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Systematic Review

A Study of the Main Mathematical Models Used in Mobility, Storage, Pickup and Delivery in Urban Logistics: A Systematic Review

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Abstract: This systematic review investigates the main mathematical models applied in urban logistics, focusing on routing, location and transshipment problems. The study addresses the growing demand for efficient and sustainable logistics solutions driven by population growth and the expansion of e-commerce. A thorough analysis of 57 scientific articles was carried out, covering deterministic and stochastic methodologies, as well as heuristic and exact solutions. This review revealed that heuristic methods are predominant due to their computational efficiency. Combining exact methods with heuristics has proven effective for complex logistics scenarios, increasing accuracy and efficiency. Synchronization and intermediate stops have also emerged as critical factors in optimizing logistics operations. This review highlights the diversity of methodologies and the need for sustainable and efficient models. The integration of stochastic simulations remains limited, representing a research gap where stochastic models have been shown to provide more robust solutions in addressing the uncertainties inherent in logistics operations. This integration can increase the robustness and applicability of logistics solutions in urban environments. By highlighting the strengths and limitations of current approaches, it paves the way for future research to develop more robust and adaptable solutions to urban logistics challenges, emphasizing interdisciplinary collaboration and the use of real-world data.

Keywords: urban logistics; pickup and delivery problem; location routing problem; transshipment location problem

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1. Introduction

Urban logistics is an area of research that covers several areas, including Human Sciences, Social Sciences and Exact Sciences, such as engineering. Although urban logistics has been investigated for several years, the topic is still evolving, driven by ongoing changes in citizens' habits, including the rise of online shopping and greater sensitivity to environmental issues. And with population growth, the demand for transportation, storage and delivery of goods has increased significantly in recent years. According to Goetz [1], approximately 60% of the population will reside in urban areas by 2030, potentially causing transportation problems for both people and goods in urban regions. Addressing the concept of transport and delivery in urban logistics opens up a significant volume of research with different directions, including the following: social aspects, as in the work of Baldi et al. [2] and Rao et al. [3]; health, as in the research by Linfati et al. [4]; or engineering, as in the works by Ballot and Fontane [5] and Anderluh et al. [6].

However, despite its growing importance and relevance, the literature on urban logistics remains fragmented, making it difficult to obtain a holistic understanding of the topic and identify gaps that need to be addressed. This literary fragmentation was minimized with systematic studies carried out, such as Lagorio et al. [7], who showed in his study the state of the art of urban logistics and the main problems addressed, such as routing with location, transshipment, pickup and delivery in urban environments, which directly influence the minimization of impacts caused by rapid social and technological development. The systematic study by Frederhausen and Klumpp [8] directly contributes to the evolution of methodologies used in urban logistics, which highlights studies on routing, location, collection and delivery, in which routing is present in many articles selected by the author. Location routing problem (LRP) and pickup and delivery problem (PDP) and their variants are highlighted in the survey carried out by the authors. Therefore, the LRP, transshipment location problem (TLP) and PDP are highly relevant in urban logistics due to their complexity, impact on operational efficiency, importance for sustainability, and technological challenges and opportunities they present. The scientific literature reinforces this relevance, highlighting these problems as key areas of research and development in urban logistics.

It is crucial to carefully choose the research objectives in urban logistics, as decision-making occurs at both strategic and operational or tactical levels, such as location and distribution, respectively [9]. Distribution and location are closely related. In real-world situations, establishing one or more depots (or storage satellites) involves planning the distribution between these facilities and customers simultaneously. In these cases, the traditional approach of first locating and then planning delivery routes is gradually being replaced by an integrated location-routing approach [10,11].

Salhi and Rand [12] argue that these components are strongly connected and should not be optimized individually. Furthermore, Nagy and Salhi [9] emphasize the importance of relating location with routing, combining strategic and tactical or operational components, allowing these decisions to be treated at the same level. The use of location routing can considerably reduce costs within a planning framework where routes can be altered [13]. As location and routing problems are separately considered NP-hard, their combination is also NP-hard, even when transshipment is included in the problem's composition. Several studies address location, routing and transshipment, such as the work of Thanapat Leelertkij [14].

This review aims to highlight the main mathematical models related to LRP, TLP and PDPs used for the mobility of goods in urban areas, directly covering collection and delivery, storage and transport of goods in urban environments, focusing on the types of modeling and simulations used in the selected studies. The main contributions of this systematic literature review are to identify the most used mathematical models from 2006 to 2023, highlighting the type of merchandise when possible, and to determine whether routing and location are fundamental factors in these studies. Another contribution is to suggest possible adaptations of the models presented for other types of goods, highlighting the importance of locating and forwarding any goods that have been collected, delivered, transported or stored. It is essential to highlight that articles with relevant models will be considered if the mode of transport is road, such as the use of Light Commercial Vehicles (LCVs), and is closely related to urban delivery.

2. Methodology

To comprehend the current state of this broad research field and analyze the key mathematical models used in the collection, delivery, storage and mobility of goods, it was essential to conduct a literature review. In this study, the strategy employed was a systematic literature review. This type of review has proven to be the general paradigm for literature reviews, inspired by a three-step methodology [15]: planning the review, executing the methodological review, and communicating and publishing the results. To maintain scientific rigor and reduce bias in the findings, this study utilizes a systematic approach by conducting a systematic literature review (SLR) in alignment with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines. The study employs various tools to enhance the processes of identification, screening, visualization and bibliographic analysis: Zotero (version 6.0.26) for reference management, StArt (version 3.3 Beta 03) for applying eligibility criteria, Microsoft Excel (version 16.0) for data handling, and the PRISMA 2020 flow diagram for illustrating the study's flow.

In the planning phase, it is crucial to determine the research scope before conducting the bibliographic search. This involves identifying the need for the review, which in this study is to visualize the current panorama and evolution of mathematical models applied in urban logistics, especially given the technological advancements in recent years. This was achieved through an initial in-depth reading of the topic, identifying the lack of comprehensive studies on the current models used and the main methodologies used in urban environments. This phase also involved finding the main keywords used in the studies, leading to the construction of final search strings for the databases. Additionally, it was necessary to draft a review proposal, formulating the research questions:

RQ1: What are the current trends in mathematical model approaches applied in urban logistics?

RQ2: What are the main models, variants and methodological approaches used to solve LRP, TLP and PDP problems in urban logistics, and how have these models evolved to meet technological changes and growing demands for sustainability?

The mobility of goods is fundamental to urban logistics, impacting the efficiency of distribution, storage and delivery, with direct consequences on the local economy and quality of life in urban areas. Analyzing the current state of mathematical models applied to collection, delivery and storage problems and their evolution was crucial for potential improvements in urban logistics. These models aim to optimize mobility management, warehouse locations and delivery routes, seeking solutions that reduce costs and increase efficiency, with a strong emphasis on minimizing environmental impact. Given urban growth and the increasing demand for quick deliveries, understanding the importance of these approaches is essential.

This justifies the need for this review, which aims to explore effective mathematical models to address urban logistics challenges. Besides detailing the steps to prepare a review protocol, inclusion criteria and database selection were also defined. StArt Software was used in the three main steps, which directly assisted in preparing the protocol and collecting data and was important in the Identification, Screening and Included steps. In this study, three relevant databases were chosen: Scopus, Web of Science and Science Direct in December 2023, with inclusion criteria as follows: (1) articles in English; (2) articles addressing LRP and/or TLP in urban areas; (3) articles covering at least one of the four situations: collection and delivery, storage, and transportation of goods; (4) peer-reviewed journal articles. Conference papers, patents or other non-journal works were excluded due to the lack of accessible information on their publication process.

In the execution phase, the research identification process involved creating a preliminary set of keywords (e.g., mathematical models, urban logistics, location-routing problem, transshipment-location problem, etc.) aimed at the preliminary mapping of scientific literature on the application of mathematical models in urban logistics, focusing on aspects like collection, delivery, storage and transshipment. This methodology aimed to filter essential articles published in highly prestigious academic journals. Subsequently, the range of keywords was expanded by including related words and expressions identified in the initial articles to cover a broader spectrum of relevant research. This iterative process of enriching the keyword set continued until reaching an adequate level of maturity, culminating in the definition of specific search chains for application in selected databases. The final search criteria established were as follows:

(1) TS = "Transshipment Location Problem"
(2) TS = "Location Transshipment Problem"
(3) TS = "Location Routing Problem" AND ("Intermediate Stops" OR "Synchronization")

For the execution of this systematic review, the temporal scope of the studies to be analyzed was delimited to the period between 2006 and 2023. Publications classified as review articles and those with little or no relevance to the proposed objectives were excluded from further analysis. Subsequently, the evaluation of pre-selected results was undertaken by applying the search strings to ensure their pertinence to the investigated theme. The detailed investigation was conducted through advanced searches in selected online databases. This strategy resulted in the identification of 740 unique records in Scopus, 246 in Science Direct and 50 in Web of Science. This significant difference between the databases shows how Scopus predominates in some research areas. However, the separation of related search terms would increase these totals to approximately 3000, 1000 and 500 records in the respective databases. Such substantial variation indicates that only a minimal fraction of articles included the specific search strings employed, suggesting the possibility of inadvertent exclusion of relevant publications due to the non-use of the applied search terms. Subsequently, from the initial collection of 1024 articles, 48 duplicates were identified and eliminated; we then proceeded with the analysis of 976 publications to determine their compliance with the previously established inclusion criteria. Of these, 196 were excluded because they did not meet the defined inclusion criteria, leaving 778 articles.

Through the 778 articles reviewed, the titles, abstracts and keywords were analyzed to verify the presence of the keywords, which resulted in the exclusion of 599 articles that did not meet the specific inclusion criteria. Therefore, 164 full texts were analyzed, culminating in the exclusion of 122 for reasons that included methodologies misaligned with the topic of interest, inadequate discussion of the results and ideas outside the scope, that is, that did not address any of the problems mentioned, such as LRP or TLP and their variants, or even that did not occur in any of the urban areas. This resulted in 42 works for inclusion. Through further reading, a new search string was identified as necessary for inclusion in this review: "Pickup and Delivery Problem with Transshipment" (PDP-T), which revealed a significant number of mathematical models applied in urban environments. This complementary search was carried out in the same databases in February 2024 but in a basic search format, considering works that contained the terms "PDP" and "Transshipment" in the title, abstract or keywords, in which 50 articles were found in the same databases, of which 26 were duplicates, and 9 were outside the defined methodological scope; therefore, 15 articles were selected in this complementary search. Consequently, 57 works were definitively selected for an in-depth analysis of employment models, as they explicitly focused on the topic according to the mentioned inclusion criteria. Subsequently, the systematic extraction of pertinent information was conducted according to the scope of our study. Finally, the studies are categorized according to the classification of mathematical models applied in urban logistics. The identified categories are analyzed based on the nature of the models, i.e., optimization with deterministic values; optimization with non-deterministic values; and simulation. Conclusively, an analysis of the current trends and existing research gaps is provided. The detailed procedure for performing the systematic literature review within the PRISMA 2020 guidelines [15] is sequentially illustrated in Figure 1.

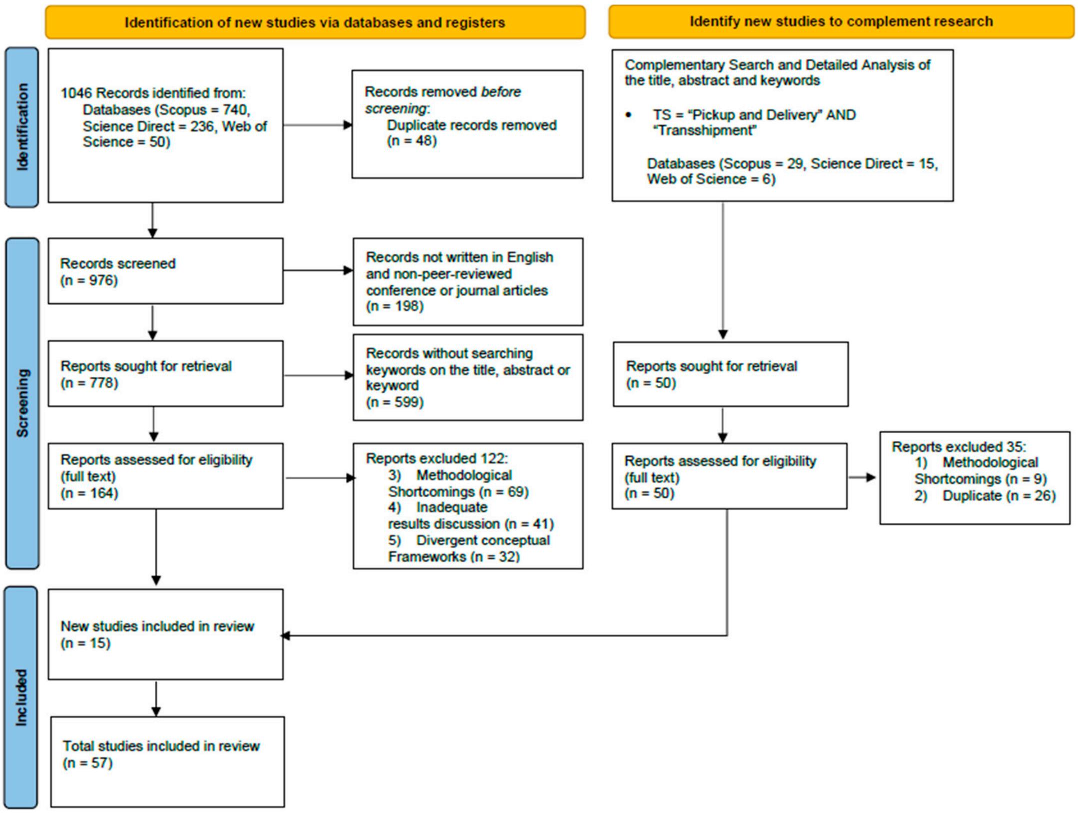


Figure 1. PRISMA flowchart describing the methodology adopted.

3. Bibliometric Analysis

Bibliometrics serves as an essential tool for evaluating the composition and trends in specific fields of knowledge. In this research, this methodology was employed to uncover the urban logistics structure and associated mathematical models [16]. This bibliometric analysis focuses on fundamental bibliographic variables, such as author (s), title, type of publication, year, journal data, keywords and institutional affiliations. These elements provided the basis for enriching our literature review and developing a comprehensive framework for understanding urban logistics. We exclusively focused on journal articles to identify and map the prevailing research trends. Furthermore, recognizing that geographic characteristics vary significantly between different cities, we considered it essential to study the regional context of the studies. This allowed us to compare and contrast proposed solutions and adapt the most suitable approaches to address specific urban logistics problems in different geographical environments.

3.1. Paper Types

In this study, the scope of analysis was limited to articles published in scientific journals, which were selected from the three relevant databases around engineering and technologies. Although conference papers may represent a significant amount of recent research on mathematical models applied to urban logistics, we chose to concentrate our focus on journal articles. Figure 2 shows the number of works published per year in the range from 2006 to 2023. The data demonstrate that between 2006 and 2018, the number of publications in journals was stable, except in 2012, when a total of five were published works. However, between 2019 and 2021, there was significant growth, with 2021 reaching the peak of publications, totaling 15 works. From 2020 onwards, there was a notable increase in publications, possibly due to the COVID-19 pandemic, mainly in 2020 and 2021, which impacted the reformulation and adaptation of collection and delivery operations in urban environments. Research was essential to encompass these changes.

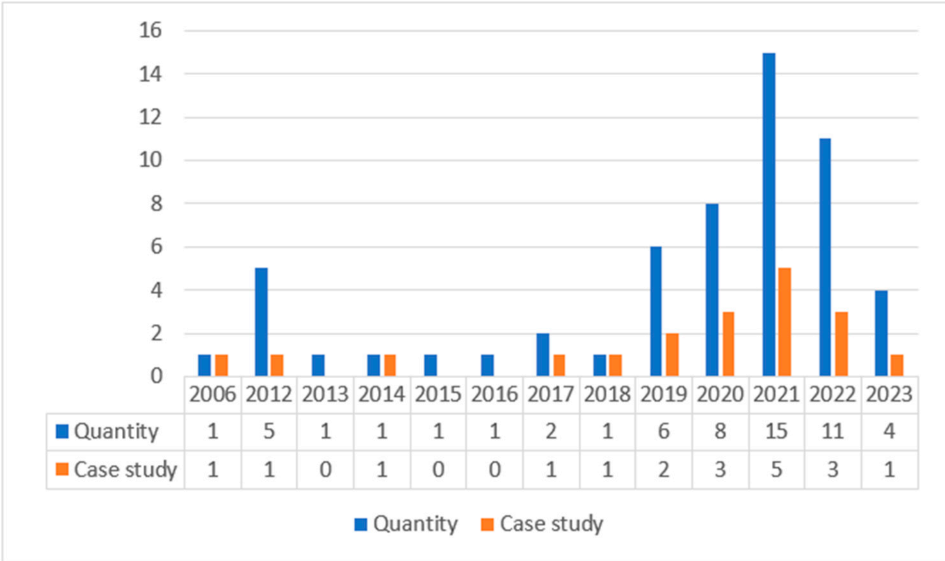


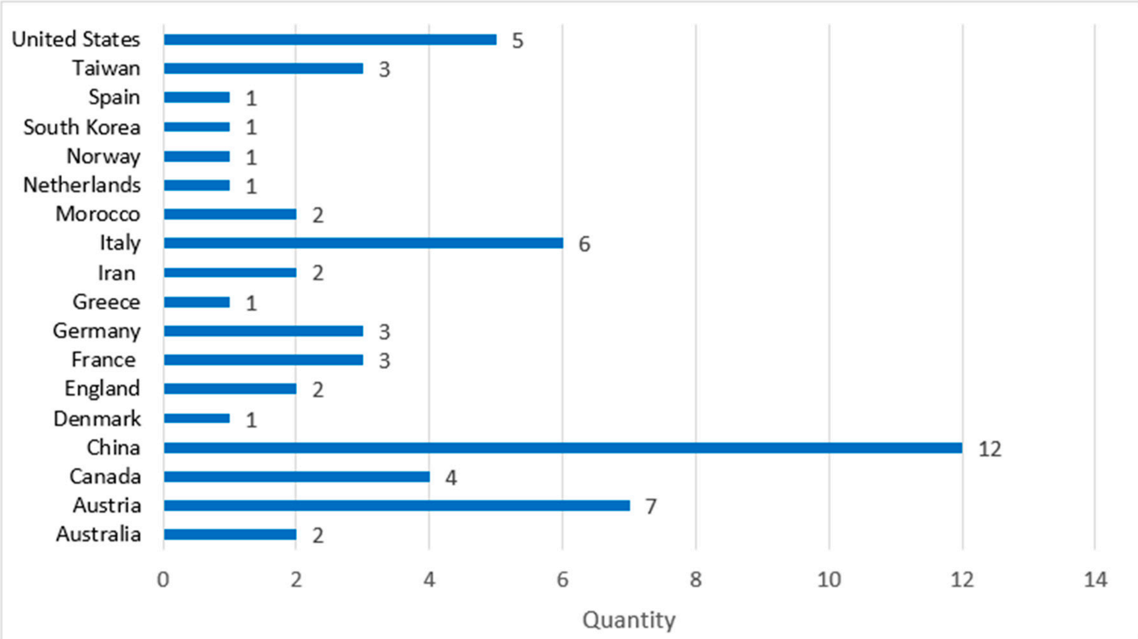
Figure 2. Typology of case studies regarding the number of publications.

A careful analysis of the articles shows that a third of them are based on real-world cases, with around 7% using simulation and 26% modeling. In total, 19 articles include at least one case study. They all resort to modeling or simulation: 90% opt for modeling and 10% for simulation. This shows that when we talk about mathematical models for LRP, TPL and PDP, understanding real scenarios is fundamental. This helps to propose practical and viable solutions for the short and medium term. Most articles deeply examine this initial stage of the urban logistics problem before proposing solutions and methods, using modeling and simulation as the main tools to deal with real-world challenges.

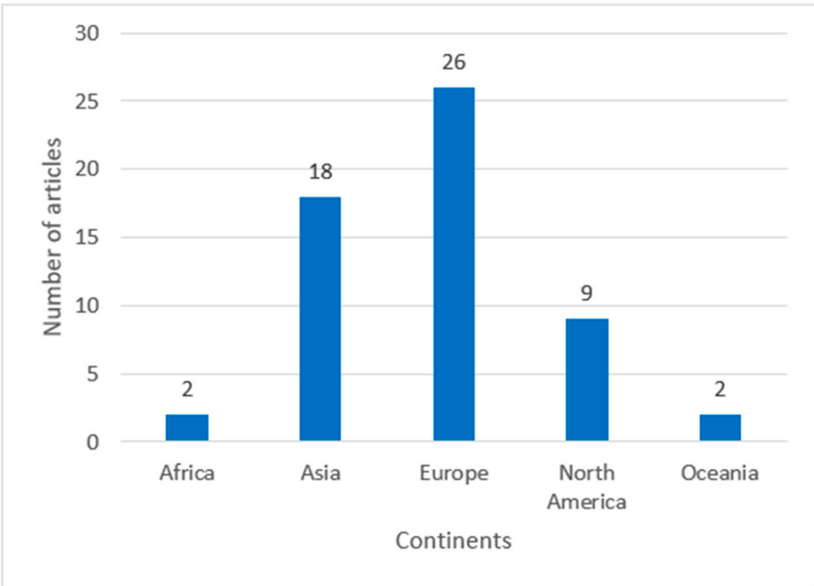
3.2. Paper Regional Profile

We considered the affiliation of the first author to attribute the research works to their respective countries. The regional classification of the articles reveals a notable global participation in the field of urban logistics and problems related to the mobility of goods, although this varies between continents. Research on the European continent is particularly relevant, with significant contributions from countries such as Germany, Austria, Denmark, Spain, France, Greece, Italy, the United Kingdom, the Netherlands and Norway, as shown in Figure 3a,b. This diversity of contributions highlights the different configurations of urban logistics that are predominant in Europe compared to other continents, with approximately 46% of the selected works in this investigation originating from Europe. Austria and Italy stand out with the highest representation in publications, as shown in Figure 3b. In this context, there seems to be a pressing need in European cities to manage small-scale deliveries in dense and historically valuable urban environments. These areas, often restricted and complex, require logistics approaches that respect heritage while promoting efficiency and sustainability. Research focuses on improving last-mile deliveries, addressing specific challenges such as routing and location in narrow streets and historic centers.

Therefore, there is a growing engagement by local authorities in Europe to develop policies and restrictions that limit vehicle traffic in congested areas. This effort aims to balance the need for logistics systems that are both environmentally sustainable and socially responsible with the preservation of cultural heritage.



(**a**)



(**b**)

Figure 3. (**a**) Regional profiles between countries; (**b**) regional profiles comparing the continents.

4. Mobility in Urban Logistics

Urban logistics mobility is a fundamental area of investigation, especially as cities accelerate development and logistical demands increase [1]. The efficiency of freight transportation in hard-to-reach urban environments is crucial not only for the sustainability of operations but also for the competitiveness of companies. The supply chain in urban environments involves multiple agents and stages, from raw material acquisition to final consumer delivery. In urban logistics, this chain needs to be extremely efficient and flexible to meet the growing demands, especially with the rise of e-commerce and the need for fast deliveries in densely populated areas. Rao et al. [3] emphasize that the strategic location of logistics centers is crucial for the success of the supply chain, allowing for operational cost reduction and increased efficiency in goods distribution. Integrating these locations with optimized transport routes ensures that products reach their destination quickly and economically, a vital aspect in urban areas where competition for space and time is intense.

Logistics operators and courier companies play a critical role in the operationalization of this supply chain, being responsible for the physical movement of goods along the different links of the chain. These operators must coordinate complex operations of collection, storage and delivery, often using advanced technologies and mathematical models to optimize their operations. Ballot and Fontane [5] suggest that collaboration between different operators can lead to load consolidation, which not only reduces costs but also minimizes the environmental impact of logistics operations, a crucial goal in urban areas. Additionally, Lyu and Yu [17] introduce the concept of the pickup and delivery problem with transshipment (PDP-T), which allows the transfer of requests between vehicles at transshipment points, improving vehicle capacity utilization and reducing travel times, especially in congested urban areas.

On the other hand, logistics centers, distribution centers, and cross-docking operations are central elements of urban logistics infrastructure, acting as convergence points where goods are received, processed and redistributed. The effectiveness of these centers is essential for the success of the supply chain, as they enable load consolidation and the reduction of transportation routes. Crainic et al. [18] highlight the importance of strategically locating these logistics satellites to enhance efficiency, while the PDP-T model, as reviewed by Lyu and Yu [17], offers an advanced approach to further improve this efficiency, especially when considering time windows and transshipment as critical variables in logistics planning. These practices, combined with the use of robust mathematical models, are fundamental to addressing logistical challenges in urban environments, where efficiency and speed are key factors for operational success. Thus, the LRP is a theoretical approach that integrates facility location decision-making and vehicle route optimization. Elements such as synchronization and intermediate stops within LRP are vital to ensure the timely and efficient delivery of goods. Additionally, the TLP offers a strategic perspective by addressing the location of transshipment points, which are essential for reducing transportation costs and enhancing operational flexibility in congested urban environments [19,20].

The PDP is central to urban logistics, focusing on the efficient collection and delivery of goods, often requiring dynamic routing to meet specific time windows. The variant of the problem that includes transshipment (PDP-T) provides greater adaptability and efficiency, particularly in urban scenarios with significant congestion. Research has evolved, and advanced models such as genetic algorithms and metaheuristics are commonly used to solve complex LRP problems. Simulation models can also be applied to LRP to predict the performance of logistics processes and strategies under different scenarios. Understanding these applications and theoretical concepts is essential for developing sustainable, efficient logistic solutions that meet the challenges of a constantly changing urban environment [21,22].

The analysis of the references reveals that most of the reviewed studies do not explicitly differentiate between types of customers, whether individual or corporate, nor between areas with low and high traffic density. Articles such as those by Crainic et al. [18], Hemmelmayr et al. [23] and Liu et al. [20], although focused on urban logistics and vehicle routing, do not make significant distinctions regarding the type of customer served or the density of the urban area where the operations take place. This pattern is also observed in works addressing the optimization of logistics operations, such as those by Yu et al. [24] and Wang et al. [25], which consider, for example, the use of electric and hybrid vehicles in urban environments without specifying whether the deliveries are intended for individual or corporate customers.

This generalization can be seen as an attempt to create more versatile logistics models capable of being applied in various urban contexts. However, the lack of specificity limits the understanding of the requirements that different types of customers and urban areas might demand, suggesting the need for future research that considers these variables in greater detail.

4.1. Location-Routing Problem

The LRP is generated by combining two classic problems: the facility location problem (FLP) and the vehicle routing problem (VRP). For Torcecilla et al. [26], the LRP is based on the combination of operational and strategic decisions related to vehicle routing and facility location, respectively. Therefore, with the integration of two complex problems, the LRP is classified as a high-complexity combinatorial optimization problem (NP-hard), making the application of heuristic and metaheuristic methods suitable approaches for solving large-dimensional instances, with simulation being a viable option for the application. The LRP addresses two fundamental aspects of logistical planning: (1) the optimal location of warehouses for storage purposes and (2) the planning of vehicle routes from these locations to customers or from customers to these warehouses. By integrating these two tasks, LRP allows for optimizing strategic warehouse locations and the efficiency of receiving or delivery routes, resulting in more efficient logistical operations [9]. In the past, these problems were often solved individually, frequently without the desired results. Since the 1960s, it has been recognized that these problems are interrelated [27,28]. In recent years, various versions of LRP have been studied [29]. Some include warehouse and vehicle constraints (CLRP) [30], multi-level networks [31], inventory management [32] and specific operating times [33].

The study by Yubin Liu et al. [20] adapted LRP to include specific service times for urban routes. This study proposed an integer programming model to optimize the operations and routes of mobile parcel lockers in urban logistics. The developed algorithm considers stochastic events that may cause delays and significantly improve the efficiency of urban routes. Zarandi et al. [34] and his team studied CLRP with uncertain travel and service times using a specific mathematical model. They also added uncertain customer requirements and created a cluster-based solution technology [33]. Studies on [29,35] are highly relevant for understanding LRP variants. Tables 1–3 present all articles found in the three databases using the string "Location routing problem", which are the results of the applied filters and address various methods and applications in the mobility of goods in urban environments and the logistical challenges for their collection or delivery.

As noted, not all articles use the nomenclature "LRP" or its variants, but rather a similar problem, VRP, which is one of the problems responsible for the generation of LRP. This does not mean that the article did not use the concept of routing with location and synchronization. In the work of Peng et al. [39], particle swarm optimization methods are used to solve the selective pickup and delivery problem with transfers, highlighting the effectiveness of this technology in significantly improving efficiency. Another important work is by Zahedi-Anaraki et al. [60], which proposed an improved Benders decomposition. This showed how the decomposition technique could be adapted to provide more efficient solutions for last-mile networks, which is very relevant in urban logistics.

There is a great diversity of methodologies discussed in the selected articles in this review, showcasing the complexity of current logistical problems. For example, in the work of Dellaert et al. [50], the routing of two-echelon vehicles with time windows is addressed, which is highly relevant for the delivery of goods in medium and large cities. In another work by Hemmelmayr et al. [23], adaptive heuristics are employed, emphasizing the importance of flexible and adaptable techniques for solving routing problems in dynamic urban environments. This contrasts with the more dimensionally constrained problem in the previous work by the same author. Another relevant work in this line is by Faugère et al. [57], which explores the use of dynamic capacity as an essential approach to optimizing parcel delivery in complex urban areas, improving resource utilization and directly reducing environmental impact.

Table 1. First Part of the LRP Papers with Synchronization and Intermediate Stops.

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
Crainic et al. [18]	Exact	Deterministic	2E-VRP [1]	Minimize routing costs in two-tier systems	Effective in realistic urban delivery scenarios
Hemmelmayr et al. [23]	Heuristic	Deterministic	2E-VRP, LRP	Develop Adaptive Large Neighborhood Search	Outperformed existing methods, found new best solutions
Bae and Moon [36]	Heuristic	Deterministic	MDVRPTW [2]	Minimize fixed and operational costs	Efficient for large instances, better than single-vehicle scheduling
Li et al. [37]	Heuristic	Deterministic	2E-TVRP [3]	Optimize two-tier routing with time constraints	Effective for realistic instances, proposed MILP and heuristic
Breunig et al. [38]	Heuristic, Exact	Deterministic	E2E-VRP [4]	Optimize routing with electric vehicles	Efficient solutions, evaluated battery capacity impact
Peng et al. [39]	Heuristic, Exact	Deterministic	SPDPT [5]	Maximize profit, minimize distance	Effective for large instances, introduced MILP model
Liu et al. [40]	Heuristic	Deterministic	2E-VRP-MV [6]	Optimize distribution with autonomous vehicles	Improved efficiency, proposed hybrid GA-PSO algorithm
Yu et al. [41]	Heuristic	Deterministic	2E-VRP	Optimize urban delivery with unmanned vehicles	Efficient for large instances, proposed MILP and heuristic
Nolz et al. [42]	Heuristic	Deterministic	2E-VRP	Synchronize urban two-tier distribution	Effective for realistic instances, proposed heuristic method
Almouhanna et al. [43]	Heuristic	Deterministic	LRPCD [7]	Optimize with electric vehicles and distance constraints	Effective for large instances, proposed BR-VNS method
Suwatcharachaitiwong et al. [11]	Heuristic	Deterministic	LRP	Optimize medication distribution using convenience stores	Efficient solutions with genetic algorithm

1—two-echelon vehicle routing problem; 2—multi-depot vehicle routing problem with time windows; 3—two-echelon time-constrained vehicle routing problem; 4—electric two-echelon vehicle routing problem; 5—selective pickup and delivery problem with transfers; 6—two-echelon vehicle routing problem with mixed vehicles; 7—location routing problem with constrained distance.

Table 2. Second Part of the Analysis of LRP Papers Featuring Synchronization and Intermediate Stops.

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
Nasri et al. [44]	Heuristic	Deterministic	VRPTW [1]	Robust vehicle routing under uncertainty	Effective in reducing delays, proposed parallel ALNS
Wang et al. [25]	Heuristic	Deterministic	LRP, PDP-TW [2]	Green logistics routing with eco-packages	Effective in reducing costs, proposed CW-NSGA-II
Luo et al. [45]	Heuristic	Deterministic	2E-CMDPDTW [3]	Minimization of total operating costs and the number of vehicles used.	The model reduced operating cost by US$11,793 and three vehicles
Drexl (a) [46]	Heuristic	Deterministic	PDPTWT [4]	Optimize one-to-one pickup and delivery with trailers	Efficient for large instances, proposed ALNS method
Drexl (b) [47]	Heuristic	Deterministic	PDPT	Test capacity feasibility in routing	Efficient for large instances, proposed constant time procedures
Anderluh et al. [6]	Heuristic	Deterministic	MO2eVRPSynGZ [5]	Optimize two-level routing with vehicle synchronization	Effective for large instances, proposed LNS method
Wang et al. [48]	Heuristic	Deterministic	MDPDPRS [6]	Optimize logistics with resource sharing	Improved efficiency, proposed KCW-NSGA-II algorithm
Yu et al. [24]	Heuristic	Deterministic	2E-VRPTW-CO-OD [7]	Minimize routing costs with occasional drivers	Efficient for large instances, proposed ALNS method
Issaoui et al. [49]	Heuristic	Deterministic	SL [8]	Optimize logistics scheduling with LSTM	High accuracy and efficiency, proposed LSTM model
Dellaert et al. [50]	Heuristic, Exact	Deterministic	MC-2E-VRPTW [9]	Manage multi-commodity two-tier routing	Effective for medium and large instances, proposed MILP
Akbay et al. [51]	Heuristic, Exact	Deterministic	2E-EVRP-TW [10]	Optimize with electric vehicles and time windows	Effective for large instances, proposed VNS method

1—vehicle routing problem with time windows; 2—pickup and delivery problem with time windows; 3—two-echelon capacitated multi-depot pickup and delivery problem with time windows; 4—pickup and delivery problem with time windows and trailers; 5—multi-objective two-echelon vehicle routing problem with synchronization and green zones; 6—multi-depot pickup and delivery problem with resource sharing; 7—two-echelon vehicle routing problem with time windows, occasional drivers, and cross-docking; 8—synchronization logistics; 9—multi-commodity two-echelon vehicle routing problem with time windows; 10—two-echelon electric vehicle routing problem with time windows.

Table 3. Third Part of Exploring LRP Studies: Synchronization and Intermediate Stops.

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
Yu et al. (a) [52]	Heuristic	Deterministic	2E-VRHPD [1]	Optimize urban delivery with hybrid vehicles	Effective for large instances, proposed ALNS method
Enzi et al. [53]	Exact, Heuristic	Deterministic	BiO-MMCP [2]	Minimize costs, maximize user satisfaction	Effective solutions with user-centered approach
Malladi et al. [54]	Heuristic	Stochastic	SFSMP [3]	Optimize fleet size and mix for urban logistics	Effective in reducing costs, proposed ALNS method
Wehbi et al. [55]	Exact, Heuristic	Deterministic	VRP-P [4]	Optimize urban parcel delivery with portering	Significant time and carbon savings, proposed MILP and heuristic
Jiang et al. [56]	Heuristic	Deterministic	VRP	Optimize e-retail order fulfillment	Effective in reducing costs, proposed hybrid VNS-ALNS method
Faugère et al. [57]	Exact, Heuristic	Stochastic	CDP [5]	Dynamic deployment of capacity modules	Significant cost and capacity savings, proposed stochastic optimization method
Yu et al. (b) [58]	Heuristic	Deterministic	CSPTW-TN-DO [6]	Minimize distribution costs with crowd-shipping	Effective solutions, proposed ALNS method
Liu and Jiang [59]	Heuristic	Deterministic	2E-VRPSDP [7]	Optimize two-tier routing with delivery and pickup	Effective solutions, proposed VNS method
Zahedi-Anaraki et al. [60]	Exact, Heuristic	Deterministic	LRP	Optimize last-mile transportation	Effective solutions, proposed Bender's decomposition with VNS
Agnimo et al. [61]	Exact	Deterministic	2E-CLRPVS [8]	Optimize location routing with synchronization	Improved efficiency and reduced costs

1—two-echelon vehicle routing problem with hybrid pickup and delivery; 2—bi-objective multimodal car-sharing problem; 3—stochastic fleet size and mix problem; 4—vehicle routing problem with portering; 5—capacity deployment problem; 6—crowd-shipping problem with time windows, transshipment nodes, and delivery options; 7—two-echelon vehicle routing problem with simultaneous delivery and pickup demands; 8—two-echelon capacitated location routing problem with vehicle synchronization.

These methodologies are essential to make urban logistics more efficient, such as last-mile distributions, which aim to optimize resources and enhance the integration of new technologies, always considering sustainability challenges, such as electric and autonomous vehicles, into existing infrastructures. The LRP is crucial for strategically determining the locations of intermediate stops and distribution centers, optimizing cargo flow and reducing operational costs. Synchronization between vehicles and logistics operations is also essential for ensuring more efficient and planned deliveries, aiming to minimize potential delays and improve resource utilization. The ongoing research on these topics is fundamental for developing innovative and sustainable solutions to current logistical problems in urban areas.

LRP with Synchronization and Intermediate Stops

The LRP is crucial for optimizing the mobility and distribution of goods, vehicle routing, and facility location decisions for warehousing. In the work of Dellaert et al. [50], the importance of LRP is highlighted, especially in creating mathematical models that integrate multiple products and constraints, such as time windows, which is essential for improving urban logistics efficiency. Another work by Wang et al. [25] addresses LRP with a focus on sustainability, integrating location selection to reduce environmental impact and optimize the distribution of eco-packages. These methodologies demonstrate how strategic location and route choices can lead to a more sustainable and, consequently, effective distribution process.

Intermediate stops play a significant role in increasing efficiency in urban logistics, such as in multi-level distribution systems. The work by Yu et al. [24] shows how intermediate stops can be strategically used to enhance logistical coverage and last-mile flexibility, utilizing occasional drivers to optimize mobility during distribution. Similarly, the research by Crainic et al. [18] studies how generalized travel costs influence the location of satellites and intermediate stops, optimizing vehicle flow and potentially reducing operational costs.

Synchronization between vehicles and logistics operations is essential to ensure efficiency and coordination in goods distribution. The study by Agnimo et al. [61] highlighted the importance of synchronization in integrating multi-level distribution systems, optimizing vehicle coordination to reduce delays and improve operational efficiency. Another example is the work by Anderluh et al. [6], which studied multi-objective optimization focusing on vehicle synchronization to serve customers in hard-to-reach areas, aiming to improve resource utilization and customer satisfaction. These approaches show how synchronization can be crucial and transformative for urban logistics, significantly improving punctual deliveries and reducing operational costs.

Analyzing the articles found in the databases, several similarities and differences in their methodological approaches and applications were observed. Various authors, like in [50] and [25], showed concerns related to route optimization and sustainability, focusing on operational efficiency and the significant reduction of environmental impact. Both authors used complex models to solve multi-level logistical problems with various constraints.

However, other authors like Yu et al. [24] and Crainic et al. [18] emphasized the importance of intermediate stops, presenting different approaches to optimize logistical coverage and reduce operational costs. Furthermore, Agnimo et al. [61] and Anderluh et al. [6] highlighted vehicle synchronization as a significant improvement in coordination and efficiency, while other articles are more focused on specific algorithms and heuristics to solve routing problems. Thus, although the articles share common goals of optimization and efficiency in urban logistics environments, their approaches vary significantly, reflecting the diversity of challenges and solutions in the field of urban logistics. Table 4 shows the authors who utilized LRP as the type of problem.

Table 4. Papers addressing the LRP.

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
Hemmelmayr et al. [23]	Heuristic	Deterministic	2E-VRP [1], LRP	Develop Adaptive Large Neighborhood Search	Outperformed existing methods, found new best solutions
Almouhanna et al. [43]	Heuristic	Deterministic	LRPCD	Optimize with electric vehicles and distance constraints	Effective for large instances, the proposed BR-VNS method
Suwatcharachaitiwong et al. [11]	Heuristic	Deterministic	LRP	Optimize medication distribution using convenience stores	Efficient solutions with genetic algorithm
Wang et al. [25]	Heuristic	Deterministic	LRP, PDP-TW	Green logistics routing with eco-packages	Effective in reducing costs, proposed CW-NSGA-II
Drexl et al. [47]	Heuristic	Deterministic	2E-LRP	Optimize multi-commodity two-tier routing	Effective solutions, proposed ALNS and MILP methods
Zahedi-Anaraki et al. [60]	Exact, Heuristic	Deterministic	LRP	Optimize last-mile transportation	Effective solutions, proposed Benders decomposition with VNS
Agnimo et al. [61]	Exact	Deterministic	2E-CLRPVS	Optimize location routing with synchronization	Improved efficiency and reduced costs

1—two-echelon vehicle routing problem.

The discussed articles present significant advancements in the field of urban logistics and transportation systems optimization, addressing different variants of the VRP and the LRP. Hemmelmayr et al. [23] propose an adaptive heuristic that outperforms existing methods for the 2E-VRP and LRP, highlighting the importance of neighborhood search operators adapted to the multi-level structure of these problems. In a similar multi-echelon context, Wang et al. [25] explore green logistics through the optimization of two-echelon location routing and pickup and delivery with time windows using the SST network to synchronize operations and reduce costs, emphasizing the relevance of location strategies in environmental efficiency. Agnimo et al. [61] also focus on synchronization, proposing the 2E-CLRPVS to optimize multi-echelon distribution systems, minimizing wait times at satellites and demonstrating the effectiveness of methods like BVF.

In terms of sustainability and efficiency, Almouhanna et al. [43] introduce electric vehicles (EVs) into the LRP, proposing fast heuristics and metaheuristics to address the limited range of EVs and suggesting future extensions to consider stochastic travel times and heterogeneous fleets. Conversely, Drexl (a) [46] and Drexl (b) [47] study pickup and delivery problems with time windows and detachable trailers, presenting exact procedures for testing task insertion feasibility in routes, which is crucial for the efficiency of the proposed algorithms. Zahedi-Anaraki et al. [60] address "last-mile transportation" in the LRP, proposing an integrated model that offers flexible delivery options to customers and uses a modified Benders decomposition algorithm to solve large-scale problems, highlighting the need for optimization strategies that consider the complexity and variability of last-mile operations. Together, these studies form a robust foundation for future research in urban logistics, especially in multi-echelon contexts and ecological practices. Additionally, they underscore the inclusion of tools that can significantly minimize costs, such as transshipment.

4.2. Transshipment Location Problem

The TLP is a central issue in logistics that involves determining strategic locations for transshipment points where goods are transferred between different vehicles or modes of transport. The primary objective of the TLP is to minimize the total costs of transportation, storage and the mobility of goods throughout the supply chain. Some variants of this problem include the multi-period transshipment location-allocation problem with flow synchronization under stochastic handling operations and the capacitated transshipment problem with stochastic handling utilities at the facilities. Thus, synchronization is an important component in the use of transshipment, whether it is in the traditional problem or more robust variants. The TLP can be approached both deterministically and stochastically, with stochastic problems being more common due to the unpredictable nature of logistical operations and transport times. Tables 5 and 6 list the authors and their respective works found in the databases with the string "Transshipment Location Problem", all of which address the mobility of goods in urban environments, as defined in the methodology.

Giusti et al. [63] explored a multi-period variant of the TLP, focusing on flow synchronization and stochastic handling operations. Meanwhile, Tadei et al. [70] address the capacitated TLP, considering stochastic variables in the handling of goods at the facilities. Another relevant article is by Crainic et al. [65], which proposes a model that integrates location and transshipment, emphasizing the synchronization of operations to optimize logistical efficiency. These studies utilize various methodologies, such as integer programming models and simulation techniques, to tackle the challenges posed by uncertainty in logistical operations.

Comparing the results of these studies reveals that all emphasize the importance of considering stochastic variables in logistical planning, highlighting the need for models capable of effectively handling uncertainty. However, gaps remain that need to be explored, such as the integration of multiple service levels and modes of transport into a unified logistical network, as discussed by Janjevic et al. [62]. Additionally, the impact of the on-demand economy, addressed in [64], introduces new dimensions to the TLP, suggesting that future research should consider the evolution of delivery practices and emerging business models. Collectively, these studies indicate a promising path for optimizing urban logistics through more integrated and adaptable models responsive to dynamic market conditions.

4.3. Pickup and Delivery Problem

Pickup and delivery problems (PDPs) are a category of vehicle routing problems where objects or people need to be transported between an origin and a destination. They are classified into three main groups. The first group, called many-to-many, allows any vertex to serve as an origin or destination for any commodity, such as in the exchange problem [71], where each vertex initially contains one type of commodity and desires another specific type. The second group, one-to-many-to-one, involves commodities that start at a depot and are delivered to customers, with pickups from customers returning to the depot. This is exemplified by the work of Mitrović-Minić and Laporte [72], which addressed optimized routing to maximize operational efficiency. The third group, one-to-one, involves commodities with specific origins and destinations, common in express courier operations and door-to-door transportation services. In the article by Santos et al. [73], differences between taxi-sharing and ride-sharing problems were explored, categorizing them as variants of the one-to-one problem, where each transport request has specific origins and destinations, as defined.

Table 5. First Part of the Objectives and Results for Transshipment and Location Problems.

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
Janjevic et al. [62]	Heuristic	Deterministic	ME-LRP [1]	Strategic design of last-mile multimodal networks in an omnichannel environment.	Demonstrates the need for a granular and integrated approach to optimizing distribution networks, showing economic benefits.
Giusti et al. [63]	Heuristic	Stochastic	TLAP [2]	Evaluate the impact of uncertainty on facility capacities and handling utility in the transshipment location–allocation problem.	Optimizing the stochastic version provides better revenues; Progressive Hedging-based heuristics outperform CPLEX in performance.
Perboli et al. [64]	Heuristic	Deterministic	SS-LM-D [3]	Analyze the efficiency and feasibility of the business model for satellite-based shared last-mile delivery.	Superiority of the consolidation approach over the classic single-level approach; managerial insights for the new Logistics and Mobility Plan in the Piemonte region.
Crainic et al. [65]	Exact	Deterministic	SLTP [4]	Improve efficiency and sustainability in synchromodal logistics by mitigating disruptive effects of unsynchronized operations.	MILP formulation for synchronizing flows and proper utilization of just-in-time logistics; economic analysis based on the proposed model.
Perboli and Rosano [66]	Heuristic	Deterministic	SS-LM-D [3]	Integrate traditional and green logistics to identify synergies, conflicts, and operational and economic consequences of adopting green vehicles.	Adoption of green vehicles can result in CO_2 emissions benefits and service quality; need to redefine contractual schemes between traditional and green subcontractors.

1—multi-echelon location routing problem; 2—transshipment location–allocation problem; 3—satellite-based shared last-mile delivery; 4—synchromodal logistics and transportation problem.

Table 6. Second Part of the Objectives and Results for Transshipment and Location Problems.

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
Nakandala et al. [67]	Heuristic	Deterministic	LT [1]	Minimize total inventory costs considering perishable products and lateral transshipment.	LT is preferred to minimize total inventory costs; study limitations include modeling approximations and the need for future studies to introduce positive lead times for LT.
Torabi et al. [68]	Exact	Deterministic	TLP	Determine the optimal delivery plan minimizing total transportation and transshipment costs after demand data realization.	Benders decomposition model outperforms CPLEX; proposed future research to consider demand uncertainty and inventory replenishment decisions.
Maggioni et al. [69]	Heuristic	Stochastic	mpTSPs [2]	Define realistic instances for routing problems in urban context with uncertainty in transportation costs.	Proposed instance generation approach qualifies and shows precise predictions of optimal tours.
Tadei et al. [70]	Heuristic	Stochastic	CTLPD [3]	Maximize net utility in freight transport considering stochastic handling utilities at facilities.	Stochastic model shows average gap with CTLPD of less than 2%; heuristic reduces computation time by up to 90%.
Baldi et al. [2]	Exact	Stochastic and Deterministic	CTLPU [4], CTLPD [3]	Minimize total cost in capacitated transshipment problems considering uncertainty in facility flow costs.	Average difference between optimal stochastic and deterministic models is about 2%; CTLPD collapses into classic capacitated transshipment location problem for certain entropy parameter values.

1—lateral transshipment; 2—multi-path traveling salesman problems; 3—capacitated transshipment location problem with stochastic handling utilities; 4—capacitated transshipment location problem with uncertainty.

With the growth of e-commerce and advances in information technology, new approaches to optimizing transportation systems have emerged. Among the most promising is the inclusion of transshipment, leading to the pickup and delivery problem with transshipment (PDP-T). A relevant study on PDP-T is [70], which explores how uncertainty in handling commodities can be managed to improve logistical performance.

Pickup and Delivery Problem with Transshipment and Variants

In PDP-T, requests can be transferred from one vehicle to another at designated transfer stations, where they are stored for a set time. Subsequently, other vehicles pick up and complete the delivery. The goal of PDP-T is to improve the efficiency of the transportation system by optimizing the capacity and availability time of the vehicles used. The works of Mitrović-Minić and Laporte [72] and Takoudjou et al. [74] highlight the importance of transshipment points, demonstrating that their use can keep drivers within their areas of origin and optimize routes by promoting load transfers between vehicles. These approaches are useful in contexts where demand is high and efficient route management is crucial for the competitiveness and sustainability of operations. In practice, collection and delivery times are often limited by time windows, which results in the collection and delivery problem with time windows and transfers (PDPTW-T). In Table 7, we can observe the works found with PDP and transshipment.

Danloup et al. [84] introduce meta-heuristics such as Large Neighborhood Search (LNS) and genetic algorithms (GAs) to solve the PDPT, demonstrating that these techniques can surpass traditional solution-finding methods such as the PDP without transshipment, which directly influences efficiency and quality. Nikolopoulou et al. [85] provide additional insights by comparing the effectiveness of direct transportation and cross-docking, revealing that the combination of these strategies can yield more robust and cost-effective logistical solutions. The study by Mirhedayatian et al. [83] on the synchronization of flows in two-echelon distribution systems also contributes to understanding the complexities involved in managing transshipments, highlighting the need for methodologies that can handle uncertainty in logistical operations.

Additionally, Zhou and Lin [82] and Guo et al. [78] explore new on-demand delivery strategies, such as P2PT, which involves the relay of packages among multiple carriers to increase efficiency without expanding the fleet. These innovative approaches are crucial to meeting the growing customer expectations for speed and flexibility in deliveries. The integration of occasional drivers, as discussed by Voigt and Kuhn [77], also proves to be a promising strategy to reduce costs and improve resource utilization, offering a dynamic solution to the increasing demand for delivery services.

Table 7. Papers addressing the PDP-T.

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
Xu and Wei [75]	Heuristic (CW-ALNS)	Deterministic	DPDPTL [1]	Construct a multi-objective model for DPDPTL	CW-ALNS improves solution quality in large-scale scenarios.
Su et al. [76]	Branch-and-price-and-cut	Deterministic	PDPCBT [2]	Minimize travel costs and compensation for crowdshippers	Proposed algorithm is efficient and effective, reducing computational time and costs.
Lyu and Yu [17]	Mixed-Integer Linear Programming	Deterministic	PDP-T, PDPTW-T	Develop a new linear programming formulation for PDPT and PDPTW-T	Proposed model outperforms existing ones in solution quality and computation time.
Voigt and Kuhn [77]	Adaptive Large Neighborhood Search (ALNS)	Deterministic	PDPTOD [3]	Integrate occasional and regular drivers in transshipment operations	Integration of occasional drivers reduces costs and increases resource utilization.
Guo et al. [78]	Heuristic	Deterministic	Collaborative routing for logistics	Develop a collaborative routing mechanism for omnichannel logistics	Improves social welfare, reducing costs and CO_2 emissions.
Wolfinger et al. [79]	Branch-and-cut	Deterministic	PDPSLT [4]	Solve PDPSLT optimally for larger instances	Demonstrated cost reductions and effectiveness of PDPSLT, suggesting directions for future research.
Wolfinger [80]	LNS	Deterministic	PDPTWSLT [5]	Minimize the sum of travel and transshipment costs	LNS effective for solving PDPTWSLT, reducing costs by 6%.
Dongyang et al. [81]	Decomposition-based heuristic	Deterministic	PDP-T	Explore transshipment planning between customers	Heuristic improves logistics efficiency, reducing operational costs.
Zhou and Lin [82]	Adaptive Bound Relaxation Heuristic (ABR)	Deterministic	P2PT [6]	Evaluate a new on-demand delivery strategy with P2PT	P2PT effective for on-demand delivery without fleet expansion.
Mirhedayatian et al. [83]	Decomposition-based heuristic	Deterministic	2E-LRP [7]	Synchronize flows in intermediate facilities	Proposed model effectively synchronizes flows.
Danloup et al. [84]	LNS and genetic algorithms	Deterministic	PDP-T	Compare LNS and GA with existing solutions for PDPT	LNS and GA are efficient, GA shows better overall performance.
Nikolopoulou et al. [85]	Local Search Optimization	Stochastic	PDP with cross-docking	Compare direct transport and cross-docking	Cross-docking can be more efficient depending on spatial and temporal characteristics.

Table 7. *Cont.*

Authors	Solution Method	Deterministic or Stochastic	Problem Type	Objectives	Results
McWilliams and McBride [86]	Branch and Limit	Deterministic	PHSP [8]	Minimize transfer operation time	Effective algorithm for small problems, suggests meta-heuristics for larger problems.
Takoudjou et al. [74]	MIP	Deterministic	PDPTW [9]	Promote cargo transfer between vehicles	Validation with test instances, obtaining optimal value by calculation.
Mitrović-Minić and Laporte [72]	MIP	Deterministic	PDP-T	Evaluate the usefulness of transshipments in courier operations	Transshipments increase efficiency by keeping drivers in their origin area.

1—dynamic pickup and delivery problem with transshipment locations; 2—pickup and delivery problem with crowd-based transportation; 3—pickup and delivery problem with transshipments and occasional drivers; 4—pickup and delivery problem with split loads and transshipments; 5—pickup and delivery problem with time windows, split loads, and transshipments; 6—peer-to-peer transportation; 7—two-echelon location routing problem; 8—parcel hub scheduling problem; 9—pickup and delivery problem with time windows.

5. Discussion

The analysis of articles on TLP, LRP and PDP reveals a variety of methodological approaches and significant results that contribute to the advancement of research in these fields. The predominance of heuristic and exact methods, with a considerable inclination towards deterministic approaches, characterizes most studies. However, the gap in the application of stochastic simulations highlights a potential area for future investigations, especially considering the importance of uncertainty in realistic logistics scenarios.

Heuristic methods are widely used due to their ability to provide high-quality solutions in reduced computational times. For instance, Hemmelmayr et al. [23] applied an Adaptive Large Neighborhood Search (ALNS) to solve 2E-VRP, demonstrating effectiveness in outperforming existing methods for 2E-VRP and LRP. Almouhanna et al. (2020) [43] also employed heuristics, combining biased randomization techniques with Variable Neighborhood Search (VNS) to optimize the use of electric vehicles in distance-constrained LRP, showing near real-time efficiency for LRPCD instances.

On the other hand, exact methods are often combined with heuristics to balance precision and computational efficiency. Wang et al. [25] utilized a network flow optimization model for green logistics routing, integrating Mixed-Integer Linear Programming (MILP) with genetic algorithms, while Drexl [46] proposed exact procedures for testing temporal and capacity feasibility in the pickup and delivery problem with detachable trailers (PDPTWT), incorporating these procedures into an ALNS algorithm for robust heuristic solutions. This combination of exact and heuristic methods allows for more robust and efficient solutions, leveraging the strengths of both approaches.

The results of the studies indicate significant improvements in operational efficiency and cost reduction. Hemmelmayr et al. [23] reported obtaining 59 new best solutions in 93 instances of 2E-VRP and improvements in 20 LRP solutions in 79 instances. Almouhanna et al. [43] demonstrated that their heuristics could generate high-quality solutions in short computational times, ideal for real-time applications. Optimization with electric vehicles is a recurring theme due to the increasing demand for sustainable logistics solutions. Studies such as Wang et al. [25] and Nasri et al. [44] addressed eco-package routing and robust urban distribution under uncertainty, respectively, using heuristic methods to reduce costs and carbon emissions.

However, the integration of stochastic methodologies remains limited. Maggioni et al. [69] and Baldi et al. [2] highlight the importance of considering uncertainty in transshipment location and transportation problems (CTLTP), showing that stochastic models can significantly reduce computation time and provide more robust solutions. Most of the reviewed studies employ deterministic approaches, which may not adequately capture the inherent uncertainty in real logistics scenarios, such as variations in demand, travel times and vehicle availability. The inclusion of stochastic simulations could improve the robustness and applicability of the proposed solutions.

Moreover, most studies focus on specific methodologies, either heuristic or exact, with few exploring the combination of leveraging their respective advantages. Future research could delve deeper into hybrid approaches, combining the precision of exact methods with the computational efficiency of heuristics. For instance, Drexl's [46,47] approach, which integrates exact procedures into an ALNS algorithm, could be expanded to other types of logistics problems to explore the full potential of this combination.

The application of electric and autonomous vehicles in routing and location problems also presents a promising area for future research. Liu et al. [40] and Yu et al. [41] have already demonstrated the potential of these technologies in improving operational efficiency. Nevertheless, there are still challenges that need to be better explored, such as the limited fleet of electric vehicles and the lack of infrastructure for car charging. Future studies could explore simulations incorporating these factors to provide more detailed insights into the feasibility and impact of these technologies in real logistics scenarios.

Another underexplored area is the integration of optimization methods with simulation tools to analyze "what-if" scenarios and the resilience of proposed solutions against uncertainties and disruptive events. This can provide a more holistic and practical view for decision-making in logistics. For example, the robust optimization models proposed by Nasri et al. [44] and the scenario simulation studies by Maggioni et al. [69] demonstrate how these approaches can effectively manage uncertainties and improve supply chain resilience.

Therefore, while the reviewed studies have significantly advanced the solution of routing, location and transshipment problems, the gap in the application of stochastic simulations and the need for more hybrid and integrated approaches highlight important opportunities for future research. Exploring these areas can lead to more robust and applicable solutions, improving the efficiency and sustainability of logistics operations in an increasingly dynamic and uncertain environment. The combination of deterministic and stochastic methodologies, along with the application of new technologies like electric and autonomous vehicles, can provide significant advancements in logistics research and practice. The COVID-19 pandemic, which began in 2020, introduced new challenges, such as the need for rapid adaptation to sudden fluctuations in demand and mobility restrictions.

The COVID-19 pandemic has significantly reassessed traditional operational models used in urban logistics, such as LRP, TLP and PDP. Before the pandemic, traditional approaches to the LRP, as highlighted in previous studies, such as those discussed in the traditional review by Nagy and Salhi [9], primarily focused on minimizing total transportation costs and strategically locating facilities to efficiently meet demand. These models generally assumed a relatively stable environment with predictable customer demand and transportation conditions. The pandemic introduced a series of challenges that necessitated a reassessment of LRP models. Instability in demand, mobility restrictions and the need to reduce physical contact required the development of more robust and flexible models. The pre-pandemic works, such as those by Hemmelmayr et al. [23] and Wang et al. [25], focused on optimizing vehicle routing and location problems in urban logistics systems. These studies applied advanced heuristics, such as ALNS and Mixed-Integer Linear Programming techniques, to solve complex problems like the 2E-VRP and LRP in relatively stable scenarios

During the COVID-19 pandemic, the need to adapt operational models became evident. The study by Suwatcharachaitiwong et al. [11] represents a significant advancement by introducing a drug distribution system that integrates convenience stores, lockers and home delivery. This study utilized a genetic algorithm to solve the LRP in a context where flexibility and responsiveness were essential, addressing the limitations imposed by the pandemic. Although efficient, this method was constrained using heuristics, which, despite being fast, did not guarantee optimal solutions in all cases. However, the post-pandemic context, addressed by Agnimo et al. [61], required significant adaptation of these operational models.

In the article by Agnimo et al. [61], an even more advanced methodological evolution is observed. Agnimo and his team adopted a hybrid approach that combines genetic algorithms with machine learning-based optimization methods, specifically deep neural networks, to dynamically adjust model parameters during the optimization process. This advanced mathematical model incorporates multiple uncertainty scenarios, using robust optimization techniques to ensure the resilience of the solutions obtained. Mathematically, the model is formulated as a MILP problem, where solutions are iteratively refined through the dynamic adjustment of neural network weights, ensuring not only speed but also the robustness of solutions against variations in demand and operational constraints. This methodological evolution reflects a direct response to the demands imposed by the pandemic, providing a significantly greater capacity for adaptation and operational resilience compared to previous methods.

The PDP and its variants have been extensively studied, particularly in terms of vehicle capacity optimization and operational cost reduction using transshipments. Danloup et al. [84] provided a robust approach by comparing Large Neighborhood Search (LNS) algorithms with genetic algorithms (GAs) to solve the PDP-T, highlighting the effectiveness of metaheuristics in finding efficient solutions to complex logistics problems. The methodology developed by Danloup et al. [84] reflected a pre-pandemic scenario, where demands and operational constraints were more predictable. In response to these new realities and adaptations required post-pandemic, Lyu and Yu [17] developed a new MILP formulation for PDP-T that is superior to previous models, being able to efficiently handle larger and more complex instances. Specifically, in situations involving up to 25 requests and two transfer stations, the model effectively solved instances that previous models could not efficiently handle at larger scales of requests and transfers, incorporating robust optimization techniques to deal with multiple scenarios of uncertainty, a direct reflection of the demands imposed by the pandemic. Although they do not directly review the work of Danloup et al. [84], the advancement proposed by Lyu and Yu [17] represents a significant evolution in the literature, providing greater computational efficiency and adaptability to the volatile conditions that have become common in the post-pandemic environment. This new approach allows solving larger instances of PDP-T with up to 96% reduction in computation time, a crucial improvement in a scenario where operational agility and resilience are essential.

Optimization models, such as those based on MILP, are widely preferred in situations where accuracy and efficiency are crucial, particularly in complex urban routing problems such as PDP-T. In addition, other studies, such as those by Breunig et al. [38] and Yu et al. [52], also reinforce the effectiveness of exact and heuristic models in dynamic urban environments. These models perform well in situations where the demand for high-quality solutions and computational time are critical factors. Route simulation is suggested as a complementary approach in scenarios of high uncertainty, such as variations in demand and travel times, as discussed by Maggioni et al. [69] and Nasri et al. [44]. Changes in distribution channels, such as the integration of parcel lockers and transfer points, can significantly impact logistics models, requiring adaptations in existing methods to accommodate new practices and technologies, as demonstrated by Lyu and Yu [17] and Giusti et al. [63]. These studies suggest that incorporating transshipment improves operational efficiency by enabling more effective load redistribution and adaptation to new market demands.

To select articles for this systematic review, the authors adhered to the PRISMA 2020 guidelines. Nonetheless, there remains a possibility that some relevant articles were inadvertently missed during the selection process. The area of study encompasses a variety of designations and terminologies, which may have led to the exclusion of articles using less common or alternative keywords.

6. Conclusions and Future Research Avenues

The systematic research conducted in this study investigated mathematical models in urban logistics, focusing on routing, location and transshipment. Due to population growth and the rise of e-commerce, urban logistics must be efficient and sustainable, in which LRP, TLP and PDP and their variants directly assist in this advancement. Fifty-seven articles were analyzed, in which deterministic and stochastic methodologies were analyzed, as well as heuristic and exact solutions. The methodology involved review planning, definition of keywords and search strings, selection of databases (Scopus, Web of Science, Science Direct) and strict inclusion criteria, in which only works that cited the mobility, storage or transshipment of goods in urban environments were considered. Works that did not have this scope were disregarded. The European continent has the largest number of publications in the sum of the selected articles, followed by Asia and the American continent. However, the country with the largest number of publications was China, followed by Austria, Italy and the United States. About a third of the selected articles are based on real-world cases.

Optimization models, particularly those based on MILP, are highly favored in scenarios where precision and efficiency are essential, especially in complex urban environments. The results analyzed on the methodologies in the fields of TLP, LRP and PDP indicate a significant preference for exact and heuristic methods, with a notable emphasis on deterministic approaches. Heuristic methods are most widely used due to their ability to provide robust and high-quality solutions in reduced computational times, which is crucial for real-time applications. These methods have been shown to significantly increase operational efficiency and reduce costs, especially in scenarios involving electric vehicles. Although exact methods are often employed to ensure accuracy, they are often combined with heuristics to achieve a balance between accuracy and computational efficiency. This hybrid approach has proven effective in improving solutions' robustness and efficiency.

However, the limited integration of stochastic methodologies suggests a gap in addressing the inherent uncertainties in real-world logistics scenarios, such as fluctuating demand and variable travel times. Most studies continue to rely on deterministic models, which may not fully capture these uncertainties. While deterministic methods have generated substantial advances, incorporating stochastic approaches and further exploring hybrid methods represent promising directions for future research, potentially leading to more resilient and adaptive logistics solutions. Among the LRP, TLP and PDP problems, all of which employ both deterministic and stochastic approaches, the TLP stands out for more frequently utilizing stochastic methods due to the inherent unpredictability of logistical operations and transportation times.

Maggioni et al. [68] and Baldi et al. [2] showed that stochastic models offer more robust solutions for logistics operations. Combining deterministic and stochastic methodologies with technologies like electric and autonomous vehicles is promising for future research. Hybrid approaches utilizing the precision of exact methods and the efficiency of heuristics can provide robust and practical solutions. Simulations for "what-if" scenarios and resilience can improve decision-making in urban logistics. This study highlights the diversity of methodologies and the need to consider operational efficiency and sustainability. Heuristic and exact methods and stochastic and hybrid approaches offer effective solutions for urban logistics challenges. Future research should integrate stochastic simulations and emerging technologies to develop more robust, sustainable and adaptable logistics solutions for dynamic urban markets. Interdisciplinary collaboration and the use of real data are essential for efficient models that address urban logistics complexities.

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