximity to end customers, enabling faster, more responsive, and cost-efficient delivery services MFCs.^{3 4}

1.2.2 Evolution of Industrial Technology

Figure 1 summarises the five major industrial revolutions that have shaped production, logistics, and society (NAMC, 2024). The progression of these revolutions has also directly influenced the design, operation, and strategic role of warehouses and fulfilment systems. Industry 1.0, characterised by mechanisation through steam and waterpower, laid the foundations for structured storage and movement of goods. Warehouses during this period were still

³ <https://www.hopstack.io/blog/evolution-warehousing-systems-history-timelines>

⁴ <https://www.newcastlesys.com/blog/the-history-of-warehousing>

relatively simple but began to benefit from mechanised handling, enabling greater volumes of trade compared to pre-industrial economies (Borsos & Koman, 2023). Industry 2.0, driven by electricity and mass production, introduced standardisation and large-scale distribution, shifting warehousing from local storage to centralised hubs designed to support rail and road networks and enabling more efficient regional fulfilment (Haradhan Kumar, 2020). This evolution planted the seeds for modern large-scale distribution centres. Industry 3.0 marked the arrival of automation and computerisation, with warehouses adopting barcode systems, automated sorting, and early inventory management software to reduce errors and increase throughput (Olofsson & Rylander, 2021). Although MFCs did not yet exist, advances in data processing and control systems established the foundations for technology-enabled, small-scale responsive storage. Industry 4.0 integrated cyber-physical systems, the Internet of Things (IoT), and advanced data-driven decision-making, enabling smart warehouses, robotics, and real-time visibility platforms (Moufaddal et al., 2021). These developments improved supply chain integration but also highlighted new challenges, particularly the inefficiencies of large, centralised distribution centres struggling with urban congestion and last-mile costs. The limitations of Industry 4.0's efficiency-oriented approach created a gap that MFCs are designed to fill. Industry 5.0 advances this trajectory by combining cutting-edge technologies with human collaboration, sustainability, and resilience as guiding principles. Unlike Industry 4.0, which prioritised full automation and efficiency, Industry 5.0 places humans at the centre of technology-enabled systems, allowing MFCs to integrate AI, robotics, and digital twins not only for efficiency but also for adaptability, ethical design, and workforce empowerment (Ghobakhloo et al., 2022). As a result, MFCs under Industry 5.0 are positioned as agile, human-centric, and sustainable nodes within urban logistics networks, capable of balancing speed, cost, and environmental impact. In summary, the trajectory of industrial revolutions shows that while Industry 1.0 to 4.0 enabled larger, more automated, and data-driven distribution systems, only Industry 5.0 provides the holistic

framework necessary for MFCs to thrive in modern urban supply chains, aligning technological innovation with sustainability and human-centric values.



Figure 1 Evolution of Industrial Technology

Source: Original work (Author)

1.3 Research Gap

Although Industry 5.0 has been extensively discussed in the context of manufacturing, warehousing, and broader logistics, its application to MFCs and LMD remains underexplored. Existing research tends to concentrate on isolated themes such as automation technologies, robotics, or digital platforms, without offering a holistic perspective on how Industry 5.0 principles of human-centricity, sustainability, and resilience can be operationalised in MFCs. Moreover, no comprehensive SLR has yet been conducted in this domain, meaning that the available knowledge is fragmented, segmented across disciplines, and lacks an integrated framework for both academics and practitioners.

This absence of synthesis leaves several important gaps unanswered: How do Industry 5.0 technologies align with the unique constraints of MFCs? What trade-offs exist between efficiency, human factors, and sustainability in different urban and regulatory contexts? And how can lessons from adjacent fields in logistics and supply chain management be transferred to the design of future-ready MFC networks?

1.4 Objective

1.4.1 Aim

To address the evidenced gap that Industry 5.0 is well studied in manufacturing, warehousing, and general logistics but remains limited in the specific context of MFCs and LMD, this thesis undertakes the first comprehensive SLR focused on this intersection. Unlike narrative reviews, the SLR will follow a transparent and replicable protocol to identify, select, appraise, and synthesise academic and industry studies, thereby consolidating segmented evidence currently dispersed across technological, organisational, and policy domains. The primary aim is to produce a rigorous evidence base that maps the state of knowledge on Industry 5.0 for MFCs and LMD, evaluates the strength of findings, and integrates them into an actionable conceptual framework. This framework will highlight Industry 5.0 enablers for MFCs, including human-centric design, sustainability, and resilience, while also clarifying contextual factors such as urban form, regulatory settings, and sectoral characteristics. In doing so, the thesis contributes in two ways: practitioner-oriented outputs, including implementation pathways and managerial guidance for MFC adoption under Industry 5.0, and scholarly outputs, including a synthesised taxonomy, a research agenda, and propositions to guide future empirical and modelling work. More broadly, the thesis evaluates the operational, environmental, and economic implications of Industry 5.0-enabled MFCs, and demonstrates how human-centric innovation, sustainability, and resilience can be embedded in future-ready urban fulfilment systems.

1.4.2 Research Question

In this thesis, three primary research questions are formulated to guide the SLR and analysis of findings.

RQ1: What does the current body of research reveal about the application of Industry 5.0 principles to MFCs in urban logistics?

RQ2: What are the main reported benefits of applying Industry 5.0 to MFCs, particularly in terms of delivery speed, cost efficiency, service quality, sustainability, and resilience?

RQ3: What strategies can supply chain managers and policymakers adopt to successfully transition existing MFCs towards Industry 5.0 frameworks, and what contextual factors influence these transitions?

1.5 Outline of Thesis

This section provides an overview of the thesis structure and clarifies how each chapter contributes to addressing the stated research questions.

1.5.1 Chapter 2 Methodology

This chapter outlines what the SLR will involve the full procedure will be described using a structured protocol to ensure transparency, replicability, and academic rigour. It will include an explanation of the search strategy, along with the criteria used for selecting the final set of papers.

1.5.2 Chapter 3 Descriptive Findings

This chapter will present the descriptive overview of the selected literature, along with a classification of the literature's features, such as methodology, geographical distribution, industries, and research methods.

1.5.3 Chapter 4 Thematic Analysis

This chapter presents an evidence-based analysis drawn from the reviewed literature. By examining recent studies on emerging technologies in Industry 5.0, it will identify and synthesise the most relevant innovations for application in MFCs. The discussion will focus on the benefits these technologies can offer, such as enhanced efficiency and human-machine collaboration, along with potential risks or implementation challenges. These findings aim to address the core research questions and objectives of the thesis while also offering insights to support future research and practical adoption of Industry 5.0 principles in MFCs.

1.5.4 Chapter 5 Discussion

This chapter will interpret and critically analyse the results of the SLR, linking them explicitly to the research questions. It will compare the findings with existing literature, extract key lessons, and propose strategies for transitioning MFCs towards Industry 5.0 adoption. Most importantly, this chapter will respond precisely and systematically to each of the three research questions, ensuring that the thesis delivers a complete and coherent answer.

1.5.5 Chapter 6 Conclusion

This chapter will summarise the overall findings of the study, emphasise their implications for both theory and practice, and restate how the research questions were addressed. It will also demonstrate clearly how each question was answered, thereby assuring examiners that all stated objectives and questions have been fully met. Finally, it will provide reflective remarks and outline potential directions for future research.

2 Methodology

This chapter presents the methodological framework employed in this thesis, which adopts a SLR as the primary research strategy. The SLR approach was selected for its ability to provide a structured, transparent, and replicable method of identifying, evaluating, and synthesising existing literature on MFCs and Industry 5.0 applications in urban logistics. Given the emerging and interdisciplinary nature of this research domain MFCs, the SLR enables a comprehensive and unbiased exploration of current academic and practitioner insights. This chapter systematically outlines the process, including the formulation of research questions, identification of relevant databases, development of search strategies, application of inclusion and exclusion criteria, and the eventual analysis and synthesis of the collected data.

2.1 Definition of SLR

A SLR is a rigorous, structured, and protocol-driven method for gathering, evaluating, and synthesising research on a defined topic. The central objective is to answer specific research questions using explicit and replicable procedures that minimise bias and ensure reliable findings. Unlike narrative reviews, which may provide a descriptive or selective overview, an SLR applies transparent inclusion and exclusion criteria, systematic search strategies, and critical appraisal of study quality (Higgins et al., 2019).

The process typically involves formulating research questions in advance, determining eligibility criteria, conducting a comprehensive search across relevant databases, and synthesising the findings through descriptive and thematic analysis (Khan et al., 2003). In addition to providing a consolidated evidence base, SLRs are particularly valuable because they help to identify consistent patterns, highlight contradictions, and most importantly, point to areas where further research is required.

In this thesis, the SLR approach is applied to the study of MFCs and Industry 5.0 in urban logistics, where knowledge is currently dispersed across multiple domains such as logistics, operations management, supply chain resilience, and sustainability. By systematically consolidating fragmented insights, the review will generate a balanced and comprehensive synthesis that not only advances academic understanding but also provides practitioners and policymakers with practical guidance for the strategic deployment of MFCs in LMD systems.

2.2 Characteristics of SLR

Traditional Literature Reviews (TLRs) are typically descriptive and interpretive in nature. They rely heavily on the author’s perspective, often lack a predefined structure, and may be difficult to replicate, which reduces their objectivity and reliability. In contrast, SLRs adopt a rigorous and protocol-driven methodology that specifies research questions, search strategies, inclusion and exclusion criteria, quality assessment, and data extraction processes. This structured approach enhances transparency, reproducibility, and robustness of findings.

By systematically synthesising evidence, SLRs reduce bias and provide a more comprehensive and trustworthy account of the existing knowledge base. This makes them particularly valuable in high-tech and rapidly evolving domains such as MFCs and Industry 5.0, where decision-making and research advancement require a reliable foundation of evidence. Table 1 presents a comparison of TLR and SLR characteristics, adapted from (Sogunie & Sogunie, 2023).

Table 1 Comparison between Traditional and Systematic Literature Review

Criteria	Traditional Literature Review	Systematic Literature Review
Authorship	One or more experts in the field; no standard collaboration	Typically conducted by multiple experts in different sections of the review process

Study Protocol Preparation	No formal protocol preparation	A detailed, step-by-step protocol is developed and followed
Research Question	Broad or unspecific; often lacks hypothesis formulation	Specific and focused, often using the PICO framework (Population, Intervention, Comparison, Outcome)
Search Strategy	Unstructured or vague search using keywords; non-reproducible	A comprehensive and reproducible search strategy, with clearly defined search terms
Study Selection Criteria	No predefined inclusion/exclusion criteria; selection is subjective	Clear inclusion/exclusion criteria are applied, minimizing selection bias
Critical Appraisal	No critical assessment of the quality or validity of studies	Rigorous quality assessment of included studies to evaluate relevance and methodological soundness
Synthesis	Narrative or qualitative synthesis based on available literature	Quantitative (Meta-analysis) or qualitative synthesis, depending on the data homogeneity
Reproducibility	Results are not easily replicable due to subjective judgment and lack of detailed methods	Methods and results are clearly documented, ensuring reproducibility

Refinement	Cannot be continuously updated or refined	Can be updated with new evidence as it becomes available
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Source: Sogunie & Sogunie, 2023

2.3 Process of SLR

The SLR process follows a structured sequence of steps: identifying clearly defined research questions, selecting relevant databases, formulating and testing comprehensive search strings, applying inclusion and exclusion criteria to screen studies, extracting relevant data using standardised forms, and synthesising the findings to draw evidence-based conclusions and identify research gaps.

Figure 2 outlines a structured process for conducting research, particularly for SLR. The process begins with identifying the core research question, which serves as the foundation of the study. Following this, keywords and search strings are formulated to guide the literature search. Once the search strategy is in place, inclusion and exclusion criteria are applied to filter the relevant studies, ensuring they align with the research scope. The search terms are then refined to optimize the research question, ensuring alignment with the desired study focus. Relevant data is extracted from the selected studies, followed by synthesizing the information to draw meaningful conclusions. The next step is to identify research gaps that may require further exploration, ensuring the research contributes to the existing body of knowledge. Finally, the scope for technology is explored, aiming to identify how technological advancements can impact and enhance the research area. This process ensures a systematic and thorough approach to literature review.

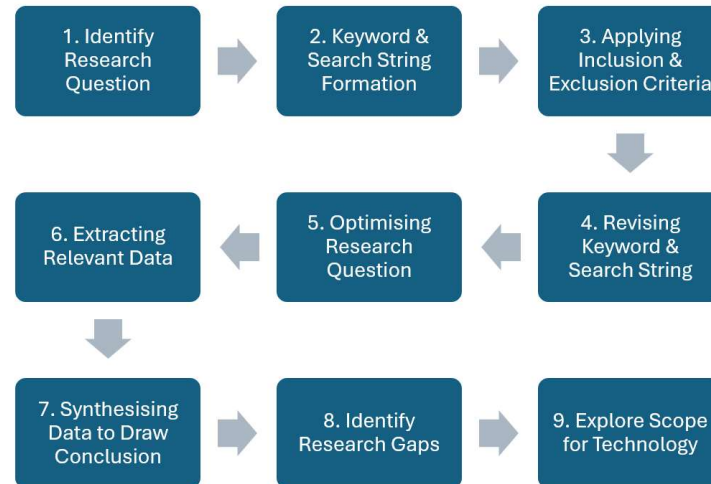


Figure 2 SLR Process Overview

Source: Original work (Author)

2.4 Identification of Research Question

This step defines the focus and analytical boundaries of the review. Clear, answerable research questions determine which studies are relevant, what evidence will be extracted, and how findings will be synthesised. In line with SLR guidance, questions must be specific, feasible to answer from existing literature, and directly aligned with the review aim, rather than broad topic statements (Stansfield, C., Gough, D., Bangpan, M., Bhimani, N. 2021).

Process used in this thesis:

1- Scoping and terminology calibration

An initial scoping search was conducted in multidisciplinary databases to identify common terms and boundaries for MFCs, LMD, and Industry 5.0. This helped consolidate synonyms and related concepts such as micro fulfilment, dark stores, urban fulfilment centres, human-machine collaboration, and digital twins.

2- Question structuring with a management-review lens

To ensure relevance to logistics and operations, the research questions were framed using the SPIDER logic.

- Sample: MFCs and last-mile operations in urban logistics.
- Phenomenon of Interest: application of Industry 5.0 principles and enabling technologies, for example AI, robotics, digital twins, human-machine collaboration, and change management.
- Design: empirical studies, modelling and simulation, case studies, and systematic reviews.
- Evaluation: operational, economic, environmental, service quality, and resilience outcomes.
- Research type: qualitative, quantitative, and mixed methods.

3- Operationalisation into eligibility dimensions

The questions were then translated into eligibility criteria covering setting (MFCs in urban contexts), concepts of interest (Industry 5.0 principles and enablers), outcomes (performance, cost, emissions, service quality, resilience), study designs, publication type and quality, timeframe, language, and geography. This ensured consistency, reproducibility, and transparency throughout the review.

4- Research questions used

RQ1: What does the current body of research reveal about the application of Industry 5.0 principles to MFCs in urban logistics?

RQ2: What are the main reported benefits of applying Industry 5.0 to MFCs, particularly in terms of delivery speed, cost efficiency, service quality, sustainability, and resilience?

RQ3: What strategies can supply chain managers and policymakers adopt to successfully transition existing MFCs towards Industry 5.0 frameworks, and what contextual factors influence these transitions?

Formulating questions in this structured way ensures alignment between the review's scope, eligibility criteria, and synthesis. It reduces selection bias, supports transparent reporting, and highlights where evidence is strong, contradictory, or absent, thus guiding priorities for future research

2.5 Data Collection Process

The effectiveness of a SLR depends on the transparency and rigour of its data collection. Databases structure citations into fields such as title, abstract, journal, year, and keywords, which enables the precise retrieval of relevant studies. Unlike internet search engines, which automatically interpret queries, academic databases require carefully defined search strategies using Boolean operators (AND, OR, NOT) and proximity functions to refine results (Stansfield, C., Gough, D., Bangpan, M., Bhimani, N. 2021).

Many specialist databases employ controlled vocabularies or thesauri, which provide standardised indexing terms to classify articles. These controlled terms can be combined with free-text keywords from titles and abstracts to build comprehensive and replicable search strings. Since thesauri vary between databases, the search strategy must be adapted to each platform. For example, databases such as Scopus and ProQuest provide subject categories and descriptors, while Web of Science lacks a thesaurus but generates terms through its Keywords Plus function.

To ensure inclusivity, the search process in this thesis integrates both controlled descriptors and free-text keywords. Terms related to MFCs, LMD, Industry 5.0, automation, human-machine collaboration, digital twins, and sustainability were iteratively refined during the scoping phase. The resulting strategy balances sensitivity (capturing as many relevant studies as possible) with precision

(minimising irrelevant retrievals). This dual approach allows a comprehensive mapping of fragmented research and supports the synthesis of evidence across different disciplinary and geographical contexts as shown in Figure 3.

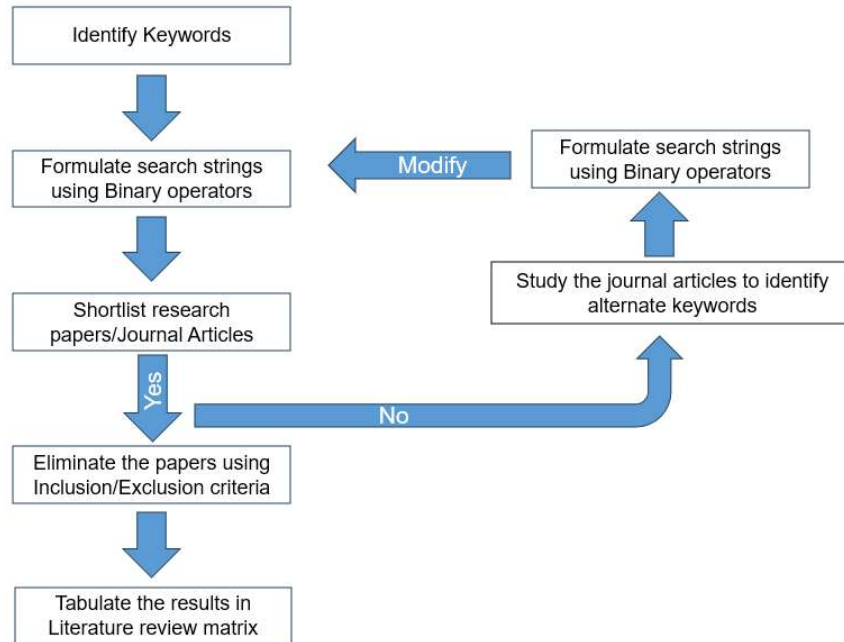


Figure 3 Data Collection Process

Source: Original work (Author)

2.5.1 Database Selection

To ensure both comprehensiveness and academic rigour, this thesis relied on two globally recognised databases: Scopus and Web of Science. These platforms were selected for their extensive coverage of peer-reviewed, high-impact literature across fields central to this study, including supply chain management, industrial engineering, information systems, and emerging technologies.

Scopus offers broad indexing of journals, conference proceedings, and trade publications, making it especially useful for capturing technological developments and applied research on logistics and fulfilment.

Web of Science, with its emphasis on multidisciplinary and high-quality sources, ensures the inclusion of influential academic contributions that shape the theoretical and conceptual discourse.

The combined use of these databases allowed the review to span both technological innovations (such as automation, robotics, and digital twins) and logistics perspectives (such as urban supply chains, LMD, and fulfilment strategies). This dual coverage was essential to addressing the interdisciplinary nature of Industry 5.0 and MFCs.

2.5.2 Keyword Identification

The identification of keywords was a multi-stage process involving iterative rounds of evaluation, testing, and refinement. The aim was to achieve both comprehensive coverage of relevant literature and precision in capturing studies that directly address the research questions. Numerous trial combinations were explored during the scoping phase, and Boolean operators were used to balance recall (breadth) with relevance (focus).

For transparency, Table 2 presents the first attempt at structuring keyword groupings. This early round of testing combined concepts related to MFCs and urban logistics with those associated with Industry 5.0 technologies and strategies. Although further refinements followed, this initial round illustrates how the thematic domains were framed before adapting and consolidating them into the final search strings applied in the selected databases.

Table 2 First Attempt at Keywords

Domain	Keywords
Micro-Fulfillment Centre/Urban Logistics	"micro-fulfillment", "urban logistics hub", "omnichannel", "last-mile", "decentralized", "automated micro-fulfillment", "decentralized warehousing", "retail micro-warehousing", "on- demand fulfillment", "in-store fulfillment", "urban consolidation center", "proximity-based fulfillment", "omnichannel warehouse", "e-grocery fulfillment center"
Industry 5.0 Technologies/Strategies	"Industry 5.0", "fifth industrial revolution", "human- centric industry", "collaborative robotics", "human- machine collaboration", "sustainable logistics", "urban logistics", "smart supply chain", "LMD", "AI in logistics", "resilient supply chain"

Source: Original work (Author)

2.5.3 Binary Search String Formation and Results

Boolean operators (AND, OR, NOT) and truncations were applied to generate database-ready binary search strings. These strings operationalised the keyword sets into reproducible queries for Scopus and Web of Science.

First Attempt

An example of the initial Boolean search string was: ("micro-fulfillment" OR "urban logistics hub" OR "omnichannel" OR "last-mile" OR "decentralized" OR "automated micro-fulfillment" OR "decentralized warehousing" OR "retail micro-warehousing" OR "on-demand fulfillment" OR "in-store fulfillment" OR "urban consolidation center" OR "proximity-based

fulfillment" OR "omnichannel warehouse" OR "e-grocery fulfillment center")

AND

("Industry 5.0" OR "fifth industrial revolution" OR "human-centric industry" OR "collaborative robotics" OR "human-machine collaboration" OR "sustainable logistics" OR "urban logistics" OR "smart supply chain" OR "LMD" OR "AI in logistics" OR "resilient supply chain")

AND NOT ("Manufacturing")

Result

This query returned 78 records from Scopus and 94 records from Web of Science, forming the base for initial screening. However, the majority of studies retrieved only indirectly touched on the integration of Industry 5.0 with distribution centres or micro-fulfilment contexts. While useful for mapping the landscape, the results lacked precision.

Second Attempt

To address this gap, the search terms were refined and optimised, producing the second-round keyword grouping as shown in Table 3.

Table 3 Second Attempt at Keyword Grouping

Domains	Keywords
Micro-Fulfilment Centre/Urban Logistics	"micro-fulfillment", "decentralized warehousing", "micro-warehousing", "fulfillment centre", "in-store fulfillment", "urban consolidation center", "urban logistics", "proximity-based fulfillment", "omnichannel warehouse", "e-grocery fulfillment

	center", "urban logistics hub", "omnichannel", "last-mile", "decentralized warehouse"
Industry 5.0 Technologies/Strategies	"Fifth Industrial", "Circular Economy", "AI Revolution", "Machine Intelligence", "Emotional Intelligence", "Industry 5.0", "human-centric industry", "collaborative robotics", "sustainable logistics", "smart supply chain", "AI in logistics"

Source: Original work (Author)

The refined Boolean search string was as follows: ("micro-fulfillment" OR "decentralized warehousing" OR "micro-warehousing" OR "fulfillment centre" OR "in-store fulfillment" OR "urban consolidation center" OR "urban logistics" OR "proximity-based fulfillment" OR "omnichannel warehouse" OR "e-grocery fulfillment center" OR "urban logistics hub" OR "omnichannel" OR "last-mile" OR "decentralized warehouse")

AND

("Fifth Industrial" OR "Circular Economy" OR "AI Revolution" OR "Machine Intelligence" OR "Emotional Intelligence" OR "Industry 5.0" OR "human-centric industry" OR "collaborative robotics" OR "sustainable logistics" OR "smart supply chain" OR "AI in logistics")

Result

This second attempt yielded 7 highly relevant papers from Scopus and 42 from Web of Science, significantly improving the precision of retrieved studies. Compared to the first round, this refined strategy narrowed the scope towards literature explicitly focused on Industry 5.0 applications within micro-fulfillment and distribution contexts, strengthening the evidence base for subsequent analysis.

2.6 Screening and Selection Criteria

The screening process was carried out in two structured stages to ensure methodological rigour and relevance:

1. Title and Abstract Screening – Initial filtering to exclude studies clearly unrelated to the topic.
2. Full-Text Review – Application of predefined inclusion and exclusion criteria to confirm eligibility.

The criteria, summarised in Table 4, were designed to align with the research questions and guarantee that only high-quality, relevant studies were retained.

Table 4 Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion	Rationale
Availability	Full-text peer-reviewed articles	Non-accessible full texts	Ensures full evaluation of context, methodology, and findings.
Language	English	Non-English publications	Guarantees consistency and avoids translation-related bias.
Publication Type	Academic journal articles and conference papers	News articles, blogs, white papers	Focuses on rigorously reviewed and citable sources.

Time Frame	2015–Present	Pre-2015	Captures studies within the timeframe of Industry 4.0 and 5.0 developments.
Industry Relevance	Supply chain, warehousing, logistics, Distribution Centre	Irrelevant sectors (e.g., aviation, generic transport, or non-logistics contexts) LMD	Maintains thematic focus on fulfilment and logistics systems.
Keywords	As defined in keyword identification section	Manufacturing-only studies	Ensures conceptual alignment with Industry 5.0 and MFC focus.

Source: Original work (Author)

2.7 Quality Appraisal

To ensure methodological consistency and robustness, the shortlisted articles were assessed for credibility, relevance, and rigour using the Quality Appraisal Framework by Habib (2012), provided in Appendix B.1 as shown in Table 9. The framework evaluates five dimensions contribution to theory, methodology, data analysis, implications for practice, and level of citations on a 0 - 3 scale, where 0 indicates insufficient information and 3 reflects strong performance.

Using this framework, the 20 most relevant papers were systematically scored across all criteria. The maximum possible score for each paper was 15, and an average score was calculated to ensure comparability. In this study, papers with an average score of 1.6 or higher were deemed methodologically robust and included for further analysis.

As shown in Table 5 Average Quality Score of Shortlisted Papers, applying Habib's (2012) framework enabled the identification of papers with strong methodological grounding and practical relevance. While the quality appraisal focuses on the 20 shortlisted articles, additional studies related to Industry 5.0 were also incorporated in subsequent sections to broaden the thematic scope of the review.

Table 5 Average Quality Score of Shortlisted Papers

Author(s)	Year	Title	Contribution to Theory Score	Methodology Score	Data Analysis Score	Implications for Practice Score	Level of Citations Score	Total Score	Average Score
Ronan de Kervenoael, Alexandre Schwob, Careen Chandra	2020	E-retailers and the engagement of delivery workers in urban LMD for sustainable logistics value creation: Leveraging legitimate concerns under time-based marketing promise	1	3	1	1	2	8	1.6
Clément Lemardelé, Miquel Estrada, Laia Pagès	2024	Uncertainty analysis of autonomous delivery robot operations for last-mile logistics in European cities	3	3	1	1	2	10	2
Maria Savall-Manyó, Imma Ribas	2022	Location of micro-urban consolidation centres for the superblocks in Barcelona	2	3	1	3	2	11	2.2

Ying Ji, Shaojian Qu, Zhensheng Yu	2017	Bi-level multi-objective optimization model for last mile delivery using a discrete approach	3	3	1	3	2	12	2.4
Maria Björklund, Henrik Johansson, Mats Abrahamsson	2017	Critical factors for viable business models for urban consolidation centres	3	1	1	3	2	10	2
Johanna Amaya, Julian Arellana, Maira Delgado- Lindeman	2020	Stakeholders perceptions to sustainable urban freight policies in emerging markets	1	2	1	1	2	7	1.4
Silvio Nocera, Federico Cavallaro	2017	Two-step method to evaluate the well-to-wheel carbon efficiency of UCC	1	1	1	1	2	6	1.2

Michael A. Gogas, Eftihia Nathanail	2017	Evaluation of Urban Consolidation Centers: A Methodological Framework	1	1	1	2	6	1.2
Jithin Suresh, Vernika Agarwal, Mukund Janardhanan, Tarik Saikouk	2024	Unlocking Sustainability: Overcoming Barriers to Circular Economy Implementation in Fulfilment Centers	1	2	1	2	9	1.8
Sten Wandel, Stefan Anderberg, Fredrik Eng Larsson, Anders Johnsson, Andreas Wells	2023	Underground capsule pipeline logistic system: Feasibility study of an urban application	3	2	1	2	9	1.8

Aleksandrs Kotlars & Valerijs Skribans	2024	Efficiency, environment and robotization in first and last mile logistics	2	3	1	1	2	9	1.8
Aldona Jarašūnienė, Kristina Čižinienė & Audrius Čereška	2023	Research on Impact of IoT on Warehouse Management	3	1	1	1	2	8	1.6
Fakhrai Rad, Oghazi, Onur & Kordestani	2025	Adoption of AI-based order picking in warehouse: benefits, challenges, and critical success factors	1	3	1	1	2	8	1.6
Hamideh Nazarian & Sharfuddin Ahmed Khan	2024	The Impact of Industry 5.0 on Supply Chain Performance	3	3	1	3	2	12	2.4

Yanbo Qu,		Digital Twin Technology of							
Ning Zhao &	2024	Human–Machine Integration in	1	3	1	1	2	8	1.6
Haojue Zhang		Cross-Belt Sorting System							
Mahmudur									
Rashid, S. M.									
Abdul Ahad,		Smart Warehouse Management							
Shahida	2019	System with RFID and Cloud	1	1	1	1	2	6	1.2
Siddique &		Database							
Tamanna									
Motahar									
Nur Hazwani									
Karim, Chandra		A systems thinking framework of							
Balijepalli,	2025	human–machine interactions and	1	1	1	3	2	8	1.6
Anthony		their impact on warehouse							
Whiteing		operations							

Sadia Samar Ali, Rajbir Kaur, Shahbaz Khan, Cenap Ozel, Aftab Hussain	2025	A framework of enablers of 3rd party logistics service providers for smart warehousing in emerging economy	1	3	1	3	2	10	2
Ali El Kihel, Soufiane Embarki	2025	Harmonizing Human-Centric Collaborative Hybrid Intelligence: A Deep Dive into the Transition from Industry 4.0 to Industry 5.0 A Case Study Experiment	1	3	1	1	2	8	1.6
Shitao Yu, Sharan Srinivas	2025	Collaborative Human–Robot Teaming for Dynamic Order Picking: Interventionist strategies for improving warehouse intralogistics operations	1	3	1	3	2	10	2
Source: Original work (Author)									

2.8 Data Extraction Analysis

A structured data extraction form was developed in Microsoft Excel as shown in the format of Table 6, to capture both descriptive and analytical attributes of each study.

Table 6 Data Extraction Criteria

Field	Description
Author(s) and Year	Full reference of the paper (e.g. names, year of publication)
Database	Source of publication (e.g. Scopus, Web of Science; journal title)
Type	Type of publication: journal article, conference paper, or practitioner report
Title	Full title of the research paper
Research Aim	Purpose or objective of the study
Methodology	Research design used: qualitative, quantitative, or mixed methods.
Key Findings	Core insights relevant to Industry 5.0 and MFCs
Limitations	Research limitations, gaps, or constraints identified in the study
Relevance to MFCs & Industry 5.0	Explanation of how the study relates to MFCs and Industry 5.0

Source: Original work (Author)

The extracted data was subsequently coded and analysed using descriptive statistics (e.g., publication trends, geographical distribution) and thematic analysis. These results are presented in detail in [Chapters 3](#) and [Chapter 4](#).

2.9 Tools Used

The following tools supported the systematic review process:

- Mendeley: Reference management and duplicate removal.
- Microsoft Excel: Data extraction, coding, and synthesis.
- Scopus and Web of Science: Primary databases for literature retrieval.

2.10 Conclusion

This chapter has presented the methodological framework employed to conduct the SLR. Each stage of the process was carefully structured to ensure transparency, replicability, and academic rigour, thereby strengthening the validity of the findings that follow.

The review began with the selection of two leading academic databases (Scopus and Web of Science) to guarantee comprehensive coverage of high-quality, peer-reviewed literature. A two-stage keyword refinement process was then conducted, balancing breadth and precision to capture the most relevant studies at the intersection of MFCs and Industry 5.0. Screening and selection were guided by well-defined inclusion and exclusion criteria, while the application of the Habib (2012) quality appraisal framework ensured methodological robustness and consistency in evaluating shortlisted papers.

A standardised data extraction template was subsequently used to capture descriptive and analytical attributes of the selected studies, which were then synthesised using both descriptive statistics and thematic analysis. The integration of tools such as Mendeley and Microsoft Excel further supported systematic organisation, duplicate removal, and structured synthesis.

By adopting this rigorous methodological approach, the study establishes a reliable foundation for answering the research questions and for drawing evidence-based insights. More importantly, it ensures that the findings are not

only academically credible but also practically relevant to the evolving landscape of smart urban logistics.

The next chapter ([Chapter 3](#)) builds directly on this methodological groundwork, presenting the descriptive analysis of the literature, including publication patterns, geographical trends, and methodological orientations of the selected studies.

3 Descriptive Analysis

This chapter presents the descriptive analysis of the literature that underpins this study. In total, 34 peer-reviewed articles, published between 2017 and 2025, were selected after a rigorous screening and appraisal process. The aim of this analysis is to characterise the fundamental attributes of each study, including research objectives, methodological approaches, empirical findings, and their contributions to both theory and practice. The analysis also considers their relevance to MFCs and the broader framework of Industry 5.0, which emphasises human-machine collaboration, sustainability, and resilience in supply chain systems.

By systematically synthesising these dimensions, this chapter serves three main purposes:

- To map the landscape of scholarly research on MFCs and Industry 5.0.
- To highlight methodological patterns across studies, identifying dominant approaches and underexplored research designs.

To provide a foundation for thematic analysis ([Chapter 4](#)), ensuring that subsequent discussions are firmly grounded in descriptive evidence.

3.1 Overview of SLR exclusion results

The initial literature search produced 273 records across multiple sources, including Scopus and Web of Science, with Boolean search strings combining keywords such as logistics, last-mile delivery, micro-fulfilment, warehouses, Industry 5.0, and sustainability. These papers spanned diverse publication types, including journal articles, conference proceedings, books, and practitioner reports.

To ensure academic rigour and thematic precision, a multi-stage screening process was undertaken. This involved:

- Title and abstract screening, which removed studies with only tangential or superficial relevance.
- Full-text reviews, applying inclusion and exclusion criteria (outlined in [Chapter 2](#)).
- Quality appraisal, using Habib's (2012) scoring framework, to ensure the credibility and robustness of the evidence base.

The exclusion process was particularly strict in three areas. First, studies that focused primarily on transportation and mobility were omitted, as the central focus of this thesis lies in distribution centres, warehouses, and fulfilment systems. Second, only papers published after 2017 were retained, reflecting the recent emergence of Industry 5.0 concepts and the rapid technological transformation of logistics systems. Third, the selected studies were required to explicitly engage with Industry 5.0 principles human-machine collaboration, human-centric design, digitalisation, and sustainable practice in the context of fulfilment and warehousing.

As a result of these procedures, 34 publications were identified as directly relevant and sufficiently rigorous to form the final dataset. Collectively, these studies offer a balanced coverage of theoretical, methodological, and applied perspectives on the integration of Industry 5.0 within MFCs and distribution centre operations.

3.2 Type of research

The distribution of the selected studies by publication type reflects the dual nature of the research landscape:

- Journal Articles (70%) – These form the dominant body of evidence, offering in-depth empirical analyses and theoretical developments. Many of these studies employ quantitative methods, including simulation

modelling, multi-objective optimisation, and statistical analysis, to evaluate MFC performance, urban logistics strategies, and Industry 5.0-enabled systems. Others adopt qualitative or conceptual approaches, contributing theoretical frameworks or critical reflections on the human-centric and sustainable dimensions of Industry 5.0. Journal articles thus provide the conceptual and empirical backbone of the review.

- **Conference Papers (30%)** – These contribute emerging insights and often showcase pilot studies, case studies, or prototypes that capture the early implementation of technologies such as digital twins, collaborative robotics, and AI-driven warehouse management. Although sometimes less mature in terms of methodological depth, these papers are invaluable in signalling future research directions and offering a practical, industry-focused complement to the more rigorous journal literature.

Taken together, the inclusion of journal and conference papers ensures the review benefits from theoretical rigour and practical applicability. The balance between these sources provides a holistic perspective, bridging academic scholarship with industrial innovation. The year-wise distribution between journal articles and conference papers is illustrated in Figure 4.

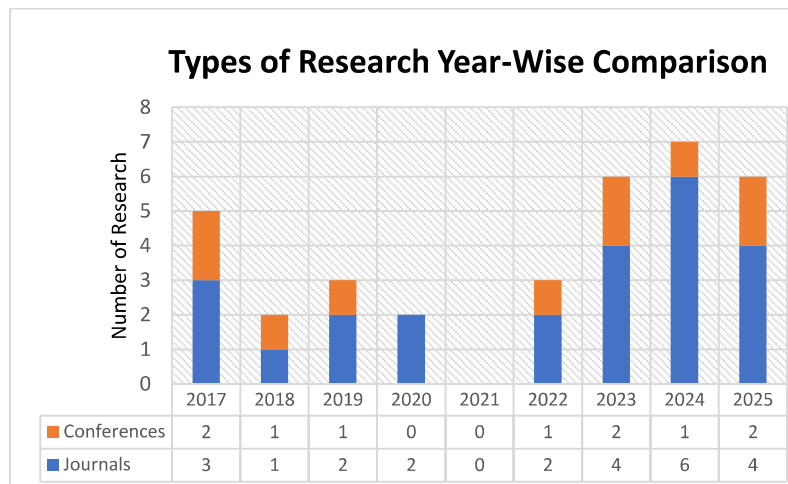


Figure 4 Pictorial Representation of Research Types Analysed

Source: Original work (Author)

3.3 Evolution of the research

Figure 5 illustrates the annual distribution of publications between 2017 and 2025. The period from 2017 to 2021 shows relatively modest and inconsistent research output, with particularly low activity between 2019 and 2021. This slowdown can be linked to the global disruption caused by the COVID-19 pandemic, which not only constrained research activity but also disrupted supply chain operations and shifted attention temporarily to crisis management rather than long-term innovation.

From 2022 onwards, however, there is a clear upward trajectory, with a strong surge in 2023 and a peak in 2024. This reflects growing academic and industry recognition of the critical role that MFCs and Industry 5.0 technologies play in enhancing supply chain resilience, sustainability, and human-machine collaboration in the post-pandemic context.

Although the figure shows slightly fewer publications for 2025 than 2024, this is due to the dataset covering only the first eight months of 2025. Given the ongoing momentum and the fact that more than four months of the year remain, it is reasonable to expect that by the end of 2025 the total output will exceed that of 2024, just as 2024 significantly surpassed 2023. In other words, the apparent dip is a reflection of time-bound indexing limitations rather than an actual reduction in research attention.

Overall, the trajectory suggests a rapidly maturing field that has moved beyond exploratory discussions toward deeper analyses of how Industry 5.0 can transform fulfilment systems, particularly in urban last-mile logistics.

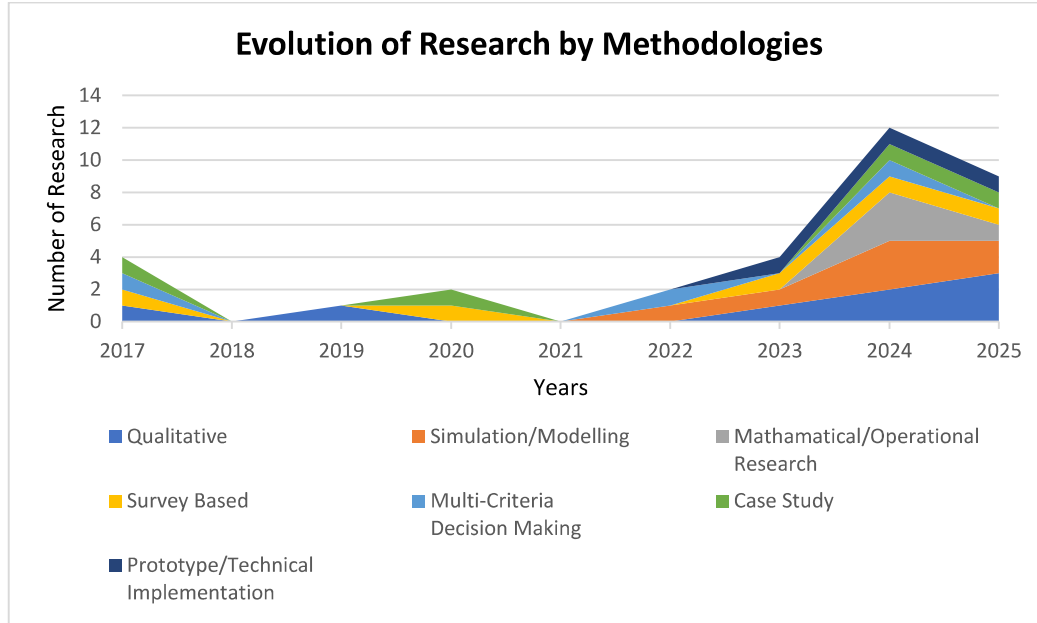


Figure 5 Annual count of included studies, 2017–2025

Source: Original work (Author)

3.4 Methodologies adopted by literatures

The reviewed literature showcases a broad range of methodological approaches, reflecting the complexity and interdisciplinary nature of research on MFCs and Industry 5.0. One of the most frequent categories was qualitative methods, which are often used to capture stakeholder perspectives and human-centric dimensions of logistics. For example, de Kervenoael, Schwob, and Chandra conducted semi-structured interviews to investigate the roles of gig workers in human-focused delivery systems (de Kervenoael et al., 2020).

Simulation and modelling approaches were also prevalent, especially in studies addressing operational uncertainty and performance optimisation. Lemardelé, Estrada, and Pagès simulated autonomous delivery robots to examine costs and uncertainty, which allowed for deeper insights into cost-related variables in robotic logistics systems (Lemardelé et al., 2024). Similarly, Kotlars and Skribans employed modelling techniques to evaluate the environmental impact of

robotised last-mile logistics, highlighting the role of environmental factors in the logistics process (Kotlars & Skribans, 2024).

Mathematical and optimisation-based approaches, such as Mixed-Integer Programming, were also commonly adopted. For instance, Savall-Manyó and Ribas optimised the location of micro-urban consolidation centres, focusing on improving logistical operations at a local scale (Savall-Manyó & Ribas, 2022). In another study, Ji, Qu, and Yu developed a bi-level optimisation model incorporating Karush-Kuhn-Tucker (KKT) conditions, which aimed to refine last-mile delivery planning and enhance operational efficiency (Ji et al., 2017).

Case studies and survey-based approaches were also used to gather empirical data. Björklund, Johansson, and Abrahamsson conducted multiple case studies to identify critical success factors for Urban Consolidation Centres (UCCs), revealing key elements for the successful implementation of UCCs in urban logistics (Björklund et al., 2017). Rad, Oghazi, Onur, and Kordestani combined performance metrics with stakeholder interviews to explore AI-driven order picking, shedding light on the impact of AI on logistics efficiency (Rad et al., 2025). Survey-based research by Nazarian and Khan applied PLS-SEM to explore the influence of Industry 5.0 on supply chain performance, demonstrating the significant impact of Industry 5.0 technologies on performance metrics in the supply chain (Nazarian & Khan, 2024). Additionally, Amaya, Arellana, and Delgado-Lindeman examined stakeholder perceptions of urban freight policies, highlighting the different viewpoints surrounding the implementation of urban logistics strategies (Amaya et al., 2020).

Further illustrating the methodological diversity, Gogas & Nathanail and Suresh used multi-criteria decision-making techniques to assess complex logistics systems, adding depth to the decision-making process in supply chain operations (Gogas & Nathanail, 2017). A prototype-based warehouse management system, offering a practical solution for managing warehouse operations (Rashid et al., 2019), while Qu, Zhao, and Zhang introduced a digital twin system for cross-belt

sorting, demonstrating the potential of digital technologies in enhancing sorting processes (Qu et al., 2024).

In conclusion, Figure 6 shows the diverse range of methodologies employed highlights that research on Industry 5.0 applications in MFCs and logistics is not only focused on technical and operational perspectives but also incorporates human, organisational, and policy-related viewpoints, emphasising the multidimensionality of the field.

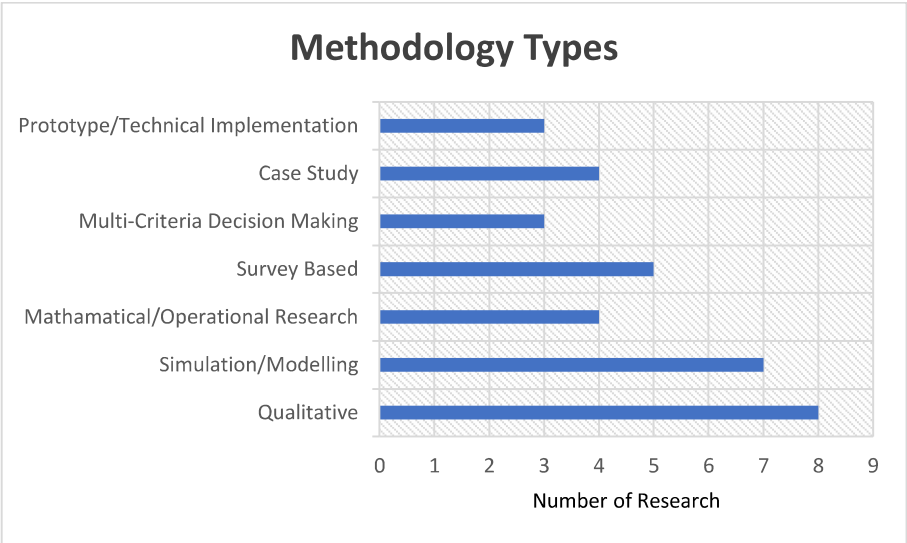


Figure 6 Methodology types applied in the reviewed studies (2017–2025)

Source: Original work (Author)

3.5 Key findings by literatures

The reviewed studies generate a wide range of insights into the evolving field of logistics and supply chain management, with clear relevance to the integration of Industry 5.0 principles into MFCs. A recurring theme is the centrality of human-centric logistics, especially in last-mile operations. For example, de Kervenoael, Schwob, and Chandra highlight how gig workers play a pivotal role in balancing flexibility and customer responsiveness, reinforcing the need to design systems that augment, rather than replace, human input (de Kervenoael et al., 2020).

Another prominent finding relates to automation and robotics. Simulation studies demonstrate the effectiveness of Autonomous Delivery Robots (ADRs) in lowering operational costs and increasing efficiency in urban logistics settings (Lemardelé et al., 2024). Similarly, Savall-Manyó and Ribas illustrate how micro-urban consolidation centres, supported by automation, can alleviate congestion and reduce environmental impact, thereby improving sustainability (Savall-Manyó & Ribas, 2022).

The literature also identifies critical success factors for consolidation centres, including location optimisation, multi-stakeholder governance, and financial viability (Björklund et al., 2017). Advanced optimisation models have further enriched these findings, showed how bi-level optimisation can balance cost and risk trade-offs, while discrete multi-objective modelling approaches contribute to designing more resilient and adaptive urban logistics systems (Ji et al., 2017).

Overall, the collective evidence indicates that the transformation of logistics is being driven by three interlinked forces: (i) automation and digitalisation, which enhance speed and accuracy, (ii) optimisation and decision analytics, which provide robust system designs, and (iii) collaborative ecosystems, where technology, people, and governance interact. Together, these forces are redefining supply chains into more sustainable, adaptive, and Industry 5.0-aligned systems.

3.6 Relevance to MFC and Industry 5.0

The literature strongly aligns with the principles of Industry 5.0 and demonstrates their growing influence on the design and operation of MFCs. A number of studies explore technology-enabled responsiveness, particularly the deployment of AI-driven optimisation, autonomous delivery robots, digital twins, and smart warehouse systems. These technologies support real-time monitoring and adaptive decision-making, which are central to the performance of MFCs in dense urban areas.

Equally significant is the role of IoT, RFID, and cloud-based systems, which decentralise control and enhance integration across fulfilment nodes. These technologies create connected, data-driven ecosystems that reduce inefficiencies in both intra-city and LMD operations.

The studies also reinforce the sustainability and collaboration dimensions of Industry 5.0. Research on capsule pipelines (Wandel et al., 2023) and urban consolidation centres demonstrates how alternative infrastructure and stakeholder collaboration can cut congestion and emissions. Similarly, survey- and case-based evidence highlights the importance of engaging workers and communities in shaping fulfilment networks, ensuring that human-centric and ethical considerations are not overlooked (de Kervenoael et al., 2020).

Finally, several studies underscore worker engagement and ergonomics, noting how collaborative robotics and intelligent decision-support systems can empower employees, reduce physical strain, and improve workplace satisfaction. These findings reflect the broader transition from Industry 4.0's efficiency-oriented automation to Industry 5.0's balanced focus on technology, sustainability, and human well-being.

Collectively, the literature indicates that MFCs embedded with Industry 5.0 principles are not just operationally efficient, but also socially and environmentally responsive, making them highly relevant to the future of urban logistics.

3.7 Conclusion

This descriptive analysis has consolidated findings from carefully selected research papers published between 2017 and 2025, providing a structured overview of how MFCs and Industry 5.0 principles intersect in the evolving domain of urban logistics. The temporal distribution of publications highlights two clear phases. Between 2017 and 2021, research output remained modest, with a noticeable dip during 2019–2021, which can be attributed to both the nascency of the topic and the global disruption caused by the COVID-19 pandemic. In

contrast, the surge in publications during 2024 and 2025 reflects a renewed academic and practitioner urgency to design resilient, sustainable, and technologically advanced supply chains, aligning with post-pandemic recovery and the broader global transition towards Industry 5.0.

From a methodological perspective, the reviewed studies draw on a diverse mix of approaches, mirroring the interdisciplinary and complex nature of this research area. Qualitative studies, including interviews and thematic analyses, shed light on human-centric dimensions such as worker engagement, ergonomics, and stakeholder perceptions. Quantitative approaches, particularly simulation and mathematical modelling, contribute rigorous analytical frameworks for testing system efficiency, cost structures, and environmental trade-offs. Case studies and survey-based research provide contextual evidence from real-world implementations, while multi-criteria decision-making frameworks and prototype-based developments illustrate the application of emerging Industry 5.0 technologies in practice. This breadth of methods reflects both the maturity of operational research traditions and the novelty of human-machine collaboration themes in fulfilment contexts.

The findings collectively underscore three dominant themes. First, technology-driven innovation such as autonomous delivery robots, digital twins, IoT, and AI-enabled optimisation is central to enhancing the agility, efficiency, and scalability of MFCs. Second, human-centricity and collaboration emerge as defining features of Industry 5.0, with studies emphasising the importance of empowering workers, engaging stakeholders, and designing adaptive and ethical fulfilment systems. Third, sustainability and resilience are consistently highlighted, with research showing how decentralised fulfilment nodes, alternative infrastructures, and intelligent routing reduce environmental impact and increase system robustness against disruptions.

These converging insights validate the central proposition of this thesis: that embedding Industry 5.0 principles into the design and operation of MFCs represents a transformative pathway for future logistics. By integrating human-

machine collaboration, advanced technologies, and sustainability imperatives, MFCs can evolve into future-ready logistics hubs capable of meeting fast-changing consumer expectations while advancing environmental and social goals.

In conclusion, this chapter has provided a comprehensive descriptive foundation for the thesis. It demonstrates not only the richness of existing research but also its fragmentation and the gaps that remain. The analysis highlights where strong evidence exists and where insights are underdeveloped, thereby setting the stage for [Chapter 4](#), where the literature is synthesised thematically to answer the research questions directly and provide clearer directions for scholars, practitioners, and policymakers.

4 Thematic Analysis

This chapter presents a thematic analysis of the literature on integrating Industry 5.0 principles into MFCs. The aim is to move beyond descriptive counting and instead synthesise recurring technologies, practices, and conceptual approaches that shape how MFCs contribute to urban logistics.

As e-commerce continues to accelerate expectations for speed, flexibility, and reliability, MFCs are becoming central nodes of last-mile distribution. Industry 5.0 reframes this evolution by emphasising human-centred innovation, collaborative interaction between humans and intelligent systems, and a stronger commitment to sustainability and resilience.

The reviewed literature highlights five recurring cross-cutting themes:

Human-machine collaboration – Workers are augmented rather than replaced through cobotics, decision support systems, and ergonomics-aware workflows.

Data-rich operations via IoT and digital twins – Real-time monitoring and predictive simulation drive adaptive planning and control in fulfilment systems (Domínguez, 2024).

AI-enabled optimisation – Machine learning and predictive analytics improve slotting, routing, and scheduling, while interfaces adapt to human needs (Božić, 2024).

Sustainability and circularity – Environmental objectives are treated as engineered outcomes through circular economy practices, waste reduction, and carbon mitigation (Adel & HS Alani, 2024).

Skills and inclusion – Workforce readiness, micro-learning, and Human Digital Twins support continuous upskilling, workload balance, and equitable task allocation (Bucci et al., 2024).

Methodologically, these themes were derived from iterative coding across the selected studies, mapping concepts, mechanisms, and outcomes into higher-level categories. This process ensured that the diversity of methods (qualitative, simulation, optimisation, case studies) was preserved while producing a coherent analytical map of how Industry 5.0 technologies and practices intersect with MFC operations.

To align the insights with the research objectives, this chapter is organised into two subsections:

[Section 4.1](#) synthesises technologies and process solutions for MFCs under Industry 5.0 (addressing RQ1).

[Section 4.2](#) summarises the reported benefits, including efficiency, cost, service, sustainability, and resilience (addressing RQ2).

The strategies for implementing these solutions in practice, including managerial and policy pathways, are examined in detail in [Chapter 5](#) (addressing RQ3).

This thematic structure not only provides a detailed account of what has been proposed or piloted but also organises findings around the three foundational pillars of Industry 5.0 – efficiency, sustainability, and human-centricity (see Figure 7).

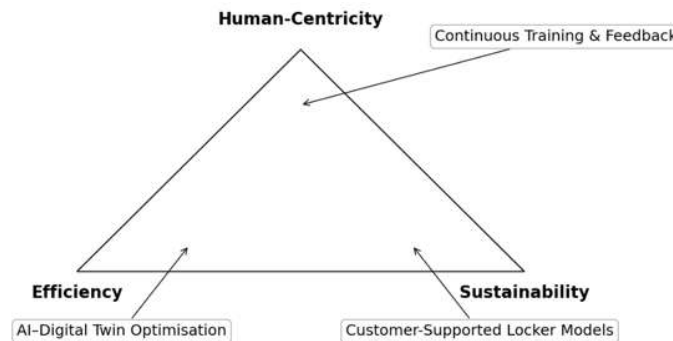


Figure 7 Conceptual view of how MFC solutions align with Industry 5.0 pillars

Source: Original work (Author)

4.1 Solutions/Technologies to Implement Industry 5.0 in MFCs

Although a significant body of research addresses future supply chain technologies, particularly in manufacturing, transportation, and last-mile logistics there remains limited focus on the application of Industry 5.0 within MFCs or dark stores. Yet, MFCs represent a crucial arena where Industry 5.0 principles can transform operations, bridging the gap between consumer demand and resilient, human-centric fulfilment.

Drawing on academic and industry insights, this section outlines three key solutions for embedding Industry 5.0 into MFCs. These span both technological enablers and process innovations, collectively aiming to enhance efficiency, strengthen sustainability, and reinforce the human-centric ethos that underpins Industry 5.0.

4.1.1 Introduction of Digital Twin Advanced AI for optimising pick locations

The integration of Digital Twin (DT) technology with advanced AI is reshaping warehouse and MFC operations. Digital twins create real-time virtual replicas of physical assets and workflows, enabling continuous simulation, monitoring, and predictive control (See Figure 8). When applied to picking processes, AI-enhanced DTs can analyse data such as order frequency, SKU velocity, and worker movement patterns to dynamically optimise pick locations. This reduces travel time, improves slotting efficiency, and increases service responsiveness (Domínguez, 2024).

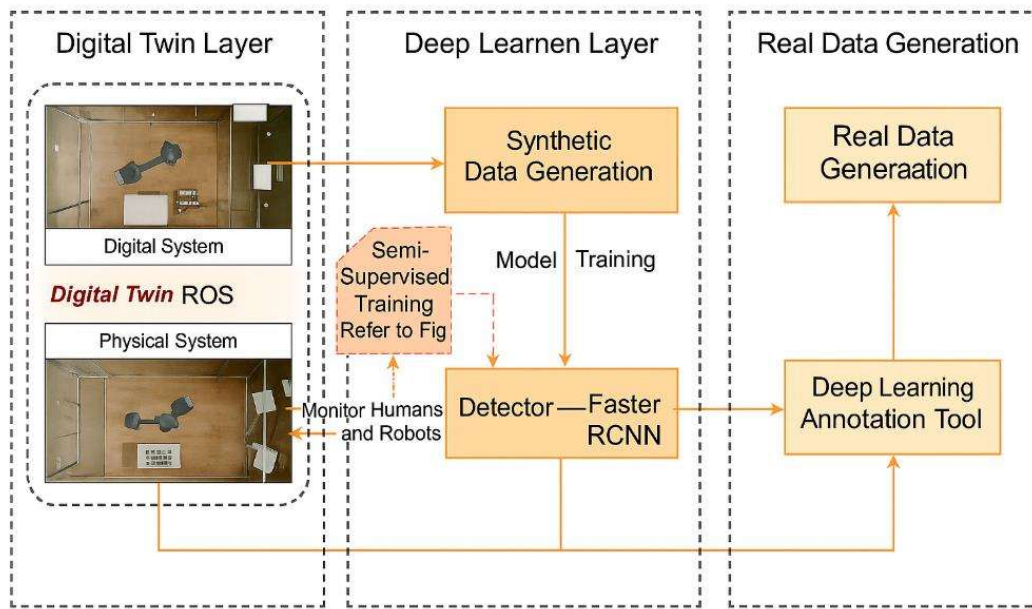


Figure 8 Data Synchronisation Between Physical World and Digital Twin

Source: Wang et al., 2024

For instance, consider daily grocery orders for high-frequency items such as milk, eggs, bread, and cheese. An AI-powered digital twin can forecast peak demand periods (e.g., early morning shopping runs) and re-slot items dynamically, ensuring fast-moving products like milk and bread are positioned closer to picker stations, while slower-moving goods are placed further away. This predictive reconfiguration streamlines throughput while maintaining ergonomic efficiency (Wang et al., 2024).

Beyond efficiency gains, DTs enable a more human-centric approach to system design, consistent with the principles of Industry 5.0. Human Digital Twins—virtual models of worker movements and workloads can highlight strain-prone zones and suggest ergonomic adjustments. For example, heavier items may be slotted at waist height to minimise lifting strain, while fragile items can be positioned to reduce handling risks (Božić, 2024). This ensures that technological optimisation also safeguards worker health and engagement.

In summary, AI-powered digital twins foster adaptive, intelligent environments that learn from both demand patterns and human interactions. They strengthen the efficiency pillar of Industry 5.0 by improving pick speed and slotting, enhance sustainability through reduced resource waste and better space use, and support the human-centric pillar by embedding ergonomics and worker well-being into system design.

4.1.2 Customer-Supported Self-Pickup and Locker Based Delivery Model

Another promising solution under the Industry 5.0 framework is the adoption of customer self-pickup and locker-based delivery systems strategically located within 1–3 km of MFCs. Instead of relying exclusively on courier-based home deliveries, customers can retrieve parcels from secure lockers, often incentivised through discounts or loyalty rewards. These lockers act as decentralised, company-managed drop-off hubs, offering flexible, contactless collection that enhances reliability, reduces failed delivery attempts, and lowers the environmental burden of last-mile transport, as illustrated in Figure 9.

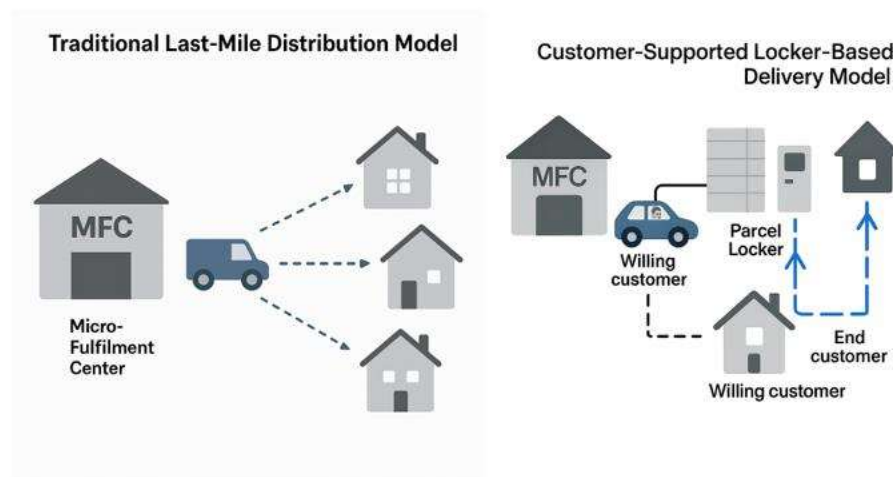


Figure 9 Traditional vs. Proposed LMD Model

Source: Original work (Author)

Building on this baseline model, organisations can incorporate community-assisted delivery, where customers travelling in specific directions can opt to carry a second parcel to a nearby locker. Upon verified drop-off, the intended recipient is notified via secure digital credentials. Such systems leverage natural human mobility patterns, transforming passive customers into active co-creators of logistics value. Routing optimisation algorithms can further support this system by accounting for locker capacity, time windows, and delivery constraints, maximising both efficiency and service quality (Dell’Amico et al., 2023).

This approach reflects the human-centric ethos of Industry 5.0 by fostering collaboration between businesses and customers, encouraging voluntary participation, and strengthening trust. It improves efficiency by reducing redundant courier trips, and it enhances sustainability by consolidating deliveries, lowering emissions, and reducing congestion in dense urban areas. Ultimately, locker-based and community-assisted models illustrate how smart infrastructure combined with shared responsibility can build resilient fulfilment ecosystems that serve both businesses and society.

4.1.3 Continuous User Training and Improvement Seeking

The successful integration of advanced Industry 5.0 technologies in MFCs depends not only on technical systems but also on the capabilities and confidence of the workforce. Continuous training ensures that new innovations from robotics and automation to AI-powered tools are used effectively, safely, and consistently. Without structured development, technological investments risk underutilisation, process inefficiencies, or safety issues in increasingly complex fulfilment environments (Dagli, 2024).

Training serves a dual function: it boosts operational efficiency by ensuring consistent outputs, and it safeguards workers by equipping them with the skills to manage and troubleshoot advanced systems. In this context, microlearning—short, focused training modules delivered in real time has gained prominence as a scalable approach for building an agile and resilient workforce (Harris, 2024).

This ensures employees are not only reactive but proactive in adapting to new technologies, a vital attribute in high-speed, tech-driven fulfilment.

Equally important is embedding continuous improvement loops. Workers who engage daily with systems often identify subtle usability issues, workflow bottlenecks, or enhancement opportunities. Structured feedback mechanisms such as check-ins, surveys, and digital reporting platforms ensure these insights inform system refinements while reinforcing worker engagement.

This approach embodies the three pillars of Industry 5.0: it enhances efficiency through consistent skills application and reduced downtime, strengthens sustainability by reducing waste linked to errors and system misuse, and foregrounds human-centricity by treating employees as active collaborators in technological adoption. Continuous training and improvement seeking thus ensure that fulfilment centres evolve adaptively, balancing automation with empowered, skilled human input.

4.2 Key Benefits

The implementation of Industry 5.0 solutions in MFCs generates significant benefits across operational, economic, and social dimensions. By embedding intelligence, adaptability, and collaboration into logistics workflows, MFCs can transition from reactive fulfilment hubs into efficient, sustainable, and human-centred systems.

One major benefit is enhanced space utilisation, achieved through AI-driven optimisation of product placement and inventory management. This ensures that storage layouts dynamically adjust to consumer demand, making limited floor space more productive and reducing congestion. A second benefit is greater productivity, derived not only from AI-supported picking and routing but also from continuous worker training and inclusive feedback systems that create agile, engaged teams. The third benefit is sustainability, where self-pickup lockers and

shared delivery models reduce the environmental burden of last-mile transport and integrate with green mobility modes.

Crucially, these three dimensions space, productivity, and sustainability are not isolated. They reinforce one another: efficient storage supports faster operations; productive workers enable more sustainable practices by reducing wasted effort; and sustainable models ease pressure on limited urban space. Together, they generate a virtuous cycle of improvement, positioning MFCs as strategic enablers of Industry 5.0.

4.2.1 Space Utilisation

Space is one of the most critical resources in MFCs, particularly in dense urban environments where facilities are small and real estate costs are high. Industry 5.0 technologies, particularly AI-driven digital twins, enable highly adaptive and predictive space management.

By analysing large datasets such as historical orders, SKU velocity, seasonality, and consumer behaviour—AI can design and reconfigure storage layouts in real time. Fast-moving products are placed near picking zones or conveyors, while slow-moving or bulky items are stored further away (Rimélé et al., 2021). This maximises efficiency by minimising wasted movements, congestion, and idle space. At the same time, space utilisation improvements support sustainability by reducing the physical footprint required for storage, thereby lowering energy use per unit stored and reducing the need for warehouse expansion. Finally, optimised layouts enhance human-centricity: ergonomic design principles can be integrated, such as positioning heavy items at waist height or isolating fragile products, which reduces worker strain and injuries (Prasanna Prabu, 2022). In short, AI-driven spatial optimisation transforms warehouses from static storage facilities into adaptive, intelligent environments that continuously balance efficiency, sustainability, and worker well-being.

4.2.2 Productivity

Productivity in MFCs is a central concern, as these facilities must balance high throughput with limited space and resources. The adoption of AI-driven optimisation and continuous user training offers a transformative approach to enhancing productivity within the Industry 5.0 framework.

AI technologies significantly improve productivity by enhancing picking efficiency and reducing the travel time of floor workers (Rimélé et al., 2021). Through the identification of product pairs or frequently purchased items, AI systems optimise warehouse layouts to ensure that such items are stored in close proximity. This strategic placement reduces travel distances for workers, streamlines picking routes, and improves overall operational flow (Prasanna Prabu, 2022).

AI further strengthens productivity by dynamically reallocating resources, such as labour and equipment, to high-demand areas, thereby preventing congestion and ensuring smoother, faster fulfilment processes. The result is a measurable reduction in delays, improved pick rates, and more efficient use of limited resources, all of which drive productivity gains.

However, productivity in Industry 5.0 MFCs extends beyond automation alone. Continuous user training is equally critical in sustaining and enhancing performance. As MFCs adopt advanced AI systems and robotics, employees must be equipped with the necessary knowledge and skills to operate these tools effectively. Regular training reduces errors, minimises confusion, and ensures that workers are confident in using new technologies (Dagli, 2024).

A well-trained workforce becomes not only more efficient but also more resilient, capable of troubleshooting issues independently and preventing small disruptions from escalating into major operational delays. Training also addresses role clarity and process ambiguities, ensuring that workflows remain consistent even in technology-rich environments.

In addition, fostering a feedback-driven organisational culture enhances productivity further. Workers who are actively involved in identifying inefficiencies or proposing improvements develop a stronger sense of ownership and responsibility for operations. Structured feedback loops, whether through regular check-ins, digital reporting systems, or participatory review sessions, allow employees to refine processes in real time. This feedback culture creates an environment where continuous improvement is embedded into everyday operations, reinforcing both worker motivation and system efficiency (Harris, 2024). Taken together, AI-based optimisation, continuous training, and feedback-driven improvement form a synergistic model of productivity. In alignment with Industry 5.0 principles, productivity here is not merely about maximising output but about creating an adaptive and collaborative ecosystem where human workers and intelligent systems reinforce one another. Such integration ensures that MFCs remain agile, responsive, and capable of meeting the dynamic demands of modern supply chains.

4.2.3 Sustainability

The rapid expansion of e-commerce has significantly increased the environmental impact of logistics, particularly in LMD. This stage of the supply chain contributes disproportionately to urban congestion and carbon emissions, making it a primary target for sustainability-driven innovations. Industry 5.0 principles frame sustainability not as a secondary outcome but as a core design objective of fulfilment systems (González-Romero et al., 2024).

Parcel lockers represent a practical and scalable solution, offering a more sustainable alternative to conventional home delivery. By consolidating multiple deliveries into centralised lockers, companies can minimise the number of individual trips required, thereby reducing vehicle emissions and easing traffic congestion in dense urban areas. This delivery model optimises routes and consolidates resources, producing measurable reductions in the overall carbon footprint of urban logistics.

The environmental benefits of parcel lockers are magnified when combined with greener transport modes, such as electric vehicles and cargo bikes. The strategic placement of lockers near residential or commercial hubs further improves delivery efficiency, ensuring short-distance transport and reduced energy consumption. These measures directly support sustainability goals while also contributing to the broader societal demand for eco-friendly delivery options (Caspersen & Navrud, 2021).

From an efficiency perspective, locker-based models also reduce costs associated with failed or repeated deliveries, optimise driver routes, and increase the reliability of parcel collection. Meanwhile, they remain inherently human-centric, as they provide customers with greater flexibility, reliability, and control over their delivery experience. Customers can collect parcels at their convenience, while businesses reduce strain on delivery personnel by lowering the frequency of door-to-door interactions.

Ultimately, the adoption of parcel locker systems demonstrates how Industry 5.0 solutions can integrate sustainability, efficiency, and human-centricity into a single innovation. By reducing emissions, cutting costs, and improving user experiences, such systems exemplify the transformative potential of Industry 5.0 in shaping a greener and more resilient logistics ecosystem.

5 Discussion

Transitioning an existing MFC to an Industry 5.0 framework is not merely a technical upgrade but a strategic transformation that requires balancing technological innovation with human-centric practices and sustainability outcomes. As shown in [Chapter 4](#), the thematic analysis emphasised three recurring solutions: (i) digital twins enhanced with AI for optimised operations, (ii) customer-supported locker-based delivery models, and (iii) continuous user training and feedback loops. Each solution maps directly onto the three pillars of Industry 5.0: efficiency, sustainability, and human-centricity and collectively provides a roadmap for rethinking fulfilment in the era of smart, resilient supply chains.

Unlike incremental adjustments to workflows, the adoption of Industry 5.0 requires a paradigm shift in operations, introducing collaborative robotics, AI-driven optimisation, and sustainable practices. If not carefully managed, such changes risk disrupting fulfilment continuity. To mitigate this, the transition should follow a structured change management pathway, integrating both best practice and academic evidence.

The first stage involves preparing a comprehensive change management proposal (Breque et al., 2021). This document should:

- Map the current operational state (technologies, workforce capacity, and customer coverage).
- Identify inefficiencies and opportunities for improvement.
- Outline proposed technological and process changes, such as digital twins, locker systems, and structured training.
- Assess potential impacts on efficiency, sustainability, and worker well-being.

- Define implementation timelines, contingency plans, and risk management strategies.

Once approved by senior leadership, attention turns to execution planning and preparation. Here, managers act as key coordinators, ensuring resource allocation, minimising disruption to daily operations, and maintaining clear communication across functional areas. In line with principle of phased change, pilot roll-outs are especially valuable in reducing risk and increasing workforce adaptability (Kotter, 2007). Early stakeholder engagement and transparent communication are essential to reduce resistance among frontline workers, who may perceive technological adoption as a threat.

5.1 Testing, Validation, and Training

Testing and validation form the backbone of successful implementation. Three complementary actions are crucial:

- **User Acceptance Testing (UAT):** Trial runs of digital twin simulations, AI-based slotting, and locker models under realistic but controlled conditions.
- **Pilot deployment:** Stepwise implementation in selected workflows to test feasibility and gather worker feedback.
- **Training programmes:** Phased microlearning-based training (Harris, 2024) that builds confidence, reduces errors, and enhances safe interaction with collaborative technologies.

In parallel, customer-facing campaigns should explain the benefits of locker-based delivery systems, thereby encouraging smoother adoption and higher satisfaction levels. Combining worker training with customer awareness ensures alignment between operational and service-side transitions.

Go-Live and Hypercare

The go-live phase marks the formal adoption of Industry 5.0 solutions. At this stage, managers must ensure:

- Seamless functioning of AI and digital twin systems under real operational loads.
- Smooth workforce adaptation to human–machine collaboration tools.
- Readiness of contingency measures for potential disruptions.

Following go-live, a hypercare period should be instituted. During this stage, performance metrics including fulfilment speed, error rates, carbon savings, and worker safety reports must be tracked. This stabilisation period enables fine-tuning and sets the foundation for continuous improvement, workforce upskilling, and resilience building (Xu et al., 2021).

5.2 Managerial Pathways

From a managerial standpoint, successful implementation requires:

1. **Investment planning** – ensuring financial resources for digital infrastructure (AI, IoT, digital twins) and considering ROI not only in terms of cost but also sustainability outcomes.
2. **Workforce engagement** – designing systems that treat workers as collaborators through Human Digital Twin modelling, ergonomics-aware slotting, and continuous learning.
3. **Cross-functional integration** – bridging IT, operations, and customer services to prevent siloed adoption of technologies.
4. **Performance monitoring** – defining KPIs that align with the three Industry 5.0 pillars: efficiency (throughput, errors, cost), sustainability (emissions,

congestion, waste reduction), and human-centricity (safety, well-being, job satisfaction).

5.3 Policy Pathways

At the policy level, enabling frameworks can accelerate Industry 5.0 adoption in MFCs by:

- Establishing regulatory standards for AI transparency, interoperability of digital twin platforms, and safe human–robot collaboration.
- Providing sustainability incentives such as tax credits or subsidies for locker-based models and electric fleet integration.
- Funding skills and training initiatives, ensuring that the logistics workforce is future-ready for human–AI collaboration.

Supporting urban planning integration, such as zoning policies that enable locker placement or small-scale MFCs near residential areas to reduce last-mile congestion.

5.4 Roles and Responsibilities

The successful transition to Industry 5.0 requires coordinated effort across all stakeholders. Table 7 summarises the roles and responsibilities of workers, supervisors, managers, senior leaders, and customers, while Table 8 presents a detailed RACI matrix showing their level of involvement across each stage of the transition. These frameworks demonstrate how Industry 5.0 adoption is not a one-dimensional technical upgrade but a multi-stakeholder process requiring collaboration across organisational layers.

Table 7 Roles and Responsibilities in MFC's transition to Industry 5.0 Principles

Roles	Key Responsibilities in Transition to Industry 5.0
Floor Workers	<ul style="list-style-type: none">• Operate new systems and workflows after phased training.• Provide feedback during pilot tests and early implementation.
Supervisor	<ul style="list-style-type: none">• Oversee floor operations during transition phases.• Report issues and progress to managers for resolution.
Manager	<ul style="list-style-type: none">• Lead change management, from planning to go-live.• Coordinate UAT, dry runs, and final implementation.
Senior Leader/Management	<ul style="list-style-type: none">• Approve proposals, budgets, and timelines.• Provide strategic direction and resource allocation.
End Customers	<ul style="list-style-type: none">• Adapt to locker-based delivery and self-pickup models.• Share feedback on convenience and service quality.

Source: Original work (Author)

Table 8 RACI Matrix

Activity / Stage	Floor Workers	Supervisor	Manager	Senior Leader / Management	End Customers
Develop change management proposal	I	C	R/A	A	-
Approve proposal and allocate resources	I	I	C	A/R	-
Conduct pilot testing & UAT	R	R/A	A	C	-
Implement phased training for staff	R	A	A	C	-
Launch customer awareness campaign (locker-based delivery)	I	C	R/A	C	C
Finalise go-live plan	I	C	R/A	A	-
Oversee go-live day operations	R	R	A	C	-
Monitor hypercare phase & resolve issues	R	R/A	A	C	-
Collect and analyse customer feedback	I	C	C	I	R
Continuous improvement & optimisation	R	C	A	A	-

Legend:

R (Responsible): Does the work to complete the task.

A (Accountable): Ultimately answerable for the task's success.

C (Consulted): Provides input before the work is done.

I (Informed): Kept updated about progress and outcomes.

Source: Original work (Author)

6 Conclusion

This thesis set out to examine how Industry 5.0 principles can be integrated into MFCs, using a SLR to synthesise findings across academic and industry studies. The research was guided by three objectives, each linked to a core research question: (i) to explore the current state of research on Industry 5.0 applications in MFCs, (ii) to identify the key benefits of adopting these technologies, and (iii) to distil practical strategies that managers and policymakers can employ to facilitate successful transitions. Together, these objectives provided a holistic understanding of how MFCs can evolve to meet the demands of modern e-commerce while aligning with the three pillars of Industry 5.0: efficiency, sustainability, and human-centricity.

6.1 Fulfilment of Objective 1

Objective 1 was to examine what current research says about applying Industry 5.0 to MFCs in urban logistics. This was achieved through the systematic review of 34 studies published between 2017 and 2025.

The findings reveal that while research explicitly labelled under “Industry 5.0” in the MFC context remains limited, there is growing evidence of influence through enabling technologies. These include digital twins for real-time operational modelling, advanced AI for slotting and demand prediction, and collaborative robotics for human-automation workflows. A strong human-centric orientation was observed, with studies emphasising the role of skilled workers supported—not replaced—by intelligent tools. Equally, sustainability has been framed as a deliberate outcome of technology adoption, with research pointing towards environmentally responsible practices such as low-carbon delivery models and waste-reduction strategies. Taken together, the literature indicates that Industry 5.0 principles are already shaping the transformation of MFCs, even if fully integrated deployments are still at an early stage.

6.2 Fulfilment of Objective 2

Objective 2 was to identify the key benefits of using Industry 5.0 in MFCs, focusing on efficiency, cost, and service improvements.

The review highlighted multiple tangible benefits. Efficiency gains stem from AI-enhanced slotting systems that reduce travel times for pickers, and digital twins that enable responsive operational planning. Cost savings are realised through better space utilisation, reduced error rates, and innovative delivery models such as customer-supported self-pickup and parcel lockers, which lower last-mile costs. Service quality is enhanced by faster and more reliable order fulfilment, improved delivery flexibility, and reduced risk of failed deliveries. Furthermore, human-machine collaboration supports greater adaptability to fluctuating demand while maintaining high service standards. Collectively, these findings demonstrate that Industry 5.0 technologies can deliver measurable and multidimensional benefits for MFCs by optimising resources, reducing costs, and improving customer satisfaction.

6.3 Fulfilment of Objective 3

Objective 3 was to identify strategies that managers can adopt to transition MFCs towards Industry 5.0 frameworks.

The analysis suggests that successful implementation requires a structured change management approach, beginning with a comprehensive proposal that maps current processes, identifies inefficiencies, and outlines technological upgrades along with risk assessments (Breque et al., 2021). Managers play a pivotal role in coordinating cross-functional teams, designing phased roll-outs, and overseeing UAT and pilot projects, particularly for digital twins and AI-driven optimisation tools. Worker training and customer awareness campaigns—especially for locker-based delivery systems—emerge as critical enablers of adoption. Following go-live, a hypercare period should be implemented to stabilise operations, monitor KPIs, and resolve critical issues before embedding long-term improvements. These strategies ensure that adoption is not disruptive

but aligns with Industry 5.0's emphasis on collaboration, resilience, and sustainability(Harris, 2024; Kotter, 2007; Xu et al., 2021).

6.4 Limitations and Future Research

This thesis has several limitations. First, the direct application of Industry 5.0 to MFCs is still at an early stage, so much of the evidence had to be interpreted from broader logistics and supply chain contexts. Second, the final pool of 34 studies provides a focused but not comprehensive global picture. Third, the diversity of methods across the reviewed studies made cross-comparison challenging. Finally, most available research offers short-term or conceptual insights, with little longitudinal evidence on long-term adoption outcomes.

Future research should address these gaps by conducting empirical case studies of MFCs implementing Industry 5.0 principles, exploring cross-regional comparisons to capture global perspectives, and developing longitudinal studies to assess the sustained impacts of digital twins, AI, and human-machine collaboration over time. Further work is also needed on the policy and governance frameworks required to scale these technologies while safeguarding workforce inclusivity and sustainability.

6.5 Final Reflections

This thesis contributes to the understanding of how MFCs can evolve within the Industry 5.0 paradigm. The review confirms that integrating digital twins, AI, collaborative robotics, and sustainable delivery models can deliver substantial operational benefits while enhancing worker well-being and environmental performance. However, the literature also highlights that large-scale implementations remain nascent, with significant gaps in empirical evidence on long-term performance, workforce adaptation, and policy integration.

From a managerial perspective, the findings underscore the importance of proactive investment planning, participatory workforce engagement, and rigorous performance monitoring. From a policy perspective, enabling frameworks such

as sustainability incentives, AI standards, and skills training programmes are essential to scale adoption.

Ultimately, this thesis validates the central proposition that embedding Industry 5.0 principles into MFCs provides a transformative pathway towards more efficient, sustainable, and human-centric logistics systems. For academics, it highlights key areas for future research, such as longitudinal studies of Industry 5.0 adoption and cross-sector comparative analyses. For practitioners and policymakers, it offers practical strategies for achieving future-ready, resilient urban logistics networks.

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Appendix A Ethical approval letter



22 May 2025

Dear Mr Mayandi Arivu ,

Reference: CURES/25274/2025

Project ID: 28563

Title: Micro-fulfilment Centres and Industry 5.0

We are pleased to inform you that you have successfully declared that your research project is a **Literature Review – based solely on openly available literature which is in the public domain, and you are undertaking desk-based research not involving any other form of data or information.**

You have also confirmed that your project **does not meet** any of the literature review specified exceptions, listed both within the relevant section of the CURES form and below:

1) Your supervisor has requested that you apply for approval through CURES because:

- The journals or data are in a sensitive area (please discuss this with your supervisor)
- The project will be embargoed **i.e. will not be publicly available via the Cranfield library immediately or longer term**

2) Approval is/will be specifically required by another external body e.g. journal publishers

Therefore, **you do not require ethical approval** and your CURES application will be automatically closed.

Please keep a copy of this letter safe, if this exception is in relation to your thesis project, you will need to include a copy with your final thesis submission.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B

B.1 Quality Appraisal Scoring Framework

Table 9 Quality Appraisal Framework

Number	Criteria	Level			
		0	1	2	3
1	Contribution to theory of disruptive trends	The publication does not provide adequate information to assess this criterion	Theoretical absence	Partial theoretical base	Strong theoretical grounding; contribution to theory of practice
2	Methodology (defensible research design)	The publication does not provide adequate information to assess this criterion	The idea of study is poorly executed; inappropriate methods	Justified research design; the idea of study is not fully executed	Research design adequately examines the research argument
3	Data analysis: sample design and composition	The publication does not provide adequate information to assess this criterion	Data sample insufficient; inconclusive research results	Appropriate data sample; adequate results but inadequate explanation	Adequate data sample; well explained results support theoretical arguments
4	Implications for practice	The publication does not provide adequate information to assess this criterion	Study fails to inform practice of implications	Limited implications for practice provided	Critical implications for practice provided
5	Level of citations	The publication does not provide adequate information to assess this criterion	Absence of citations	Some level of citation present	Comprehensive citation list

Source: Habib, 2012