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Contextualizing alternative delivery points in last mile delivery

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ABSTRACT

This study presents a comprehensive literature analysis to explore the role of Alternative Delivery Points (ADPs), such as parcel lockers (PLs), within logistics and transportation. Through a structured methodology that includes the 'Plan,' 'Design,' and 'Evaluation' stages, this research provides a new perspective on the research gaps, obstacles, and prospective areas for future study in the domain of ADPs. The investigation delineates critical prerequisites, determinants of success, optimization strategies, and key performance indicators relevant to deploying ADPs. The insights consolidate existing knowledge and act as a roadmap for forthcoming scholarly endeavors concerning ADPs. The study aims to advance the dialogue and stimulate innovation in urban delivery systems employing ADPs by focusing on under-researched areas and underscoring topics needing further scrutiny.

1. Introduction

Unprecedented growth in e-commerce and online shopping has dramatically increased direct business-to-customer (B2C) and reciprocal customer-to-business (C2B) return freight flows. It is widely known in the literature that last-mile delivery (LMD) is the supply chain's most expensive and least efficient leg. Challenges associated with LMD are attributed to low economies of scale and operational challenges carriers face in delivering goods to customers' doorstep in large residential buildings (Perboli et al., 2021). Difficulties in finding the exact delivery addresses in urban and suburban areas and shortage of loading spaces in central business districts (CBDs) are other factors that further complicate the LMD process (González-Varona et al., 2020). At the same time, carriers face several challenges in fleet and personnel capacity management due to the volatile nature of LMD demand throughout the year (Mohri et al., 2022). Environmentally and socially, increased LMD activity adds pressure on the transport network and worsens air pollution and other externalities (Taniguchi et al., 2023). At the same time, customers' expectations for free, convenient, and fast delivery services are also increasing, creating disproportional infrastructure utilization (Statista, 2021).

To address these issues, several initiatives have been introduced by academia and practitioners, including technological, behavioral, and infrastructure-based solutions that aim to improve collaboration and coordination among urban logistics stakeholders (Cleophas et al., 2019; Ghaderi et al., 2022a; Mohri et al., 2024d). A class of LMD initiatives that focuses on enhancing collaboration and delivery performance between customers and carriers is the alternative delivery points (ADPs), which aim to substitute customers' exact delivery addresses with more accessible, sustainable, and secure options (Pan et al., 2021). ADPs are reshaping the LMD

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landscape by offering greater flexibility, convenience, and efficiency to both customers and carriers. Demand for secure delivery and increased e-commerce logistics (both forward and reverse) are further propelling the proliferation of ADPs within urban freight environments, with smart parcel lockers (PLs) known as the most prevalent type. According to Fortune Business Insights (2024), the size of the smart PL market was estimated at USD 902.6 million in 2023 and is estimated to grow from USD 1,012.0 million in 2024 to USD 2,552.4 million by 2032, showing a compound annual growth rate of 12.3 %.

The academic literature proposes several types of ADPs, such as local post offices, collection and delivery points (CDPs), click-and-collect points, pick-up points (e.g., a nearby facility like a store or library), and most notably, smart PLs in the form of stationary and mobile. This study defines ADPs in LMD as "*locations or facilities other than customers' primary address, where parcels can be collected and delivered*". Taxonomically, ADPs can be studied based on two dimensions. The first dimension pertains to the ownership of facilities, and the second one relates to whether or not staff attends them. Examples of attended ADP facilities owned by carriers include post offices, while smart PLs are unattended options. News agencies are the example of attended facilities and car trunks as unattended options when carriers do not own ADPs. ADPs can be the initial delivery address or a backup point for failed attempts (Mohri et al., 2023). ADPs are also employed when customers want to return their products to the shippers. The literature also reports on examples where ADPs are utilized to facilitate collaboration among carriers or crowdshippers to exchange goods (Mohri et al., 2023; Mohri et al., 2024a; Mohri et al., 2024b; Pan et al., 2021; Ensafian et al., 2023). In this work, studies that examine the role of ADPs as transshipment points are excluded, mainly because of the limited customer-facing implications of such PL applications.

While the extant body of knowledge indicates the growing momentum of studies exploring various operational aspects of ADPs, their large-scale uptake around the globe is also becoming more evident (Thompson et al., 2019; Lin et al., 2020). For example, the number of papers on this topic has steadily increased, with 59 high-quality papers published between 2018 and 2023. Despite this growing interest, there is a lack of conclusive understanding of the role of ADPs in addressing the sustainability challenges of urban logistics systems. Specifically, no systematic study examines how ADPs should be efficiently designed and integrated into existing urban logistics systems and, most importantly, what constitutes a well-performing ADP system, mainly learned from real-world deployments. A handful of studies have been proposed to develop guidelines and support practitioners in deploying and utilizing ADPs. For example, Lagorio and Pinto (2020) examine the link between availability, accessibility, and security of PLs with LMD performance by capturing data from real-world implementations. Similarly, Rohmer and Gendron (2020) provide an informative guide on the current challenges and planning decisions associated with implementing automated PLs from an operations research (OR) perspective. Janinhoff et al. (2024) recently reviewed studies published since 2021 that focus on designing delivery networks using ADPs. This study, specifically, provides an operations research and optimization perspective, particularly emphasizing facility location, routing, and location-routing problems.

This study aims to bridge the gap by presenting a systematic and analytical literature review, specifically to serve as a vehicle for researchers and practitioners to understand the current landscape of ADP research. We follow a systematic 'Plan,' 'Design,' and 'Evaluation' approach to dive deeply into multiple aspects of studies on the applications of ADPs in LMD systems. This unique conceptualization allows us to understand prerequisite conditions, critical success factors, optimization mechanisms, and the performance measurement of implementing such systems. Through this endeavor, we aim to contribute significantly to the knowledge base surrounding LMD systems. The remainder of this manuscript is organized as follows. In Section 2, we describe the review methodology. Section 3 reviews the literature from a planning perspective, followed by design and evaluation in Sections 4 and 5. Finally, discussion and conclusions are provided in Sections 6 and 7, respectively.

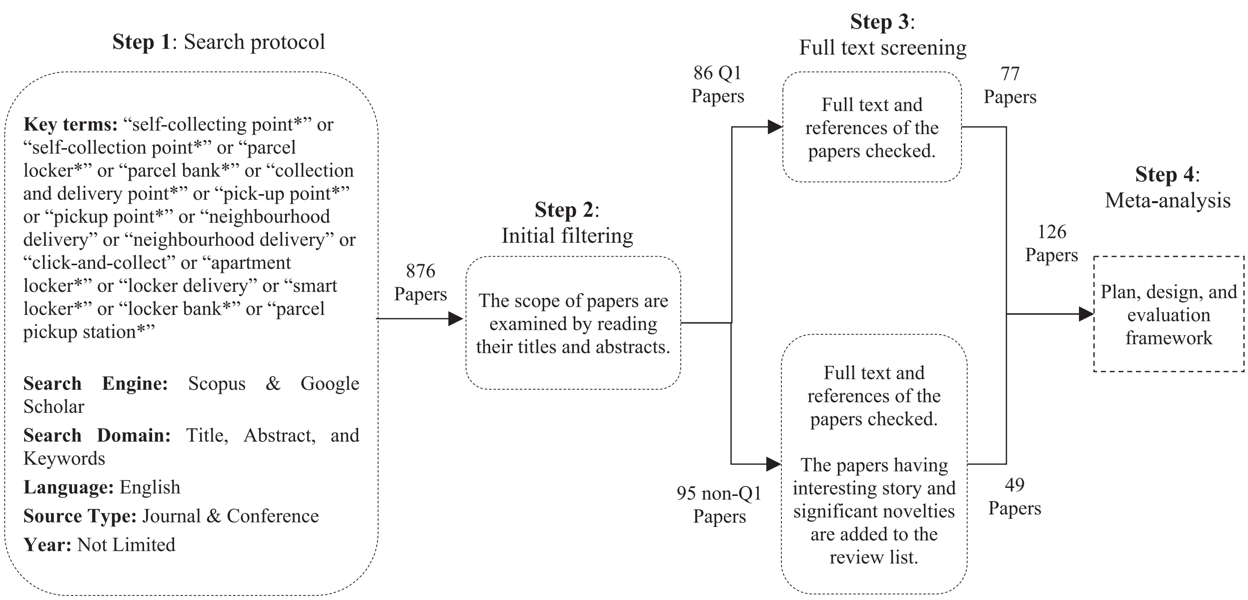

Fig. 1. Search and screening mechanism.

2. Research method

This research aims to survey the extant literature on the applications of ADPs in LMD systems and identify current and emerging topics, research gaps, and opportunities for future research. To fulfill this goal, we perform a systematic literature review (SLR), an effective and unbiased approach to contextualize the knowledge base and contribute to theory building (Pournader et al., 2021). Contrary to traditional narrative reviews that are less structured, SLRs utilize systematic procedures to examine research developments (Perera et al., 2019), which is an important feature when studying emerging research topics such as ADPs (Mohri et al., 2023). Conducting an SLR requires adopting a systematic framework to guide the search, selection, and analysis processes of relevant scholarly works. As shown in Fig. 1, we follow a four-step approach, including (1) development of search protocol, (2) initial filtering, (3) full-text scanning and (4) *meta*-analysis. The search protocol employed in this study includes papers published in English until 26 July 2024. We formulated a keyword string encompassing the most established terms used in ADP research, specifically those relating to their role and applications within LMD systems. Due to its sophisticated search engine functionality and source comprehensiveness, we opted for Scopus as our primary database (Pournader et al., 2021). It is important to note that due to the emerging and multi-disciplinary nature of ADP research, we included Q1 and Q2 journals based on the SCImago (SJR) ranking and peer-reviewed conference papers to incorporate state-of-the-art developments. In Step 1, an initial list of 876 papers was generated. In Step 2, we filtered the studies by reviewing their title and abstracts, producing a list of 86 Q1, 71 Q2 journal papers, and 24 peer-reviewed conference papers, a total of 181 papers. In Step 3, the full text of selected papers was screened, resulting in the final pool of 126 high-quality scholarly works for a full review. Finally, in Step 4, the selection of papers was surveyed and categorized according to the research framework. The search and screening mechanism, illustrated in Fig. 1, is followed to identify the targeted research papers for review.

Fig. 2(a) depicts the chronology of publications, highlighting significant growth from 2017. Surprisingly, while ADPs have been used in some European countries such as the Netherlands for more than two decades, the topic did not attract the interest of academics until 2015. Fig. 2(b) shows publication distribution by publication outlet (minimum of 2 papers). The top avenues are Transportation Research Part E, Journal of Retailing and Consumer Services, and European Journal of Operational Research.

For this SLR, we opt for a literature-driven research framework. As shown in Fig. 3, the framework serves as a vehicle to systematically identify, categorize, and examine the extant body of literature on the nexus of ADPs and LMD. As part of the search and screening process, three main research streams were revealed by which the paper is structured.

Plan: In this stream, researchers highlight the planning aspects of delivery systems with ADPs, particularly focusing on user and stakeholder behaviors, expectations, and systems capabilities. These studies inform the design features of ADP systems, such as geospatial and physical characteristics (Section 3).

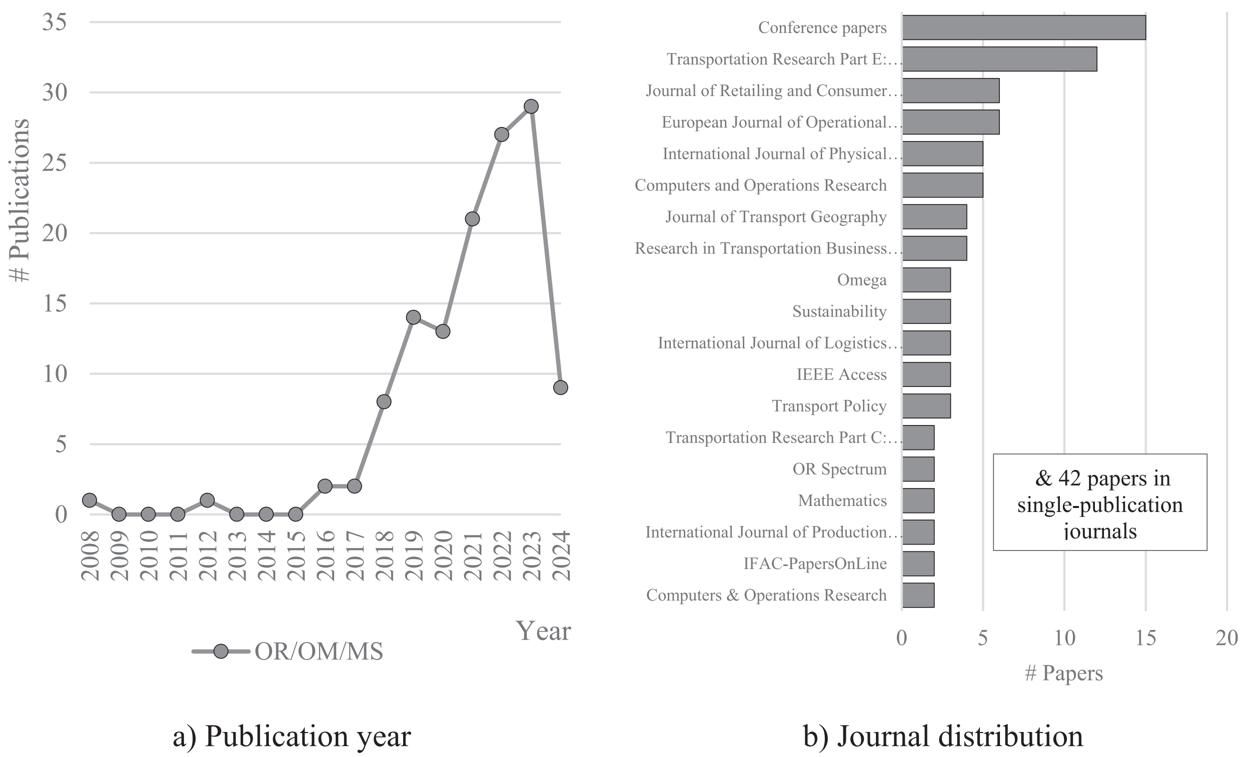

Fig. 2. Count and publication outlet.

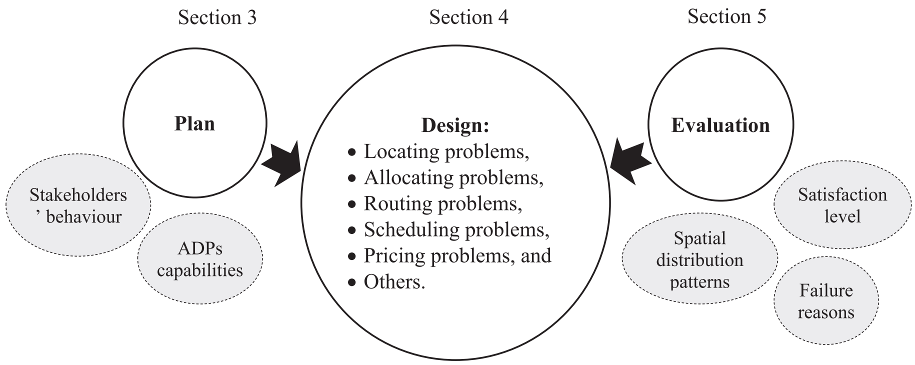

Fig. 3. Schematic of the review paper's framework.

Design: Modelling and optimizing ADP systems within urban freight networks at operational, tactical, and strategic decision-making levels dominate the studies in the planning stream. Specifically, locating, allocating, location-routing, routing, scheduling, and pricing are the main decisions of interest (Section 4).

Evaluation: In this stream, the assessments of real-world implementation of ADP systems are studied, particularly by focusing on how carriers design and use ADP systems, examination of customer satisfaction, and identification of success and failure factors (Section 5).

3. Plan

In this section, we focus on studies that aim to demystify the planning aspects of ADP systems, particularly those related to advantages, disadvantages, user behavior, and key methodologies employed.

3.1. Advantages and disadvantages of ADPs

To successfully implement LMD service involving ADPs, their perceived value must outstrip traditional delivery systems for both customers and carriers (Mohri et al., 2024c). In this sub-section, we provide an overview of the advantages and disadvantages of ADP services for different stakeholders. The literature, historically, places a particular focus on the benefits of ADPs for receivers or customers. Giuffrida et al. (2012) emphasize that ADPs could eliminate the likelihood of failed deliveries as the result of the not-at-home problem, while Iwan et al. (2016) and Oliveira et al. (2017) point to the benefits associated with greater collection flexibility (e.g., 24/7 access) and improved delivery time window, respectively. Zenezini et al. (2018) and Calabrò et al. (2023) highlight that ADPs could lead to lower delivery costs. More recently, improved parcel security and ease of returns were examined by Lee et al. (2019), Van Duin et al. (2020), and An et al. (2022). Specifically, An et al. (2022) observed a positive correlation between consumers' intention to use ADPS and their revealed experience with package and personal information loss. On the other hand, the need for additional collection trips to ADPs (Zenezini et al., 2018), loss of human contact, the complexity of the retrieval process, systems failure, and extra waiting time (Vakulenko et al., 2018), unsuitable for large and odd-shaped parcels (Faugère and Montreuil, 2020) and privacy issues as the result of sharing personal information with PL providers (Tsai and Tiwasing, 2021; An et al., 2022) have been highlighted as the barriers towards acceptance of ADP services by customers. When it comes to carriers, Zenezini et al. (2018), Lemardelé et al. (2021), Seghezzi et al. (2022), and Dong et al. (2023) highlight that ADPs could lower carriers' operational costs as the reductions in routing and dropping costs. Consequently, such outcomes could reduce fleet size and long-term staff numbers (Milewski and Milewska, 2021; Carotenuto et al., 2022). While Seghezzi et al. (2022) concluded the benefits of ADPs would be more significant in rural areas due to lower investments and costs compared to home delivery, Mommens et al. (2021) and Calabrò et al. (2023) concluded that investments in ADPs are beneficial for areas with high demand and failed delivery rate.

ADPs could also lead to ease in locating addresses and prevention of incorrect address delivery, especially in large apartment complexes (Zenezini et al., 2018). Shortened delivery time, elimination of re-delivery, and increased efficiency due to fewer drops per trip in ADP systems are other benefits for carriers (Mohri et al., 2024c). Furthermore, less interaction with residents and the public has been reported to improve delivery productivity (An et al., 2022). On the negative aspects, loss of social contact with customers (Vakulenko et al., 2018), high fixed and operational costs of running ADPs or access fees to other ADP networks (Xu et al., 2021), inadequate functionality for specific parcel configurations (Choi et al., 2021) and security issues (Quan et al., 2022) have been reported in the literature. Indirectly, ADPs benefit other stakeholders, such as local governments and the public. For instance, reduced delivery vehicle activity could result in lowered environmental and social externalities in dense urban areas (Carotenuto et al., 2018; Carotenuto et al., 2022; Pinchasik et al., 2023; Niemeijer and Buijs, 2023; Dong et al., 2023), improved energy saving and network efficiency (Milewski and Milewska, 2021) and enhanced sidewalk utilization (Mohri et al., 2024c). However, the poor harmonization and compatibility between ADP systems and urban design (González-Varona et al., 2020), along with increased transport activity and externalities related to customers' pick-up trips to ADPs (Zhang et al., 2018; Schwerdfeger and Boysen, 2020; Liu et al., 2019; Mommens et al., 2021; Gutenschwager et al. 2024), result in disadvantages for the hosting locations. A summary of the advantages and disadvantages for various stakeholders is provided in Table 1.

3.2. ADP acceptance

Many planning studies focus on understanding and measuring customers' acceptance of ADP systems. A review of these studies reveals that their findings vary depending on the geography of the studied cases. For example, the surrounding culture, environment, and geospatial configuration of transportation systems can significantly impact customers' acceptance of ADP services (Paker, 2021). Accordingly, most studies that model ADP service acceptance are case-specific and can hardly be generalized to other regions and use cases. Therefore, in this section, we review the studies based on their geography, followed by a summary of the advantages and disadvantages of ADP systems for various stakeholders.

These factors include parking availability, CDP network density, flexible operational hours, safety, security, and proximity to customers' homes or workplaces. The study also found that while customers favor CDPs, they prefer to use them only for failed deliveries unless financial incentives are offered.

Oliveira et al. (2017) conducted a survey in Belo Horizonte, Brazil, comparing the acceptance of home delivery versus automated pick-up points. Using a Multinomial Logit (MNL) model, they identified information and traceability as the most influential factors in customers' decision-making processes, followed by delivery time, cost, and location. The study found that offering pick-up points with flexible delivery times significantly increased acceptance by 4 % to 11 %, and 92 % of respondents showed a preference for locating pick-up points in supermarkets, stores, and shopping malls (Silva et al., 2019). Additionally, a majority of respondents preferred to pick up their parcels by driving to the pick-up points, with a travel time of 15–30 min.

In Singapore, Yuen et al. (2018) and Wang et al. (2019) investigated customers' intentions to use self-collection points and parcel lockers (PLs). Yuen et al. (2018) found that the demographic characteristics of Singaporean customers, such as gender, age, and employment status, did not significantly affect their intention to use self-collection points. Instead, the features of the delivery systems, including trialability, compatibility, relative advantage (positive impacts), and complexity (negative impact), were the main factors influencing acceptance. Specifically, relative advantages were characterized as reduced delivery price, sustainability benefits, and flexibility in parcel collection. Wang et al. (2019) identified that 24/7 access to PLs, short waiting times, and en-route delivery options were the most influential factors motivating customers to accept self-collection services.

In Brussels, Belgium, Rai et al. (2020) explored how consumers use CDPs and their travel habits to and from these points. Their study revealed that 72 % of participants view CDPs as a solution for failed home deliveries, with the majority choosing to travel to these points by car, followed by public transport, walking, and cycling. Most respondents preferred to combine parcel collection with existing trips, traveling less than 15 min to collect their parcels.

Table 1
An overview of ADPs' advantages, disadvantages, and implementational barriers.

	Advantages	Disadvantages
Receivers	• Lowered delivery cost (Zenezini et al., 2018).Greater collection flexibility, such as 24/7 access (Iwan et al., 2016).Improved delivery time window (Oliveira et al., 2017).Eliminating failed delivery (Giuffrida et al., 2012; Calabrò et al., 2023).Enhanced parcel security (Lee et al., 2019; An et al., 2022) Ease of returns (Van Duin et al. 2020)	• Requires additional trips to PLs (Zenezini et al., 2018)Loss of human contact (Vakulenko et al., 2018)Privacy issues and sharing of personal information with PL providers (Tsai and Tiwasing, 2021)Waiting time at ADPs (Vakulenko et al., 2018)Retrieval process complexity (Vakulenko et al., 2018) Potential systems failure, including hardware and software components (Vakulenko et al., 2018)Unfit for heavy and large parcels (Faugère and Montreuil, 2020)
Carriers	• Lowered routing costs (Lemardelé et al., 2021; Dong et al., 2023) Shortened delivery time (Mohri et al., 2024c)Elimination of re-delivery (Calabrò et al., 2023)Increased delivery volume per trip (Mohri et al., 2024c)Reduced fleet size and staff number (Milewski and Milewska, 2021; Carotenuto et al., 2022) Elimination of incorrect address delivery (Zenezini et al., 2018).Ease of navigation and delivery in large buildings (Mohri et al., 2024c Less unnecessary interactions with residents and the public (An et al., 2022)Facilitate transshipment among carriers (Ghaderi et al., 2022b; Pan et al., 2021)	• Loss of social contact with customers (Vakulenko et al., 2018) High fixed and operational costs of ADPs or access fees to other networks (Xu et al., 2021)Inadequate functionality for specific product types (Choi et al., 2021)Security challenges (Khokher et al., 2023)
Government & public	• Reduced delivery vehicle activity resulting in lowered externalities (Carotenuto et al., 2018; Carotenuto et al., 2022; Niemeijer and Buijs, 2023; Dong et al., 2023)Energy saving and network efficiency (Milewski and Milewska, 2021) Improved sidewalk utilization (Mohri et al., 2024c)Reducing social damage costs due to Alleviating traffic congestion (Pinchasik et al., 2023)	• Lack of fitness between ADP and urban design (González-Varona et al., 2020)Increased externalities associated with customers pick-up trip to ADPs (Zhang et al., 2018; Schwerdfeger and Boysen, 2020; Liu et al., 2019; Mommens et al., 2021; Gutenschwager et al., 2024)

In Brussels, Belgium, Rai et al. (2020) explored how consumers use CDPs and their travel habits to and from these points. Their study revealed that 72 % of participants view CDPs as a solution for failed home deliveries, with the majority choosing to travel to these points by car, followed by public transport, walking, and cycling. Most respondents preferred to combine parcel collection with existing trips, traveling less than 15 min to collect their parcels. Milioti et al. (2020) examined the intention to use click-and-collect services in Greece. Their study found that high-income respondents and elderly individuals were less likely to use these services, while those with environmental concerns and prior experience with failed home deliveries were more likely to accept them. Additionally, respondents who frequently traveled to the city center by car showed a higher likelihood of acceptance due to the convenience of collecting their orders on the way home.

In Turin, Italy, Mitrea et al. (2020) investigated the socio-economic characteristics of automated PL users and their locational preferences. They found a negative correlation between PL use and several socio-economic characteristics, including age over 66, large families, and frequent online shoppers. However, flexibility in collecting parcels and the sustainability benefits of PLs were identified as key factors driving their use, particularly when PLs were conveniently located near homes, workplaces, or on routine trips. In another study using MNL, Iannaccone et al. (2021) studied young residents in Rome, Italy, to compare preferences between home delivery and PLs. Their findings indicated a general preference toward home delivery, but offering longer access hours, incentives, and environmentally friendly services increased the acceptance of PLs. The study also found that consumers were willing to pay more for closer lockers, 24/7 access, and sustainable delivery options.

Tsai and Tiwasing (2021) explored consumers' intentions to use smart PLs in Thailand and found that complexity and data privacy concerns were significant barriers. However, the relative advantages of PLs, such as flexible delivery times, incentives, and lower costs, were identified as positive factors that can enhance acceptance. Recently, Molin et al. (2022) used a choice survey to analyse factors (i.e., delivery price, delivery time (date/time), opening hours, and distance to collection facilities) influencing the acceptance of home delivery, service points, and PLs in the Netherlands. Their study showed that price was the most influential factor, with even slight increases leading to lower acceptance of service points and PLs. The study also found that older respondents were willing to pay more for human-operated service points and that increasing the distance to PLs or service points reduced their acceptance.

Kim and Wang (2022) investigated how residents of New York City adapt to ADPs, focusing on the distance they are willing to travel to collect parcels. Based on the New York City (NYC) Department of Transportation (DOT) Citywide Mobility Survey in 2018 and utilizing binary and ordered probit models, their study found that increasing parcel delivery frequency reduced adaptation but did not change the distance customers were willing to travel. Demographic factors, such as income and education levels, played a critical role, with males and full-time students willing to travel longer distances, while elderly and apartment residents preferred shorter trips.

Rossolov (2023) measured the probability of choosing between home delivery and post office delivery in Ukraine. The study revealed that higher income and the number of working households were associated with lower acceptance of post office delivery while increasing age would enhance acceptance. Furthermore, proximity to post offices was a significant factor, and certain commodities, like perfumes and electronics, were more likely to be delivered to post offices. In another study, Chen et al. (2023) investigated the impact of smart lockers (pull factor) on senders' intentions to switch from traditional to home deliveries. The findings suggest that express couriers can enhance the attractiveness of smart lockers by prioritizing reliability and convenience and implementing targeted marketing strategies to affect user interest.

Neto et al. (2023) in São Paulo, Brazil, explored the impact of income inequality on consumer behavior toward pick-up point services. Their study found that lower-income groups strongly preferred pick-up points due to delivery issues, while higher-income segments preferred home delivery.

Chen et al. (2014) in Nanjing, China, examined consumer preferences between stationary and mobile PLs. The study found that access distance was a critical factor, with a general preference for stationary PLs, especially among older consumers. Younger consumers were more willing to try mobile PLs. Finally, Jang et al. (2024) studied consumer adoption of automated PL systems in Seoul, Korea, during COVID-19. They found that the perceived risk of COVID-19 increased the perceived usefulness of PL systems, leading to higher adoption rates. Distrust reduced perceived usefulness and adoption, while innovativeness and user experience positively influenced adoption.

The following general insights can be then provided regarding the factors impacting the acceptance of ADPs:

- Main influential factors – Among different factors, the availability of parking, network density, operational flexibility, safety, proximity, information and traceability, delivery time, cost, and service convenience are the key influential factors.
- Geographical factors – Customer acceptance of ADP systems is highly dependent on the geographical context, with factors such as culture, environment, and transportation infrastructure playing significant roles. Additionally, each study provides insights specific to its region, showing that while certain trends are global, the implementation of ADP systems must consider local socio-economic conditions and customer expectations to be successful.
- Demographic factors – Factors such as age, income level, education, and employment status play a crucial role in shaping customer preferences toward ADP services. These factors often interact with other elements, such as price sensitivity and the convenience of service locations.
- Technological and environmental factors – Technological adoption, as influenced by the perceived complexity and relative advantages of ADP systems, as well as environmental concerns, can significantly affect customer behavior. Flexibility, sustainability, and the perceived risk during events like the COVID-19 pandemic further modulate acceptance rates.
- Customer preferences – The preferences for delivery methods (home delivery vs. pick-up points) and the locations of these services vary significantly across different regions, reflecting the specific needs and behaviors of the local population.

3.2.1. Key methodologies

Researchers have used qualitative and quantitative approaches to model acceptance and behavioral factors associated with ADP use (Table 2). However, quantitative methods remain the prevalent approach. In the stream of qualitative methods, Kedia et al. (2017) used interviews to capture stated preferences to measure ADP service acceptance. Interviews are beneficial when applying grounded theory, which is less known in the literature. Within qualitative studies, the works of Wang et al. (2019) opted for a questionnaire using the Kano model.

On the other hand, quantitative models have received attention for modeling ADP acceptance and use, whereas discrete choice (DC) modeling is a popular technique. However, basic choice modeling methods such as MNL mostly estimate the acceptance probability. While mixed models, latent-class choice models, and choice models with latent variables basic assumptions of MNL models, they have been applied less. These advanced choice models can better define the distribution of error terms in choice models, explore the nonlinear correlation between dependent and independent variables, model interactions between independent variables, and capture heterogeneity in preferences. Studies such as Green and Hensher (2003), Hensher et al. (2005), and Louviere et al. (2009) provided important insight into how such models can be applied to ADP acceptance models. From the data viewpoint, existing studies rely on primary data collected through questionnaires. Therefore, using real-world data collected from smart PLs as a secondary source (revealed data) could provide important insights that are missing in the literature. Future studies could even leverage a mixture of stated and revealed data sources.

3.2.2. User and service attributes impacting ADP use and acceptance

The literature has identified several attributes that impact ADP use and acceptance probability. Principally, these attributes can be linked to service or user characteristics, with many studies aimed to demystify the relationship between them.

Several attributes in service configuration are known to influence ADP acceptance positively. According to Rai et al. (2020) and Silva et al. (2019), improving the accessibility of ADP services increases the likelihood of acceptance. Additionally, Iannaccone et al. (2021) and Oliveira et al. (2017) suggest that extending the working hours of ADP facilities can lead to increased usage. Literature also highlights the effectiveness of offering incentives or lower delivery fees (Silva et al., 2019; Yuen et al., 2018) in improving ADP acceptance. Table 3 summarizes the attributes identified by the studies in the literature.

Among the other service attributes providing parking facilities around ADPs (Kedia et al., 2017), improving ADPs' sustainability aspects (Mitrea et al., 2020), and reducing parcel retrieval complexity (Tsai and Tiwasing, 2021), mainly from automated and smart PLs, are known to encourage ADP services acceptance by customers. Furthermore, there exist intricacies between carriers' decisions when designing service configurations. For example, to improve accessibility, carriers need to invest in a large number of ADP locations, resulting in high fixed and operational costs. Accordingly, the higher cost potentially would no longer allow for offering financial incentives or extended working hours. Therefore, understanding users' behavioral considerations is key to determining the optimal service configuration.

Regarding user attributes, the literature discusses factors that relate to employment status, age, income, marital status, online shopping, and knowledge and experience with ADP systems. However, there exist opposite views among researchers, predominantly because of socio-economic and contextual factors associated with the region of study. For example, while Rossolov (2023) and Kim and Wang (2022) concluded that a lower level of education is associated with higher ADP acceptance probability, Iannaccone et al. (2021) and El Moussaoui et al. (2022) believed in the opposite. Similarly, Rossolov (2023) concluded senior adults would probability better accept ADP services, while Rai et al. (2020), Milioti et al. (2020), El Moussaoui et al. (2022), and Kim and Wang (2022) indicated that younger people depict a higher degree of accepting ADP services. Milioti et al. (2020) and Kim and Wang (2022) stated that frequent online shopping would lower the acceptance of ADP services. On the other hand, Rai et al. (2020) concluded that such behavior is linked to improved acceptance. While the cultural, environmental, and economic factors of participants in these studies could have led

Table 2
Summary of key methodologies.

Reference	Method	Data	Analysis
Kedia et al. (2017)	Content analysis	Interview	Qualitative
Wang et al. (2019)	Kano model	Questionnaire	
Tsai and Tiwasing (2021)	Resource matching theory, innovation diffusion theory, and theory of planned behavior		
Mitrea et al. (2020)	Descriptive methods	Questionnaire	Quantitative
Rai et al. (2020)	Descriptive methods		
Yuen et al. (2018)	Hierarchical regression		
Oliveira et al. (2017)	DC: MNL		
Silva et al. (2019)	DC: MNL		
Milioti et al. (2020)	DC: MNL		
Iannaccone et al., (2021)	DC: MNL		
Kim and Wang (2022)	DC: Binary and Ordered Probit		
Molin et al. (2022)	DC: Mixed Logit		
Rossolov (2023)	DC: Mixed Logit		
Chen et al. (2023)	PLS-SEM		
Neto et al. (2023)	PLS-SEM		
Chen et al. (2014)	DC: MNL & Mixed logit		
Jang et al. (2024)	SEM		

Table 3
Factors impacting the probability of accepting ADP services.

References	Case	Service attributes											Users' attributes																
		Increasing access /accessibility to ADPs	Increasing ADPs' working hours	Decreasing delivery fees/offering incentive	Providing parking around ADPs	Improving sustainability aspects of ADP	Deceasing complexity in using ADP service	Providing attended ADPs	Proving errorless and reliable ADP service	Protecting the privacy of ADP users	Providing safe and secure ADP service	Proving parcel traceability	Single	Income = Low	Income = High	Education Level= Low	Education Level= High	Age= Senior adult	Young adult	Household size = Large	Employment status: Full-time student	Gender = Male	Dwelling type = Apartment	Employment status = Employed	Staying at home/working from home	Frequently shop online	Experiencing ADP delivery	Caring for sustainability aspects	Experiencing unsuccessful home delivery
El Moussaoui et al. (2022)	Morocco																+		+					+					
Kim and Wang (2022)	The US													+		+		–			+	+	–			–			
Molin et al. (2022)	Netherlands	+	+	+				+																					
Rossolov (2023)	Ukraine	+	+	+													–	+	–		+			–					
Tsai and Tiwasing (2021)	Thailand		+	+			+		+	+																			
Mitrea et al. (2020)	Italy	+	+			+																							
Iannaccone et al. (2021)	Italy		+	+		+		+									+								–		+		
Kedia et al. (2017)	New Zealand	+	+	+	+						+																		
Oliveira et al. (2017)	Brazil		+	+	+							+																	
Silva et al. (2019)	Brazil	+	+	+	+																								
Yuen et al. (2018)	Singapore	+	+	+		+	+																						
Wang et al. (2019)	Singapore	+	+				+																						
Rai et al. (2020)	Belgium	+			+								+						+							+			
Milioti et al. (2020)	Greece														–			–								–		+	+

to such conflicting views, study design could also be instrumental. Table 3 summarizes both user and service-related attributes and their impact on the acceptance and use of ADP services. In this table, green cells indicate attributes that positively impact acceptance probability, while red cells signify a negative impact. Uncolored (white) cells represent attributes that were not investigated in the study.

Broadly speaking, the main takeaways about the impact of user and service characteristics on the acceptance of ADPs can be listed as follows:

Here are the main important insights from the text:

- In terms of user characteristics, employment status, age, income, marital status, online shopping habits, and familiarity with ADP systems significantly impact ADP acceptance, with varying impacts based on socio-economic and regional contexts.
- In terms of service characteristics, key service attributes that positively influence ADP acceptance include improving accessibility, extending working hours, offering incentives or lower delivery fees, providing parking facilities, enhancing sustainability, and reducing parcel retrieval complexity.
- In terms of challenges, carriers face trade-offs in service design, such as balancing the need for more ADP locations (which increases costs) with the ability to offer financial incentives and extended hours.
- Finally, there are contradictory views among researchers regarding the influence of education level, age, and online shopping frequency on ADP acceptance, highlighting the role of contextual factors and study design in these differences.

4. Design

Designing urban freight distribution systems (UFDSs) with ADPs is the most general research area for OR researchers, and it has many published papers. Design models optimize various decisions across three levels of decision-making: *strategic*, *tactical*, and *operational*. Furthermore, in this category, we cover problems and topics relating to the day-to-day operations and functional configurations of ADPs, including physical configuration. The corresponding stakeholders of these decisions vary based on the problem specifications. For instance, ADP networks are sometimes deployed by carriers, third-party logistics providers, or local governments, each having different objectives. Table 4 presents a high-level comparison of design model decisions, highlighting the stakeholders involved and the decision-making levels associated with each decision.

Delivery address setting – ADPs provide customers with a range of options for their preferred delivery locations. Accurately determining customers' locational preferences is essential for effectively designing UFDSs with ADPs. Typically, in design models, customers are viewed as followers, and ADP network providers re leaders. The network provider must consider customer preferences and selection probabilities when determining optimal ADP locations. This information is essential and typically serves as a critical input in ADP location optimization. Accordingly, decisions related to delivery address setting are primarily related to determining the optimal spatial configurations (subsection 4.1).

ADP configuration setting – In this category, through various location-based problems, the ADP configuration setting decisions are optimized. Predominantly, these decisions are sometimes made by carriers such as Amazon, InPost, and Australia Post (Fang et al., 2019; Iwan et al., 2016). At a national scale, the ADP locating decision is sometimes made by government stakeholders such as the Singaporean "Locker Alliance" program concerning the optimal locations of PLs by various providers in Singapore (Lin et al., 2020). In some cases, specialized PL providers such as Luxer One in the United States and Groundfloor in Australia locate on-premises PLs (OPLs) (Ranjbari et al., 2023a; Mohri et al., 2024c). Locating decisions can be made at strategic, tactical, or operational levels. For example, large-scale deployment of stationary ADPs, like post offices, is considered a strategic decision. At the same time, the placement of mobile ADPs and PLs can be classified as tactical or operational, depending on the network's size and scale and the frequency of location adjustments (Schwerdfeger and Boysen, 2022). In addition to location identification, other secondary decisions can be included, such as configuring the facilities (e.g., capacity and type of ADP facilities), price setting, incentivization, and scheduling services (sub-section 4.2).

Vehicle routing – The third preliminary decision, known as routing, differs from traditional routing decisions that can be solved as Travelling Salesman Problems (TSPs) or Vehicle Routing Problems (VRPs). Instead, ADP routing formulations are based on the Generalized VRP (GVRP) or Generalized TSP (GTSP) due to the possibility of delivering a customer's parcel to multiple delivery points, such as their home and ADPs, where only one can be activated (Dumez et al., 2021). In GTSP or GVRP, nodes are partitioned into clusters, and route(s) must pass through only one node in each cluster. This problem integrates two simultaneous decisions of *node selection* and *node sequencing* (Laporte, 1988). Other secondary decisions, such as vehicle scheduling, fleet assignment, and fleet

Table 4
Primary decisions for designing UFDSs with ADPs.

Decision	Decision making level	Stakeholders	Section number
Delivery address setting	Operational	Customers	Section 4.1
ADP configuration setting	Strategic, tactical or operational	Government, carriers, or 3PL(s)	Section 4.2
Vehicle routing	Tactical or operational	Carriers	Section 4.3
Hybrid models (combinations of delivery address setting, vehicle routing, and ADP configuration setting)	Strategic, tactical or operational	Customers, government, carriers, or/and 3PL(s)	Section 4.4

planning, could be incorporated and optimized in such problem formulations (subsection 4.3).

The literature of city logistics reports on hybrid problems such as ADP location and vehicle routing as a single model (Enthoven et al., 2020). Such integration primarily leads to a multi-stakeholder decision-making problem since vehicle routing is the carrier's responsibility while locating ADP can be performed by other stakeholders, such as local governments or specialized PL providers. (subsection 4.4).

4.1. Delivery address setting

Setting the delivery address for customers is a key consideration when designing UFDSs with ADPs, and various techniques are utilized by researchers (Table 5). A group of researchers reflects on customer delivery address settings using a set of simplistic constraints based on generic operations research models. In particular, "Declared ranking," as one of the prevalent techniques, considers

Table 5
Existing techniques for delivery address setting.

Type	Name	Definition	Available Delivery options	References	Problem
Constrained-based techniques	Declared ranking systems	Assuming ranked delivery options are provided by customers in advance.	ADP and home	Tilk et al. (2021), Dumez et al. (2021)	RP
				Janjevic et al. (2021)	LPR
	Cut-off distance function	Each ADP has a specific coverage distance, and all customers within that distance will accept the ADP service.	ADP	Xu et al. (2021), Kahr (2022), Jiang et al. (2022)	LP
				Ulmer and Streng (2019)	RP
				Veenstra et al. (2018), Hong et al. (2019), Leyerer et al. (2020), Janjevic et al. (2019), Schwerdfeger and Boysen (2020), Schwerdfeger and Boysen (2020)	LRP
	Inverse distance function	ADP selection probability is inversely proportional to the distance from the customer.	ADP	Deutsch and Golany (2018)	LP
				Jiang et al. (2019)	RP
	Conditional choice models	The probability of customers selecting a locker delivery versus home delivery, as well as the probability of choosing a specific ADP from a set of options, are calculated using binary logit and MNL models. Combining these models leads to the probability of a customer selecting a particular ADP when home delivery is also available.	ADP and home	Lyu and Teo (2022)	LP
Objective function-based techniques	Single-level optimization with choice models	ADP selection probability is calculated via logistic regression with a single variable: distance from customer to ADP. Using the probability, ADP service level is calculated and maximized by the objective function.	ADP	Lin et al. (2020)	LP
		A distance decay function sets the attractiveness of ADPs. The function is used later in choice models (e.g., MNL) to calculate the probability of accepting ADPs. ADP provider's profit is then maximized.	ADP and home	Lin et al. (2022)	LP
	Single-level optimization with disutility compensation	Assigning customers to ADPs incurs a penalty cost, which represents the compensation fee for preferring ADP delivery over home delivery.	ADP and home	Sitek and Wikarek (2019)	RP
		Compensation is limited to customers within a specific coverage distance around ADPs.	ADP and home	Mancini and Gansterer (2021)	RP
		The penalty cost (compensation fee) increases linearly with travel distance to ADPs.	ADP and home	Enthoven et al. (2020)	LRP
	Multi-objective optimization with cut-off distance	Accessibility to ADP is maximized using a distance decay function, which restricts access to only those customers within the coverage distance of the ADPs based on the cut-off distance function.	ADP	Luo et al. (2022a)	LP
	Bi-level optimization	The lower level minimizes customer travel distances to ADPs to set appropriate ADPs for customers.	ADP	Yang et al. (2020)	LP

LP: Locating problem; LRP: Location-routing problem; RP: Routing problem.

ADP acceptance as a known variable. In this context, Tilk et al. (2021), Dumez et al. (2021), and Janjevic et al. (2021) assumed that customers provide a ranking preference for home and ADP delivery options in advance. Therefore, the design models attempted to provide delivery options with the highest possible customer ranks. While this technique could be used in a situation involving fixed ADP locations, it can hardly be applied to problems with mobile or many potential ADPs.

The cut-off distance, time, or cost constraints approach is a simple and common method for determining ADP acceptance (Veenstra et al., 2018; Hong et al., 2019; Schwerdfeger and Boysen, 2020), where customers within a specified range are assumed to accept the service. However, many studies have modeled ADP acceptance probabilistically (Yuen et al., 2018; Oliveira et al., 2017; Silva et al., 2019; Milioti et al., 2020; Iannaccone et al., 2021), using distance as an explanatory variable, making the cut-off technique less applicable in real-world scenarios. To address this limitation, researchers like Deutsch and Golany (2018) and Jiang et al. (2019) suggested using a linear inverse distance function, where the probability of ADP acceptance decreases linearly as distance increases.

In this context, constraints in optimization models can be reflected in the objective function, such as a penalty function or Lagrangian relaxation. Sitek and Wikarek (2019), Enthoven et al. (2020), and Mancini and Gansterer (2021) used a penalty function to model the probabilistic nature of acceptance. They assumed assigning customers to ADPs incurs an additional cost as compensation for substituting home addresses with ADPs, using single-objective optimization models in which penalty costs are incorporated into the objective function. Sitek and Wikarek (2019) and Mancini and Gansterer (2021) considered the penalty costs are fixed without variation in the travel distance imposed on customers to collect their parcels from ADPs, while Enthoven et al. (2020) assumed that the penalty costs increase linearly. It's important to note that while these methods can effectively incorporate constraints into the objective function, they may introduce additional challenges, such as convergence issues or sensitivity to penalty coefficients. Hence, setting the penalty coefficients remains a challenge in this domain. Also, since the penalty costs might change depending on the characteristics of both parcels and receivers, it is recommended that future studies consider the expected value or the worst-case value of the penalty costs in their design models. Deutsch and Golany (2018), Jiang et al. (2019), and Enthoven et al. (2020) modeled ADP acceptance as a linear function of distance, capturing its probabilistic nature. However, Lin et al. (2020), Lyu and Teo (2022), and Lin et al. (2022) suggested using logit models to calculate acceptance probability based on the attractiveness of choices. Lin et al. (2020) and Lyu and Teo (2022) used linear functions of distance, while Lin et al. (2022) applied a nonlinear distance decay function. These logit models are better suited for capturing the nonlinear relationship between ADP acceptance and factors such as parcel characteristics and service complexities. Yang et al. (2020) proposed a bi-level optimization model for locating ADPs, which focuses on minimizing total travel costs between customers and ADPs. However, this could lead to assigning customers to ADPs beyond acceptable distances. To address this, Luo et al. (2022a) proposed a bi-objective model that integrates home delivery as an option for customers located too far from ADPs and aims to maximize customer accessibility while minimizing both fixed and variable costs of ADP facilities. Future studies should integrate multi-variable choice models into ADP system design.

4.2. ADP configuration setting

Various organizations provide ADP services, including carriers, local and national governments, and firms that provide PL solutions. At the broadest level, the preliminary decision associated with ADP service provision involves determining the type, location, and capacity. Furthermore, other considerations such as routing vehicles, pricing or incentivizing services, configuring locker compartment types, setting, scheduling, and partnering (e.g., with supermarkets or libraries) for ADP placement are also core to providers' decision-making. This research categorizes such decisions, as shown in Fig. 4, under the 'ADP configuration setting' domain.

4.2.1. ADP locating

The study of Deutsch and Golany (2018) is one of the first to minimize the cost of an ADP network using a mixed integer linear locating problem, which primarily decides whether to open a PL facility. The costs of opening PLs include fixed and operational expenses, while not opening them results in lost potential profits minus the expected cost of discounting PL delivery fees for customers. The discounting cost is calculated based on the probability of customers accepting the service, which is inversely proportional to the distance from the locker.

Yang et al. (2020) approached PL location optimization as a leader–follower game, formulating a bi-level optimization model. The

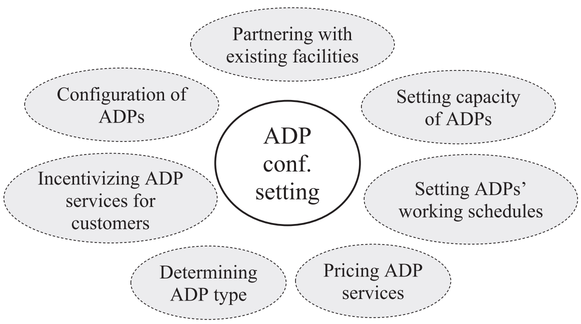

Fig. 4. Location problem decisions.

upper level locates PLs while minimizing PL construction, operating, transportation, and penalty costs. The lower level assumes customers choose the closest PL, minimizing their collection costs. This model was solved using a genetic algorithm (GA) in a case study in Hunan Province, China, identifying 12 optimal PL locations. Yang et al. (2023) later modified the model to maximize the profit of a third-party PL provider.

Lin et al. (2020) proposed a model to maximize the expected service level of deployed PLs, defined as the proportion of customers likely to accept PL services, using an MNL approach. The study, inspired by Singapore's "Locker Alliance" program, considers both PLs and existing Pick Own Parcel (POP) Stations, deciding where to locate new PLs and close some POP Stations. The model is linearized for small cases and enhanced with McCormick inequalities for larger ones. The findings emphasize the critical impact of accurately modeling customer behavior in choosing ADPs.

Xu et al. (2021) proposed a model for locating CDPs by applying data mining techniques to historical shopping records to account for dynamic delivery demand. Their model uses a cut-off distance function to allocate customers to CDPs, ensuring that each customer is covered by at least one CDP. The objective is to minimize the operational costs of CDPs while maintaining a specified coverage level. The study found that reducing coverage levels exponentially increases total costs.

Luo et al. (2022a) expanded on this by proposing a bi-objective model that minimizes locker facility costs (locker purchase and setup costs) while maximizing accessibility and solved the model using an active-learning Pareto evolutionary algorithm with a case study from Shenyang, China. The finding showed that solutions are highly sensitive to the maximum acceptable walking distance. Che et al. (2022) introduced a multi-objective optimization framework for PL locations, aiming to maximize coverage, minimize overlap, and reduce idle capacity. After solving the model using a combination of the Taguchi method (TA) and nondominant sorting GA II (NSGA-II), the results showed that focusing solely on coverage does not improve facility utilization; a more balanced approach is more effective.

Lin et al. (2022) and Lyu and Teo (2022) expanded on the work of Lin et al. (2020) by refining the locker acceptance probability model. Lin et al. (2022) introduced an outside alternative to home delivery into the set of locker delivery options, which has a fixed attractiveness in the MNL model. To simplify the complexity of the MNL, they applied the threshold Luce model (TLM), which excludes dominated locker alternatives based on a comparison of attractiveness. In this model, a locker option A dominates another B if its attractiveness exceeds $1 + \lambda$ times B's attractiveness, where $0 \leq \lambda$ is the threshold Luce parameter. The attractiveness of locker alternatives was modeled using a gravity model with a distance decay function. The authors proposed a locating problem aimed at maximizing total expected profit by covering the maximum expected demand. They developed an exact solution using a conic formulation strengthened with path-based inequalities. The results showed that the BNL and MNL models provided pessimistic and optimistic revenue estimates, respectively, while the TLM offered more realistic solutions.

Lyu and Teo (2022) examined locker delivery data in Singapore and identified a cannibalization effect among existing PLs. They modeled the probability of selecting a PL based on the choice between locker and home delivery using MNL models. In their locker choice model, only the third root of distance and locker type (binary variable for proximity to mass transit and shopping malls) were significant. They proposed a locating problem to minimize undelivered parcels, ensuring every household has access to a locker within 250 m. Their model, tested with a cap of 1500 PLs, revealed that placing PLs only in the central business district (CBD) would increase delivery demand there, shifting 17.5 % of home deliveries to lockers. Conversely, excluding the CBD and placing lockers near homes rather than workplaces would reduce CBD delivery demand by at least 7.5 %.

Peppel and Spinler (2022) tackle environmental and cost challenges in LMD through a novel stationary PL network design. Using observed PL delivery data, the authors employed an MNL model to gauge recipients' inclination towards PL use based on home availability and travel distance. Subsequently, they developed a mixed-integer linear programming model to identify the optimal PL locations. Results indicate that optimal stationary PL placements could yield significant carrier cost savings of up to 11.0 %. At the same time, PLs could reduce CO2 equivalent (CO2e) emissions in urban areas by up to 2.5 % while increasing emissions by 4.6 % in less populated regions due to longer pick-up travel distances.

Studies have explored ADP facility placement under uncertainty (Wang et al., 2022a; Yalcin Kavus et al., 2023; Mancini et al., 2023). Wang et al. (2022) used robust optimization to identify resilient PL locations amidst demand uncertainty, achieving minimal cost increases. Yalcin Kavus et al. (2023) applied a hybrid fuzzy MCDM approach combining the Bayesian Best Worst Method (B-BWM) with Pythagorean fuzzy Weighted Aggregated Sum Product Assessment (PF-WASPAS) to evaluate five sites in Istanbul, using thirty-two sub-criteria in six categories. Similarly, Mancini et al. (2023) addressed PL location under uncertain demand and capacity by developing a two-stage stochastic model for maximum coverage with a fixed number of facilities. Their approach aimed to maximize customer assignments and minimize average distance to PLs, considering capacity reductions. Using heuristics on a case study in Turin, Italy, they found that strategically placed stationary lockers work best in low variability scenarios, while mobile PLs are more suitable for high variability in demand and supply.

Moslem et al. (2024) proposed an MCDM model to optimize PL placements in Dublin, Ireland, using the Decomposed Fuzzy Analytical Hierarchy Process (DF-AHP) and Decomposed Fuzzy Combinative Distance-Based Assessment (DF-CODAS) methods. Considering five criteria of reliability, accessibility, traffic and operation, security, and environmental impact, this study found post offices to be the best locations for PLs, followed by private car parking, public transport stops, commercial areas, high population density areas, and pedestrian zones. Table 6 provides a summary of ADP locating issues, including methods, case studies, data, and solution algorithms, with a focus on optimization techniques and their associated features.

4.2.2. Capacity and configuration of ADP facilities

Due to spatiotemporal uncertainties in demand, customer behavior, environmental factors, and operational requirements, ADP systems often face challenges with under- and over-capacity. These uncertainties hinder optimal capacity determination, leading to

Table 6
Key aspects of locating studies.

Study	Modelling technique	Objectives												Constraints			Decision		Case study	Solution algorithm
		Min: ADP setup costs	Min: Compensation costs	Min: Customers access costs	Min: ADP operational costs	Min: ADP environmental costs	Min: ADP over-utilization costs	Max: ADP profit for supplier	Max: ADP users' satisfaction	Max: ADP service level	Min: Unmet demand by ADPs	Max: ADP coverage	Min: Number of ADPs	Full ADP coverage	Limited number of ADPs	ADP capacity restriction	Location & allocation	ADP capacity		
Deutsch and Golany (2018)	MILP	*	*											*			*		H	CS
Yang et al. (2020)	BMILP	*		*	*		*									*	*		R	GA
Yang et al. (2023)	BMILP							*	*							*	*		R	GA
Luo et al. (2022a)	SP																*		R	-
Che et al. (2022)	MMILP			*									*				*		H	NSGA-II
Lin et al. (2022)	NP							*									*		H	E
Wang et al. (2022a)	RO	*			*												*	*	H	CS
Yalcin Kavus et al. (2023)	MCDM																*		R	-
Mancini et al. (2023)	MILP			*								*				*	*		H&R	TS, VNS
Lyu and Teo (2022)	RO										*			*			*		R	E
Lin et al. (2020)	MILP									*					*		*		H	CS
Xu et al. (2021)	MILP				*									*			*		H	E
Peppel and Spinler (2022)	MILP	*			*	*										*	*		H	CS
Moslem et al. (2024)	MCDM																*		R	

BMILP: Bi-level mixed integer linear programming; CS: Commercial solvers; E: Exact; H: hypothetical; MCDM: Multi-criteria decision making; MILP: Mixed integer linear programming; NSGA-II: Non-Dominated Sorting GA II NP: non-linear programming; R: Real; RO: Robust optimization; TS: Tabu search; VNS: Variable neighborhood search.

asset under-utilization and increased costs. Specifically, parcel size, which affects PL configuration (e.g., form factor, size, number of lockers, type), is unpredictable in advance (Faugère and Montreuil, 2020). This section discusses the solutions in the literature to address these issues. Faugère and Montreuil (2020) linked PL providers' profit to PL configuration, defining it as revenue from servicing orders minus ergonomic, space acquisition, and implementation costs. They proposed two mathematical models for optimizing PL configurations with fixed and modular capacities. Results indicated that both fixed and modular locker banks can yield similar profits for providers.

In contrast, Faugère et al. (2022) explored the dynamic deployment of modular, relocatable PLs under time–space uncertainty. Their study focused on modular locker configurations placed at access hubs, connecting riders with couriers or parcel receivers. Riders handle deliveries between depots and access hubs, while couriers manage LMD and collection. To address dynamic demand and optimize storage, the authors proposed a two-stage stochastic optimization model for adjusting locker capacity. This model aims to minimize system costs, including PL capacity deployment, relocation, and routing costs. Using rolling horizon and Benders Decomposition algorithms, results demonstrated a reduction in LMD costs and increased PL capacity utilization by up to 28 % and 26 %, respectively, improving the management of lockers in uncertain demand scenarios.

Grabenschweiger et al. (2021) proposed that parcels from single or multiple carriers can be combined in a single locker without reducing customer compensation, thus improving PL utilization. They introduced a VRP with either home or PL delivery, using heterogeneous locker sizes. Their objective was to minimize carrier routing and compensation costs. The model, solved with an adaptive large neighborhood search (LNS) algorithm, showed that multi-size lockers result in fewer direct deliveries compared to standard-size lockers in large networks. Schnieder et al. (2021) suggested integrating staffed CDPs with a PL network to reduce idle locker capacity during low-demand periods. They proposed a model to determine the optimal number of lockers at each CDP, aiming to minimize total locker and staff costs. Their case study in London found that combining PLs with CDPs is more cost-effective than a modular locker system, with fewer (60 % less) lockers needed in the fixed PL system to achieve similar utilization.

Zeng et al. (2021) addressed optimizing parcel delivery times from distribution centers to PLs. The authors developed an integer programming model for the truck departure problem, where parcels are delivered to lockers. A Sample Average Approximation (SAA) method was then applied to handle the uncertainty of parcel arrival times. Numerical experiments demonstrated that the proposed algorithm could reduce parcel turnover time by around 6.8 % compared to traditional methods, saving more than 0.25 h per parcel on average. While the primary goal was to increase customer satisfaction by optimizing turnover time, this approach also enhanced the available capacity of PLs, as parcels are held in lockers for shorter durations. Kahr (2022) proposed a stochastic optimization model integrating PL location and configuration decisions under uncertain demand and parcel sizes. The model aims to maximize customer coverage and minimize idle capacity by determining optimal PL locations. It uses a cut-off distance function for coverage calculations and applies a Bender decomposition algorithm for medium-sized cases in Austria. Results indicate an average return on PL investment of 75.7 % and an amortization period of 1.4 years. Additionally, small and medium-sized compartments are found to be more effective than large ones for optimal PL design.

In pick-up points, parcels are held until customer collection, impacting facilities' capacity and delaying future deliveries. Nguyen et al. (2023) compared pick-up point load management forecasting methods to balance delivery flows and prevent overload. The forecasting process incorporates the parcel life-cycle by modeling parcel order flow, delivery delays, and the pick-up process. The results show that including parcel life-cycle factors improves forecasting, with the best method predicting load 1 to 4 days ahead, with errors ranging from 3.16 parcels (1 day ahead) to 8.51 parcels (4 days ahead). Zhou et al. (2023) tackled the PL locating problem by incorporating a self-pickup cost formula and financial incentives for customer efforts. They considered commuters picking up parcels along their route and home-based customers retrieving parcels near their residences. Their mathematical model, solved with an improved scatter-search algorithm, showed that the "Pickup on the way" strategy reduced operational costs by up to 16.8 % with optimal PL placement near high-traffic areas. Using heterogeneous locker capacities also cut total costs by up to 63.97 %, balancing fixed-opening, incentive, and penalty costs. Raviv (2023) addressed the challenge of queuing at ADPs due to parcel delivery uncertainties by integrating expected parcel rejections and postponements into a mathematical model for network optimization. This model, applied to cities like Linz, Graz, and Vienna, considers trade-offs between setup, operational costs, and service quality to determine optimal ADP locations and capacities.

Li et al. (2024) studied the strategic sharing of CDP capacity between a CDP provider and a CDP receiver in a competitive market. They used a game model to analyse the optimal decisions and found that CDP sharing always benefits the provider by generating extra

Table 7
Existing approaches for managing ADP capacity and configuration.

Reference	ADP capacity and configuration problem
Faugère and Montreuil (2020)	Optimized fixed and modular locker banks to maximize the service provider's expected profit, considering various costs.
Faugère et al. (2022)	Implemented dynamic deployment of relocatable modular lockers to manage fluctuating demand and reduce costs.
Grabenschweiger et al. (2021)	Evaluated the efficiency of storing parcels from single and multiple carriers in heterogeneous locker sizes to optimize usage.
Schnieder et al. (2021)	Combined staffed CDPs with PL networks to reduce idle locker capacity and handle demand fluctuations effectively.
Zeng et al. (2021)	Optimized turnover time at PLs helps reduce parcel holding times and increases locker capacity.
Kahr (2022)	Integrated location and configuration of PLs under uncertain demand to maximize customer coverage and minimize idle capacity.
Nguyen et al. (2023)	Compared forecasting methods for managing pick-up point loads to balance delivery flows and prevent overload.
Zhou et al. (2023)	Addressed PL capacity and location decisions using self-pickup cost formulas and financial incentives to optimize operations.
Raviv (2023)	Modeled parcel rejections and postponements to optimize network configuration and manage ADP capacity effectively.
Li et al. (2024)	Shared CDP capacities with carriers without these facilities and charged them a service fee.

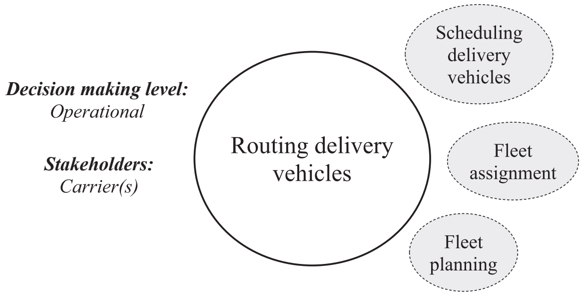

Fig. 5. Decisions in routing problems.

revenue and reducing price competition, though benefits for the receiver vary based on CDP efficiency and third-party fees.

Zeng et al. (2021) developed an integer programming model for optimizing parcel delivery times from distribution centers to PLs, using an SAA method to address arrival time uncertainties. Their approach reduced parcel turnover time by 6.8 %, saving over 0.25 h per parcel, which can also increase PL capacity by reducing the time parcels spend in lockers. Table 7 summarizes the approaches and ideas from the studies discussed in this section for optimally managing and configuring ADP capacity.

4.3. Vehicle routing

The GVRP represents the most closely related extension of VRPs for addressing routing challenges in UFDSs with ADPs. In such GVRPs, fulfilling a delivery order may involve multiple potential delivery locations. The ADPs and other delivery points (e.g., home or workplace) associated with a given order collectively form the set of potential delivery locations. While the GVRP concept was first introduced in 1988 (Laporte, 1988), its specific application to urban freight systems and parcel delivery with ADPs did not emerge until 2019. Building upon the foundational problem definition of GVRP, various extensions have been proposed to cater to the specific requirements of routing problems involving ADPs. These extended variations of GVRP have been referred to by different names in practical contexts, such as “flexible parcel delivery problem” or “VRP with delivery options,” as explored by Orenstein et al. (2019) and Dumez et al. (2021).

There are similarities and differences between traditional routing problems and those involving ADPs. Both aim to minimize routing costs and include time-windows and vehicle capacity constraints. They also manage demand uncertainty, use common optimization algorithms like tabu search and GA, and consider geographical constraints such as road networks and traffic conditions. The key differences lie in the delivery addresses and time windows. In ADP routing problems, multiple delivery addresses exist for each order, requiring a decision on which address to visit. In contrast, traditional routing problems involve only one fixed delivery address per order. Additionally, delivery time windows are more flexible with ADPs, allowing deliveries to final points such as PLs at any time, unlike home deliveries, which are typically restricted to daytime hours.

As shown in Fig. 5, vehicle routing is primarily a problem at the operational level for carriers, and delivery address setting is an inseparable part of problem formulation involving ADPs. However, other operational decisions of vehicle scheduling and fleet assignments or strategic decisions such as fleet planning can also be integrated into VRPs. In the following, we study research works concerning VRPs with ADPs.

Jiang et al. (2019) and Jiang et al. (2022) proposed TSPs for routing in UFDSs with ADPs. Jiang et al. (2019) developed a TSP model where a vehicle visits customers at home or adjacent PLs, aiming to minimize route distance, customers’ self-collection costs, and PL opening costs. Based on the distance from the customer’s home to PLs, the self-collection cost was modeled linearly. Solved with an iterated local search (ILS) algorithm, the model applied to Hefei, China, showed a reduction in total delivery and carbon emissions costs by 4.5 % to 51.2 % and 18.7 % to 51.2 %, respectively. Jiang et al. (2022) introduced an orienteering problem with ADPs (a TSP with profit) to maximize serviced customers in a Hamiltonian cycle with fixed cost, considering PL capacities and customer consent for PL delivery. This problem was addressed using a two-phase heuristic approach for route construction and improvement.

Orenstein et al. (2019) introduced a VRP with an ADP delivery option, focusing on ADP delivery with limited locker capacities and the possibility of postponed deliveries. Formulated as a GVRP with vehicle capacity constraints, the model incorporates costs for postponed deliveries, defined by penalty costs, into the objective function. The compatibility of parcel sizes with locker sizes is also considered. Solutions were developed using saving and petal algorithms to minimize vehicle routing, penalty, and fixed costs, and tabu search was employed for route optimization. Results from 22 hypothetical cases suggest that a 12 % to 15.2 % reduction in total routing costs can be achieved if one-third of parcels have two potential service points and one-third have three.

Sitek and Wikarek (2019) proposed a CGVRP with delivery time windows, offering both home and PL deliveries, with a penalty cost for PL deliveries due to customer preference for home delivery. The objective function minimizes total delivery distances and penalty costs. Mancini and Gansterer (2021) formulated a GVRP with time windows and PL capacity constraints, including customer compensation costs in the objective function. Solved using an LNS algorithm, the PL capacity was modeled based on locker numbers and unpicked orders from the previous day. While Orenstein et al. (2019), Sitek and Wikarek (2019), and Mancini and Gansterer (2021) incorporated penalty costs to reflect customers’ reluctance for ADP delivery, Tilk et al. (2021) and Dumez et al. (2021) used customer-declared preferences. Tilk et al. (2021) considered home and shared delivery options in a GVRP with time windows and service level constraints, ensuring a significant percentage of customers are served via their preferred delivery options.

This modeling approach is similar to prize-collecting VRPs. A branch-price-and-cut algorithm was used to solve the model on hypothetical benchmarks, revealing that reducing the delivery to the most preferred options from 100 % to 60 % results in a 22 % increase in routing costs. Dumez et al. (2021) built on Tilk et al. (2021) by proposing a GVRP with time-window constraints where customers specify multiple delivery options, including PL delivery, with associated preferences and time windows. The model routes delivery vehicles based on these preferences and constraints, aiming to assign top-ranked options to most customers while minimizing fleet size and routing costs. An LNS algorithm combined with set partitioning and various remove-and-repair operators was used. Results indicated that serving at least 80 % of the top-ranked delivery points can reduce costs by 29.2 %.

Driver shortages and high delivery costs challenge same-day delivery. Ulmer and Streng (2019) suggested that ADPs could address these issues by leveraging economies of scale. They proposed a system where customers collect parcels from capacitated pickup stations. Each customer has a preferred station but accepts others within a set distance. The problem was modeled as a dynamic routing problem using a Markov decision process, where decisions involve dispatching vehicles to stations based on new order arrivals. A policy function approximation (PFA) was used to balance fast delivery and consolidation for real-time optimization. Tested on a DHL case study in Braunschweig, Germany, with 1,000 daily orders, the results showed that vehicles could handle 100 orders per day and deliver to stations within 2 h.

Vincent et al. (2022) proposed a VRP with parcel lockers (VRPPL) to minimize total travel costs. They used a simulated annealing algorithm, achieving near-optimal results with a maximum gap of 0.76 % for small instances. Yu et al. (2023) developed an adaptive large neighborhood search (ALNS) algorithm for a GVRP involving electric vehicles and both PL and home delivery options. Their findings showed that ALNS provided optimal solutions faster than the GUROBI solver. Dragomir et al. (2022) introduced a GVRP with time windows for parcel pickup and delivery, focusing on minimizing transportation costs while accommodating customer convenience. Their multi-start ALNS approach, tested with real data from an Austrian logistics provider, achieved nearly 30 % cost savings for carriers and demonstrated that allowing roaming locations remains profitable even if only 25 % of customers disclose their preferred pickup locations.

Vukićević et al. (2023) developed a GVRP with PLs, enabling vehicle charging at PLs and relaxing the predetermined customer assignments to PLS within a specific travel time. A Variable Neighbourhood Search (VNS) heuristic was introduced to solve the model. Results indicate that the algorithm effectively handles complex problems that the CPLEX MIP solver struggles with in most cases. Janinhoff et al. (2023) proposed a GVRP incorporating location-specific costs, where each visit incurs compensation for location

Table 8
Key aspects of routing studies.

Reference	Routing problem	Delivery options	Objective function	Time-window	ADP capacity	Solution algorithm
Jiang et al. (2019)	GTSP	ADPs and home	Min: Routing, customers' self-collection, and PL opening costs			Iterated local search (ILS)
Jiang et al. (2022)	GTSP with profits	ADPs and home	Min: Routing, customers' self-collection, and PL opening costs		√	Heuristics
Orenstein et al. (2019)	GVRP with scheduling	ADPs	Min: Routing, late delivery, and vehicle fixed costs		√	Saving and petal algorithms with Tabu search
Sitek and Wikarek (2019)	GVRP	ADPs and home	Min: Routing distance and penalty costs for PL delivery	√		Heuristic
Mancini and Gansterer (2021)	GVRP	ADPs and home	Min: Routing, vehicle usage, and PL delivery compensation costs	√	√	LNS
Tilk et al. (2021)	Prize-collecting VRP	ADPs and home	Min: Fleet size and routing costs	√	√	branch-price-and-cut algorithm
Dumez et al. (2021)	Multi-objective GVRP	ADPs and home	Min: Fleet size and routing costs	√	√	LNS (VNS)
Ulmer and Streng (2019)	Online GVRP	ADPs	Min: Delivery time		√	Dynamic programming and Markov chain
Vincent et al. (2022)	GVRP	ADPs and home	Min: Routing costs	√		Simulated Annealing Algorithm
Yu et al. (2023)	Green GVRP	ADPs and home	Min: Routing distances	√	√	ALNS
Vukićević et al. (2023)	Green GVRP	ADPs and home	Min: Routing and electric vehicle charging time			VNS
Janinhoff et al. (2023)	GVRP	ADPs and home	Min: Routing, fixed vehicle, and location-specific delivery costs	√	√	ALNS
Niemeijer and Buijs (2023)	GVRP	ADPs and home	Min: Routing distances			Continuous approximation techniques
Zang et al. (2023)	GVRP	ADPs and home	Min: routing costs and parcel pickup costs for customers	√	√	branch-price-and-cut and VNS algorithms
Dragomir et al. (2022)	GVRP	ADPs and home	Min: Routing costs	√		VNS
Galiullina et al. (2023)	Stochastic VRP	ADPs and home	Min: Routing costs			Branch-and-bound algorithm

owners and customers. A mathematical model is formulated and solved using an ALNS algorithm based on a European parcel service (GLS Group) case study. Findings demonstrate that order consolidation in pick-up stations could lead to significant cost savings.

Additionally, savings are found to be greater in rural delivery regions compared to urban areas. Niemeijer and Buijs (2023) examined the carbon emission implications of utilizing pickup points for parcel LMD. While pickup points are often viewed as sustainable due to potential reductions in delivery vehicle emissions, this research highlights the negative impact of emissions produced by customers traveling to these points. By incorporating continuous approximation techniques and multinomial logistic regression, authors evaluate delivery route efficiency, customer travel distance, and mode choice.

Contrary to the belief that pickup points are universally sustainable, their impact varies by location. Urban pickup points may reduce net carbon emissions, while rural ones may lead to higher customer travel emissions despite improved route efficiency. Zang et al. (2023) proposed a GVRP for delivering parcels with conflicting time windows to accessible facilities, using a mixed-integer model to minimize delivery and pickup costs while keeping customer pickup costs within a threshold. They used a linear programming-based variable neighborhood search (VNS) heuristic, solving the problem for up to 150 vertices within an hour. Table 8 provides a comparative analysis of routing problems, delivery options, time windows, and solution algorithms from these studies.

Galiullina et al. (2023) studied a new LMD problem involving integrated incentive and routing decisions under uncertainty. To enhance efficiency, online retailers can implement pickup points and incentivize customers to use them instead of home delivery, with customer acceptance being uncertain. They modeled the problem as a two-stage stochastic program: in the first stage, retailers decide which customers to incentivize, while in the second stage, after customers' choices are known, a vehicle route is planned. They developed an exact branch-and-bound algorithm and heuristics, solving instances with up to 50 customers and achieving 4 % to 8 % lower delivery costs than traditional methods.

4.4. Hybrid models

In this section, we review the studies exploring combining more than one technique.

4.4.1. Locating-routing problems

As a class of OR problems, location-routing problems optimize both location and routing decisions and have been extensively studied. Veenstra et al. (2018) addressed healthcare logistics by designing a model where locker locations and delivery routes are decision variables for shipping medical equipment to either lockers or homes. Their objective was to minimize total routing and locker opening costs, solved exactly for small cases and heuristically for larger ones. Hong et al. (2019) focused on on-demand delivery systems with only locker delivery, proposing a TSP model with delivery time windows and PL locating decisions. Their model aimed to minimize routing distances, customer travel to lockers, locker operating costs, and late delivery penalties, using a heuristic based on an ant colony algorithm for up to 100 customers.

Wang et al. (2022b) investigated battery electric vehicles for LMD, developing a mixed-integer linear programming model to optimize self-service station locations and routing plans. Their goal was to minimize costs for pick-up stations and electric vehicle routing, using a branch-and-price algorithm that outperformed commercial solvers like CPLEX. Results emphasized the impact of accommodation capacity and the benefits of allowing large vehicles to access multiple stations and combine routes. Bonomi et al. (2022) addressed location and routing for PL-based delivery, aiming to minimize environmental impacts by reducing total vehicle and consumer travel distances. Their mathematical model, solved with Gurobi, analysed 1680 instances and highlighted how consumer behavior can significantly reduce emissions, underscoring that eco-friendly choices are crucial for achieving sustainability beyond just installing PLs.

4.4.2. Two-echelon problems

The application of ADPs in two-echelon delivery systems is another hybrid approach explored in the literature. In these systems, satellites function as intermediary hubs for freight transshipment, playing a crucial role in the first echelon for receiving and sorting large volumes of goods before transferring them to the second echelon for final delivery. It is important to clarify that satellites are not classified as ADPs. However, they are discussed here to illustrate the integration of ADPs within two-echelon systems. This distinction further highlights the role of ADPs in the final leg of urban logistics systems.

Janjevic et al. (2019) proposed a two-echelon delivery system where parcels are first shipped from a depot to satellites with restricted capacities and then delivered to customers at home or CDPs from these satellites. Assuming only 20 % of parcels within a 5 km radius of each CDP can be serviced, their model aims to minimize routing and operational costs using a heuristic resembling branch-and-price. Results from a São Paulo case study with 15,500 deliveries showed cost reductions of up to 5.0 % by integrating CDPs. Enthoven et al. (2020) studied a similar two-echelon system, where trucks deliver parcels from a depot to covering facilities (with lockers) and satellites. From satellites, bikes handle LMD. Their model minimizes total traveling and connection costs, with the connection cost being a function of distance. An ALNS heuristic revealed that using covering facilities can reduce total costs by up to 35 %, cut second-echelon travel costs by 60.4 %, but increase first-echelon costs by 37.8 %.

Leyerer et al. (2020) explored a two-echelon grocery delivery network using both refrigerated and standard lockers. In the first echelon, vans transport groceries from a depot to lockers. In the second, cargo bikes deliver them from lockers to customers. Their model includes three sub-models: the first locates lockers, determines their types, and optimizes van routes; the second solves the VRP for bike deliveries; and the third adjusts for refrigerated deliveries. Testing in Hannover, Germany, showed a 25 % increase in home deliveries compared to locker pickups, with a 1.5 % rise in total system costs.

Janjevic et al. (2021) proposed a three-echelon multi-modal delivery network incorporating CDPs. The first echelon involves large-capacity vehicles transporting parcels from a depot to satellites. In the second, some parcels are transferred to local transshipment points (LPPs), while others continue to LMD vehicles. Routes include home delivery, CDP, and blended options. The third echelon involves LMD routes from LPPs. Their study in São Paulo, Brazil, demonstrated that integrating CDPs improves flexibility and reduces transportation costs through consolidated deliveries.

Rautela et al. (2022) evaluated the economic benefits of integrating CDPs into LMD networks. The study proposed a two-echelon delivery system similar to the one proposed by Janjevic et al. (2019). However, this model accounts for changes in demand density due to CDP placement and considers the impact of failed deliveries and returns on routing costs. The research found that a 20 % shift in deliveries could lead to 14 % savings in last-mile costs and 5.5 % in total costs. However, aggregating return flows has a limited effect, with only a marginal increase in total savings (from 5.5 % to 5.6 %) when returns are 15 % of deliveries due to the lower number of pickups compared to deliveries.

4.4.3. Mobile ADPs

The high cost of stationary ADPs and the spatiotemporal uncertainties in delivery demand and supply justify the need for flexible, mobile ADP solutions. Mobile ADPs offer greater flexibility and can dynamically expand service coverage compared to stationary ones (Kötschau et al., 2023; Peppel et al., 2024). Schwerdfeger and Boysen (2020) investigate how autonomous vehicles might outperform stationary lockers in parcel delivery. Their mobile PL location-routing model aims to optimize the fleet size of mobile lockers to meet all delivery demands. Customers specify preferred delivery locations and schedules, and a mobile locker must align with at least one of these criteria to serve them.

Furthermore, customers can be served by a parked mobile locker if they are within a predefined walking range based on the maximum walking distance individuals are willing to accept. An overlap in time intervals is included to minimize the risk of customers and mobile lockers missing each other. The model, solved using a greedy heuristic, found that (i) the superiority of mobile lockers decreases if customers are willing to walk longer distances, (ii) an overlap time interval of one hour can reduce the required fleet of mobile lockers by 343 %, (iii) mobile lockers with a small capacity of 20 compartments can potentially reduce the need for stationary lockers by up to 67 %, and (iv) as overall locker acceptance increases, mobile solutions become less attractive. Schwerdfeger and Boysen (2022) further refined their model by distinguishing between different types of mobile PL systems, such as those fixedly mounted on vehicles versus those loaded into vehicles, as well as varying vehicle types (staff-driven or self-driving) and driver arrangements (fixed or swapping drivers). They used a multi-stage heuristic approach based on tabu search to minimize total fixed and operational costs. The results indicated that mobile PLs could lower delivery costs, particularly when enhancing customer service levels (e.g., shorter walking distances and longer parcel retrieval times). Additionally, using loaded lockers and allowing drivers to swap between lockers improved service levels while maintaining the lowest marginal cost. However, mobile PL systems can increase overall vehicle activity compared to stationary PLs.

Kötschau et al. (2023) analysed the effectiveness of stationary versus mobile PLs in enhancing delivery efficiency and customer convenience. Mobile lockers, which use autonomously operating vehicles to provide temporary collection points at various locations, can reduce pickup distances but may impose time restrictions on customers. They formulated a heterogeneous locker location and routing problem to compare the performance of combined stationary and mobile PL fleets against traditional home deliveries. By accounting for customers with both restricted and flexible pickup distance and time preferences, the model aimed to maximize customer coverage and service quality. The findings showed that integrating mobile PLs could increase customer coverage by 14 % to 19 % and better accommodate individual preferences. In another study, Liu et al. (2023) addressed the optimization of stopover locations and delivery routes for mobile PLs using a Hybrid Q-Learning-Network-based Method (HQM). This method outperformed GA and exact methods in both optimization performance and computation time. The study considered factors such as time window constraints, locker capacity, and network density. The results suggested that dispatching mobile PLs before peak commuting hours could improve demand fulfillment and that deploying them in less congested areas could reduce traffic disruptions and emissions, thus supporting urban sustainability. This research provides valuable insights for logistics operators aiming to enhance large urban distribution networks through machine learning and artificial intelligence applications.

Peppel et al. (2024) investigated integrating mobile PLs into LMD networks, which currently rely on home deliveries and stationery PLs. They developed a location-routing model to identify optimal locations and routes for mobile PLs, using an MNL model to capture customer preferences based on travel distances and home availability. The study analysed home delivery, stationary PLs, and mobile PLs to minimize delivery costs and environmental impacts. Findings show that integrating mobile PLs results in 8.7 % cost savings and 5.4 % reduction in CO_2 emissions, with more significant benefits in urban areas. The authors conclude that mobile PLs should be strategically deployed in cities with populations over 20,000.

Wang et al. (2024) investigated the routing problem for mobile parcel lockers (MPLs) under uncertain demands and time windows. Demand uncertainty can cause planned routes to fail, leading to unmet service expectations. To address this issue, authors developed an optimization approach integrated with recourse strategies to manage uncertain demands and potential service failures. The methodology included a tailored tabu search algorithm to determine optimal a priori routes for MPLs and recourse strategies to respond to service failures, thereby enhancing route reliability proactively. The results from numerical experiments revealed that the proposed approach significantly improved service reliability with only a marginal increase in operational costs. Table 9 summarizes the key aspects of these studies, including their approaches to hybrid problems in logistics.

5. Evaluation

ADP networks have been implemented in different countries, such as Amazon lockers in the US, China Post CDPs, Australia Post

Table 9
Key aspects of hybrid studies.

Reference	Routing problem	Delivery options	Time windows	ADP capacity	Solution algorithm	Case study
Veenstra et al. (2018)	VRP	ADPs & home			Branch-and-bound & heuristics	Hypothetical
Hong et al. (2019)	Online TSP	ADPs	√		Ant colony	Hypothetical
Janjevic et al. (2019)	2E-VRP	ADPs & home		√	Branch-and-price & heuristics	Sao Paulo, Brazil
Enthoven et al. (2020)	2E-VRP	ADPs & home			ALNS	Hypothetical
Leyerer et al. (2020)	2E-VRP	ADPs & home		√	Commercial solver	Hannover, Germany
Janjevic et al. (2021)	3E-VRP	ADPs & home	√		continuous approximation	Sao Paulo, Brazil
Rautela et al. (2022)	2E-VRP	ADPs & home		√	continuous approximation	Sao Paulo, Brazil
Schwerdfeger and Boysen (2020)	VRP for mobile PLs	ADPs	√	√	Greedy heuristics algorithm	Hypothetical
Schwerdfeger and Boysen (2022)	VRP for mobile PLs	ADPs	√	√	Tabu search and decomposition heuristics	Braunschweig, Germany
Bonomi et al. (2022)	VRP	ADPs & home	√		MIP solver (Gurobi)	Hypothetical
Kötschau et al. (2023)	TSP (for placing mobile PLs)	ADPs & home	√	√	Not mentioned	Hypothetical
Liu et al. (2023)	VRP for mobile PLs	ADPs	√	√	Hybrid Q-Learning-Network-based Method (HQM)	Hypothetical
Peppel et al. (2024)	VRP for mobile PLs	Mobile and stationary ADPs &home		√	Greedy heuristic	a European country
Wang et al. (2024)	VRP for mobile PLs	ADPs	√	√	Tabu search	Hypothetical

PLs, and In Post PLs in Poland. These projects allow researchers to evaluate their performance and uptake, identifying critical success factors and failure reasons for improved (re)design. This section summarizes the studies about the post-implementation evaluation of UFDSs with ADPs.

5.1. Spatial distribution patterns

Several studies have explored locating spatial patterns of ADP implementation, which are reviewed in this section.

Amazon Lockers in the US – Amazon has been establishing further vertical integration among e-commerce companies and customers by utilizing PLs. Amazon PL implementation started in 2011, resulting in the deployment of facilities in nearly 900 cities in the US. By evaluating the spatial distribution patterns of Amazon lockers in Los Angeles, US, Fang et al. (2019) examined the underlying socio-economic and environmental factors determining the location of PLs. First, using clustering techniques of Kernel density and K-function, the authors explored whether lockers are dispersed, clustered, or randomly distributed. Results show that a three-tier clustering pattern can define the distribution of Amazon lockers in Los Angeles. By grouping the network zones into nine clusters based on their accessibility to lockers (i.e., from zero to more than seven lockers), regression and correlation models were applied to explore the relationship between clusters and socio-economic and environmental attributes. Results indicate that income, transit and parking footprint, population, internet use, walkability, and education can explain 44 % of cluster variations.

Similarly, Schaefer and Figliozzi (2021) used a clustering approach to analyse the spatial distribution of 176 Amazon PLs in Portland, Oregon. They applied Kernel density estimation (KDE) to assess accessibility and equity, focusing on metrics such as population coverage, employment density, and transportation modes. Their findings showed that Amazon lockers are concentrated in accessible locations, including small retail stores, major roads, mixed-use zones, and areas with high population and employment density. However, they also noted that walking accessibility to these lockers is significantly less than driving accessibility, which raises potential concerns. In terms of equity, the study found that while income and internet access influence locker accessibility, marginalized groups—including Hispanics, individuals with limited English proficiency, and those with lower education levels—often face lower accessibility to PLs.

CDPs and PLs in China – Xue et al. (2019) analysed the spatial patterns of attended CDPs and PLs in Changsha City, China, using point-of-interest data and various analytical methods. They found that CDPs predominantly operate through a franchise model and serve communities, schools, and businesses. About 77 % of CDPs are located at service area exits, while others are centrally positioned. The distribution of CDPs aligns with population density, economic development, and road accessibility. Lin et al. (2019) studied automated PL demand and supply dynamics in Hangzhou, China, focusing on walking accessibility and equity. They used field observations and surveys to estimate demand and applied a two-step floating catchment area method to identify spatial disparities. The study revealed that walking accessibility to PLs is uneven, with greater disparities in open communities compared to gated ones, highlighting the need for improved accessibility in areas with higher aging populations.

Luo et al. (2022b) assessed the convenience of CDPs in Wuhan City by analysing service targets, adjacency, accessibility, and agglomeration. They found that CDPs mainly serve residential and commercial areas, with suburban residents facing lower delivery comfort than those in downtown areas. The study also noted significant accessibility inequities, particularly affecting older adults, and observed that CDPs tend to cluster, with unattended CDPs being more densely located than attended ones.

Mehmood et al. (2022) examined the spatial distribution and accessibility of CDPs in Nanjing, China. This study utilizes data from

1224 CDPs, including 424 China Post stations and 800 Cainiao stations, along with population and gross domestic product (GDP) data for spatial analysis. Results indicate a significant positive correlation between CDP distribution, population, and GDP. Access to CDPs varies significantly across different modes of transportation. Specifically, walking and cycling provide access to 13.8 % and 25.3 % of China Post Stations, while these figures are 9.2 % and 28.9 % for Cainiao stations. On the other hand, driving provides access to 71.8 % of China Post and 71.1 % of Cainiao stations.

Ding et al. (2023a) assessed Smart PL supply and demand in Tianjin, China, analysing 2,693 residential communities and 479 smart PLs. They found that high-demand areas are within 300 m of homes, while high-supply areas are 300 to 600 m away. The study, using metrics like the Gini coefficient, showed that the top 20 % of the population has access to 80 % of PLs, highlighting oversupply issues and inequities. Ding et al. (2023b) studied Smart PL distribution in Tianjin's central urban area before and after the pandemic (2019 and 2022). Using kernel density estimation and other analyses, they noted a rise in PLs from 51 to 479 over three years, predominantly in residential areas. Post-pandemic, the distribution shifted from random to clustered, influenced by factors such as population density and income.

Australia Post's PLs in Australia – Leung et al. (2023) explored site characteristics (micro-level) and regional location characteristics (macro-level) of Australia Post's PL facilities in five South East Queensland regions, Australia. Micro-level characteristics are PL access possibilities by various transportation modes, physical characteristics of PL sites and types of surroundings, and perceived safety score for them. The macro-level characteristics defined for regions with PL facilities are related to three groups of land use variables (e.g., dwelling types and percentages), population (e.g., population or employment density), and transport variables. A hierarchical clustering technique was then applied to understand where PLs typically are located by the company, showing the main locations being 1) urban areas with high walking and cycling infrastructures, 2) suburban areas with high parking access and street visibility, 3) suburban areas having post locations with indoor lockers, and 4) shopping centers with abundant parking spaces. In addition to the hierarchical clustering technique, multivariate logistic regression was employed to explain the presence of lockers in suburbs using a set of explanatory variables. The results show a positive link between PLs' presence and parcel collection facilities, population density, and share of households of internet access. Overall, the research concludes that at the current level, Australia Post's PLs partially meet the objectives of a sustainable city.

Poland's CDPs – Parcel collection points in Gdańsk, Poland, are in the forms of PLs, newsstands, or convenient stores that InPost, Polish Post, and Żabka provide. Chaberek (2021) evaluated the accessibility to CDPs in Gdańsk from residence, work, and school locations. In their work, the authors assumed that consumers' mode choice for the collection journey depends on the availability of transportation infrastructure and the journey's travel time and distance. Results show that CDPs are easily accessible by car, in some cases accessible by bicycle, and hardly accessible by walking. The authors believe that although, in practice, CDPs can reduce the movements of delivery vehicles in transportation networks and contribute to reduced traffic if the parcel collection journeys by customers are performed by private cars, traffic savings are minimal.

In summary, international studies report on various factors influencing the spatial distribution of CDPs and PLs. While common factors such as income, education and age have been examined more extensively, researchers have also explored location and site specific attributes such as parking availability and internet access. Furthermore, it is important to note these factors demonstrate varying impacts in different regions.

5.2. *Satisfaction level and failure factors*

Measuring customer satisfaction levels with ADP services is essential to evaluate their use and service adjustments. This sub-section reviews the extant scholarly works reporting on satisfaction levels.

PLs in China –Lai et al. (2022) investigated how different dimensions of service quality affect consumer satisfaction with PL services in China. They evaluated service quality across five dimensions: tangibility (design, size, number, technology, speed), responsiveness (notification system, troubleshooting speed, management system), security, reliability, and timeliness (traceability, service access). Using a survey of 321 users, structural equation modeling revealed that while all dimensions positively impact satisfaction, timeliness is the strongest predictor, followed by reliability, security, responsiveness, and tangibility. Tang et al. (2021) explored customer perceptions of IoT-based smart PLs versus traditional LMD systems in China. An online survey of 273 respondents from Yaohai District assessed service quality based on price, reliability, convenience, fault-handling, and service diversity. Confirmatory factor analysis showed that price does not positively affect satisfaction, but service diversity and fault-handling capability have significant positive impacts.

InPost PLs in Poland – Iwan et al. (2016) evaluated the feedback and expectations of InPost PL users in Szczecin, Poland. Eighty-three persons were interviewed using a questionnaire comprising attributes related to the overall rating of PLs, reasons for utilization, expectations regarding the PLs' locations, and rating of the current locations. Basic descriptive analyses show that customers provide an overrating of 8.1/10 for PL services. Price (27 %), 24-hour availability (23 %), localization (22 %), time (18 %), and parcel tracking (7 %) were the reasons contributing to PLs uptake. From a location point of view, closeness to home (33 %), being on the way home (21 %), and having car park space in the proximity (19 %) were key factors. The overall rating of the current locations was rated at 7.46/10. The study's results also show a satisfaction level of 80 % for the InPost PL system. In a similar work, Lemke et al. (2016) also found a high customer satisfaction level for InPost PL services. The authors explored the usability of PLs by surveying 2933 responses to measure overall satisfaction and location quality. Results of this study reveal that 95 % of PL users are satisfied with the services, 40 % of the users are satisfied with the locations, and 15 % seek improvement in the locations to use them more frequently.

CDPs provided by DHL, GLS, and Kiala in the Netherlands – Weltevreden (2008) is one of the first studies conducting empirical research to explore the uptake of CDPs provided by DHL, GLS, and Kiala in the Netherlands. A nationwide online survey was conducted on the use of CDPs by online shoppers in the Netherlands. Results show that 2006 nearly 920 CDPs were jointly operated by the abovementioned companies. However, only 19 % of Dutch online shoppers used them, accounting for only 1.4 % of the total volume of online deliveries in 2006. Evaluating car accessibility in three levels of 5, 10, and 15 min showed that more than 50 % of the Dutch population cannot reach a CDP within 5 min, while within 15 min of driving at least one CDP is available. Authors conclude that a 5-minute driving distance is critical for large-scale uptake of CDPs, pointing to the need for a denser CDP network.

Furthermore, Weltevreden (2008) found that only 40 (5.9 %) online retailers offered delivery through CDPs to their customers. It was also highlighted that people's socioeconomic characteristics might impact the uptake of CDPs. Applying a binomial logistic regression, it was found that CDPs would have higher acceptance by women, low-educated people, and people who frequently shop online.

CDPs in Turkey – Vural and Aktepe (2021) explored the reasons behind the failure of sustainable urban distribution networks with CDPs in Istanbul, Turkey. Using multiple data sources from companies, interviews with LMD carriers, customer surveys, newspaper reports, online blogs, and consumer complaint portals, it was found that IT integration, regulation, and security issues are some of the underlying reasons for the technical failure of CDPs.

Smart PLs in Vietnam – Quan et al. (2022) investigated the impact of smart PL usage on customer satisfaction in online shopping. Data from 442 smart locker users in Vietnam were analysed using structural equation modeling. Results indicate that convenience, privacy, security, and reliability significantly influence user satisfaction through perceived value and transaction costs. The findings highlight the potential value of smart PLs in the online shopping experience.

Locker Alliance Network in Singapore – Self-service PL technology addresses LMD challenges, but its voluntary adoption remains limited, with customers preferring home delivery. Sun et al. (2023) examined how to encourage adoption by controlling two factors: the exposure effect (changes in usage after an initial trial) and the popularity effect (impact of nearby locker popularity on usage). Using data from the Locker Alliance Network pilot program in Singapore, the study tracked 2,210 participants' locker usage over nine months, compared to home delivery data. Results show that the exposure effect significantly boosts locker delivery adoption among new users, emphasizing the need for continuous promotion by locker operators. The popularity of nearby lockers also increases adoption among prior users, highlighting the importance of strategic locker placement. Simulations revealed that even a single promotional event could substantially increase long-term PL usage, supporting the sustainable expansion of the locker system.

The review of research investigating success factors emphasize on the critical role of proximity of CDP and PLs to customers' home or transit stations, as shown in studies conducted in Poland and Netherland. On the other, poor technology integration, reliability and security concerns were the key barriers for successful implementation. Furthermroe, inadequate promotion and awareness could lead to sub-optimal locker utilization, and eventually, low return on investment.

6. Discussion and future research directions

This section discusses theoretical and managerial aspects of plan, design, and evaluation of ADPs in UFDSs. The extant literature on the planning aspect could be labeled as the foundation of ADP research. Studies in this stream predominantly have focused on assessing advantages, behavioral and demographical considerations, acceptance models, and factors impacting the degree of acceptance among different groups of users. From a stakeholder perspective, most research has addressed the benefits and challenges related to the end user of ADPs (Iwan et al., 2016; Zenezini et al., 2018; Vakulenko et al., 2018). More recently, studies such as Schwerdfeger and Boysen (2020), Pan et al. (2021), and Mohri et al. (2024c) have expanded on a user-centric assessment and examined the pros and cons of ADPs from the view of carriers, government, and communities. To improve ADP acceptance, many researchers have proposed placing them in locations that best overlap with customers' travel patterns (Ghaderi et al., 2022b). These candidate locations include supermarkets, shopping centers, parks, libraries, petrol stations, or public transportation stations. However, since other types of stakeholders manage these locations, it is essential to examine the conditions under which ADPs could be implemented, what partnership structures exist, and how the revenue and pricing should be formulated (Rohmer and Gendron, 2020). Surprisingly, there is a limited knowledge base when cross-examining stakeholder behavior and acceptance levels among two or more countries or regions.

In the stream of design, our review indicates that problems could be formulated as single objective (e.g., Deutsch and Golany, 2018), multi-objective (Luo et al., 2022a), and bi-level optimization models (Yang et al., 2020), with most studies, follow a single-objective approach. Since ADPs can be established and operated by various stakeholders, individually or collaboratively, we suggest future studies focus on multi-objective models to reflect the needs and operational features of different stakeholders effectively. The analysis also indicated that researchers have mainly relied on deterministic optimization models. Therefore, the applications of non-deterministic models to reflect the stochastic nature of demand, delivery characteristics (e.g., size, weight, type, value, etc.), and varying ADP acceptance levels by customers could add significant value to the emerging body of knowledge. Furthermore, since locating is a strategic decision, RO techniques' applications are currently absent. From a routing perspective, our review shows that GTSP and GVRP are the most commonly employed variations. Therefore, future research could benefit from other selective VRPs to model ADP-enabled LMD systems (Aras et al., 2011; Gunawan et al., 2016). For instance, prize-collecting VRP and TSP with profit consideration are among the variations that have been recently used (Tilk et al., 2021; Jiang et al., 2022). However, basic formulations of orienteering and profitable tour problems have not yet been extensively utilized for routing. The classic combinatorial optimization literature also provides pathways for future research. For example, the inventory routing problem (IRP) or locating inventory routing problem (LIRP) are promising extensions for ADP models involving commodities with holding and carrying costs. Specifically, retailers and supermarkets utilizing ADPs to distribute popular and standard items could benefit from these extensions to fully reflect direct and indirect inventory costs.

Except for Dumez et al. (2021), almost all other studies have proposed single-objective routing models. Heuristic approaches such as LNS have been widely used in solution algorithms, while only a few studies have employed exact solution algorithms such as branch-price-and-cut and dynamic programming techniques (Tilk et al., 2021; Ulmer and Streng, 2019). In addition, integrating machine learning techniques into metaheuristics models could provide significant value for addressing large-size problems (Karimi-Mamaghan et al., 2020a;b).

Furthermore, integrating fleet assignment and planning decisions into routing problems is crucial. Routing problems often involve utilizing multiple delivery vehicles or mobile PLs with varying speeds or capacities. Therefore, determining the optimal assignment of heterogeneous fleets to different delivery routes becomes essential. Although fleet planning is typically considered a strategic decision, it can be effectively incorporated into routing problems to establish the optimal number of required delivery vehicles or mobile PLs with distinct types, speeds, and capacities. Integration of routing and locating decisions within an operational system ensures alignment between strategic and operational solutions. This alignment becomes even more critical when a single stakeholder is responsible for optimizing both decisions instead of when different stakeholders are involved. Existing location-routing studies primarily focus on single-stakeholder scenarios and multi-echelon delivery systems (Janjevic et al., 2019; Leyerer et al., 2020). However, in the case of the Singaporean Locker Alliance program, locating and routing are the concerns of various stakeholders.

Moreover, previous studies predominantly consider ADPs and home as delivery options. However, studies involving mobile ADPs exclude home delivery as an option (Schwerdfeger and Boysen, 2020). Mobile PLs provide unparalleled convenience, allowing customers to collect their parcels at their preferred time, thereby accommodating the fast-paced lifestyles of modern consumers. Nevertheless, there may be heterogeneity in the community's preference for mobile PLs over other options, including home delivery. Therefore, future research should consider delivery systems with multiple options, including stationary ADPs, mobile ADPs, and home delivery.

In the evaluation stream, researchers employed various measures, which can be categorized into three main groups. The first category encompasses the socioeconomic attributes of ADP users. For instance, Fang et al. (2019), Schaefer and Figliozzi (2021), and Xue et al. (2019) discovered that Amazon PLs and China Post CDPs predominantly cater to educated customers. The second category comprises attributes related to ADP service, including safety, security, complexity, walking and driving accessibility, and working schedules (Tang et al., 2021; Chaberek, 2021). However, incentivizing ADP services, overlapping the first and second categories, remains unexplored. Specifically, there is uncertainty about whether compensating customers for additional parcel collection costs through incentive plans leads to successful ADP implementation.

Consequently, future studies may evaluate ADP projects with and without incentive plans to assess the viability of such compensation strategies. The third category involves attributes associated with delivery characteristics, which have received less attention in the literature. Understanding the characteristics of parcels delivered through ADP systems is crucial. For example, do ADP users manifest the same attitude when considering factors such as parcel value? In terms of evaluation baseline, to date, the literature has relied on observed macro-level data such as locations, capacity, and types of ADP facilities (Lachapelle et al., 2018), as well as micro-level data collected through surveys (Lai et al., 2022). In future research, the evaluation of ADP projects could be enriched by exploring historical data on parcel deliveries, providing valuable insights into the socioeconomic aspects of ADP users and parcel characteristics. Finally, the literature on the performance evaluation of ADPs has only focused on public facilities or those managed by carriers.

Given the rise in the deployment of on-premises and private PLs (OPLs) (Mohri et al., 2024c), future research could benefit from modeling the benefits, acceptance, and optimization of shared and/or restricted networks. So far, few academic studies have been done in this scope, highlighting the benefits of the lockers for other stakeholders such as carriers and the local government and the appropriate size of OPLs for buildings (Ranjbari et al., 2023a; Mohri et al., 2024c; Ranjbari et al., 2023b). This research stream should be extended by developing some behavioral models describing the acceptance probability of the services by residents and their willingness to pay for the services. Also, it is worth exploring who prefers public PLs and OPLs. These heterogeneities in preferences can direct carriers to know where to locate PLs and whether to incentivize or charge customers. Surprisingly, within our search boundaries, our review did not identify a study with a dedicated focus on the regulatory aspects of ADPs. Few studies, however, have conceptually examined the issues related to access rights and regulation. Ambrosini et al. (2023) contend that regulating access to PL networks is unnecessary since such facilities are not categorized as essential. On the other hand, using an economic perspective, Cerpickis et al. (2023) point to the recent discussions suggesting the need for legislation and ex ante-regulated access to PL networks across Europe. Therefore, a promising avenue for future research is in the assessment of introducing regulation in ADP markets.

7. Conclusions

This work presents a scoping literature review on the topic of ADPs, a study that preliminary aims to assess the knowledge base size, emerging trends, employed methodologies, gaps, and directions for future research. While following the conventional SLR protocols, we employed a unique road map to structure our work into three unique components: plan, design, and evaluation. This conceptualization allows us to determine key topics of interest while examining their interdependencies. A trajectory of research growth has been observed since the late 2010 s, predominantly owed to the commercial uptake of PLs by key national carriers globally and the need to improve the sustainability of urban freight systems. While still in its infancy, our work exhibits diverse methodologies within the literature. More specifically, studies in the category 'plan' tend to follow qualitative methodologies focusing on behavioral aspects of ADP users. In contrast, design studies were narrowed to mathematical modeling, and studies in the evaluation category tend to benefit from analytical approaches. We acknowledge that our work comes with limitations, which opens new avenues for future research. First, we did not examine the applications of ADPs as transshipment points. Second, our paper search was mainly driven by transportation, logistics, and retail journals and conferences. Third, in this study, we did not examine how ADPs have evolved and what factors determine their physical and digital design and configurations. Research on the application of ADPs in LMD systems could also benefit from other disciplines. For example, when underutilized, ADPs' environmental externalities and footprint could outweigh their operational benefits; hence, an estimation of their full life cycle assessment is necessary. Furthermore, we could not identify valid research investigating the implications of ADP use from a retailer's point of view. Specifically, how retailers could promote the use of ADPs to their customers as part of the shopping experience is of an area of interest.

CRediT authorship contribution statement

Seyed Sina Mohri: Writing – original draft, Methodology, Investigation, Conceptualization. **Hadi Ghaderi:** Writing – review & editing, Methodology, Investigation. **Tom Van Woensel:** Writing – review & editing, Methodology. **Mehrdad Mohammadi:** Writing – review & editing, Methodology. **Neema Nassir:** Writing – review & editing, Supervision, Investigation. **Russell G. Thompson:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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