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Out-of-home delivery in last-mile logistics: A review

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ABSTRACT

In light of labor shortages, rising fuel costs, and thin profit margins, providers of last-mile delivery services face a mounting pressure to innovate. One avenue to more efficient last-mile operations is the incorporation of out-of-home delivery (OOHD) services. OOHD, i.e., the delivery to parcel shops and parcel lockers, instead of customers' homes, offers manifold advantages, including the consolidation of customers into a single delivery location and a reduction in the number of failed delivery attempts. In the past five years, the number of scientific publications dealing with optimization problems in the context of OOHD has increased rapidly.

In this survey, we assess the various opportunities for optimization in OOHD-based concepts for last mile logistics. Categorizing their manifold aspects, we provide a classification of problem components and point out key challenges. We then present comprehensive overviews of the literature for all three major decision types (facility location, vehicle routing, location routing). Finally, we extensively discuss gaps in the current literature and indicate directions for future research.

1. Introduction

Parcel deliveries have increased dramatically in recent years. From 64 billion parcels sent worldwide in 2016, the number of parcels has climbed to over 161 billion in 2022 and is forecast to reach 225 billion by 2028 (Pitney Bowes, 2023). Major issues in the delivery sector arise from this growth in the form of high costs, rising carbon dioxide emissions, and traffic congestion. To tackle these problems, researchers and practitioners strive to improve the efficiency and sustainability of the cost-intensive last leg of the delivery process, commonly referred to as the last mile.

Out-of-home delivery (OOHD) is an innovative component of modern concepts aiming to make the last-mile delivery process more efficient. In contrast to traditional home delivery, parcels are not delivered to the recipients' front doors but to a nearby pickup facility. The recipients can then pick up their parcels at their preferred time. This requires specific infrastructure, i.e., parcel lockers or parcel shops that allow storage and the release of parcels to the recipients.

OOHD enables the last-mile delivery process to be more efficient in many ways:

- Recipients can be consolidated so that instead of multiple locations, only one OOHD facility needs to be served by a delivery vehicle. This enables delivery tours with fewer stops and shorter total distance.
- OOHD provides flexibility in route planning. Recipients may be willing to pick up their parcel from not only one, but several OOHD facilities.
- As OOHD often extends an existing door-to-door delivery concept, the recipients' home addresses may be included in the list of possible delivery locations. Hence, delivery providers can select from a variety of possible combinations of locations to be served, which aids in the construction of efficient vehicle routes.
- OOHD decouples the delivery process from the receiving process since delivery drivers no longer interact with recipients. This can greatly reduce costly failed deliveries (Lim et al., 2022) that regularly occur when recipients are not on site to receive their parcels, necessitating further delivery attempts. Note that the severity of this issue varies from country to country (Loqate, 2021). As a potential solution, delivery drivers might leave the parcel on the recipient's doorstep unattended. However, this strategy runs the risk of theft ('porch piracy'). In contrast, OOHD tackles the problem of failed deliveries while simultaneously ensuring security.
- Provided that recipients perform their pickup trips by bike or on foot, reducing the number of required delivery vehicles and covered

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kilometers can help lower emissions and traffic volume, especially in congested city centers.

Of course, the use of OOHD also poses challenges. Most importantly, OOHD relies on dedicated infrastructure. Proprietary networks of OOHD facilities require high initial investments, such that the setup is often not worthwhile, particularly for smaller delivery providers with comparatively low parcel volumes. In addition, a successful OOHD-based concept needs to consider recipients' behavior. On the one hand, providers must incentivize recipients to agree to OOHD through attractive pickup locations or other (e.g., monetary) incentives. On the other hand, recipients influence the capacity of OOHD facilities through their pickup behavior.

In recent years, the role of OOHD in last-mile delivery concepts has been growing rapidly. In practice, German logistics provider DHL plans to expand its network of parcel lockers from about 4,000 in 2019 and 8,500 in 2021 to 15,000 by the end of 2023 (DHL, 2022). While only 3 percent of parcels in Germany were delivered to parcel lockers in 2019, by 2025, the share of parcels delivered to recipients via parcel lockers is expected to account for 10 percent of the total parcel volume (DHL, 2019).

In operations research, mathematical optimization problems occurring in last-mile parcel delivery considering OOHD have also received increasing attention. This survey gives an overview of the corresponding literature. While we refer to the practice of delivering parcels to parcel shops and parcel lockers as OOHD, numerous different terms are used in the literature, owing to the novelty of the infrastructure and the fact that there are multiple names for parcel shops and lockers in practice: The signifiers 'delivery options', 'covering options', 'service points', 'collection-and-delivery points', 'pickup stations', '(automated parcel) lockers', 'parcel machines', 'flexible locations', 'shared locations', and 'alternative locations' all usually point to optimization problems with OOHD.

The survey covers the processes of order capture, last-mile transport, and out-of-home storage, thereby excluding operations that are carried out independently of the delivery concept in use, like long-haul shipping, order preprocessing, etc. With decisions on facility location and vehicle routing, the optimization problems discussed here are, of course, related to classes of well-known optimization problems. Nevertheless, for reasons of brevity, we do not list exponents of problems that are merely related or could be applied to an OOHD problem. Instead, we limit this survey to publications that explicitly address OOHD and only give a brief overview of more general problem types here. Problems that highlight location decisions belong to the class of facility location problems (cf. Revelle, 1986; Haase and Müller, 2014). Vehicle routing problems related to the OOHD environment vary to such an extent that it is difficult to name common problem characteristics. The basic problem types with the most similar setups include the vehicle routing problem with profits (VRPP; Archetti et al., 2014), the covering tour problem (CTP; Gendreau et al., 1997), and the generalized vehicle routing problem (GVRP; Ghiani and Improta, 2000). They all share the property that it is not necessary to visit every vertex of the underlying graph. Lastly, the class of location routing problems deals with combined routing and facility location problems, traditionally focusing on depot and satellite facilities instead of OOHD facilities (Prodhon and Prins, 2014; Drexl and Schneider, 2015).

To further specify the scope, we give examples of related optimization problems <u>outside</u> of it. We exclude problems involving no recipient pickup, e.g., vehicle routing with roaming delivery locations (Reyes et al., 2017) and vehicle routing with transshipment points (Friedrich and Elbert, 2021; Li et al., 2021). Also, we do not consider problems that are not explicitly located in parcel delivery, for example, omni-channel approaches (e.g., Glaeser et al., 2017; Frey et al., 2023). Lastly, we omit problems that do not deal with a dedicated OOHD infrastructure (parcel shops, parcel lockers), as such setups (e.g., Allahyari et al., 2014) lead to business questions quite distinct from the ones in a context of OOHD infrastructure.

OOHD has already been subject to literature reviews. Boysen et al. (2021) and Silva et al. (2023) address it among other delivery modes. These papers put forward a structured comparison of how last-mile delivery can be carried out or organized (cargo bikes, drones, crowdshipping, etc.). In contrast, we focus on OOHD and survey the corresponding literature on a more granular level. Further, our work is separate from surveys with explicit OOHD focus as follows: Ma et al. (2022) provide an overview of empirical research about recipient preferences/behavior and how these aspects are incorporated into the operations research literature. Consequently, they focus on the interface with the recipient, while we take a more holistic view. Rohmer and Gendron (2020) set up a research agenda for problems related to OOHD. Since most papers on OOHD have been published since 2021, our literature review is much more extensive.

The main contributions of this article are:

- We provide a structured assessment of the OOHD landscape, outlining the interplay of service providers, recipients, and infrastructure in OOHD business models. We identify the emerging decisions on different planning levels for various service providers, specify recipients' behavior, and differentiate types of OOHD infrastructure.
- We identify how to translate these real-world aspects into operations research problem components. Highlighting frequently made assumptions, we introduce categories to classify the existing literature.
- Building on this, we provide a comprehensive tabular overview of the publications on the main problem types: facility location, vehicle routing, and location-routing. The tables allow the reader to quickly grasp the publications' central characteristics and research focus and enable comparisons within and across problem types. Moreover, we discuss problem-specific aspects and show how the literature deals with them.
- Finally, we present a systematic overview on research gaps and promising directions for future research by contrasting the previous research focus and real-world problem perspectives.

The remainder of this survey is structured as follows: Sect. 2 presents a characterization of OOHD through its business models, recipients, and infrastructure. Sect. 3 is devoted to the issues addressed by the OR literature and the modeling of key aspects of OOHD. It introduces the categories that form the basis of the literature overview. Sect. 4 presents overview tables for the three problem classes and comprehensively discusses problem-specific aspects. Sect. 5 maps the observations of the previous sections to the real-world perspective from Sect. 2, identifying underrepresented problem aspects and pointing out promising research directions. Sect. 6 concludes the survey.

2. Business models and their components

This section presents a holistic view of out-of-home delivery and introduces central terminology. Sect. 2.1 systematizes business models arising in the context of OOHD by taking a look at different types of service providers. For a successful business model, both addressing recipient behavior and choosing the right infrastructure are crucial. Therefore, Sect. 2.2 discusses the recipients' interests and goals, as well as their role within the OOHD process, while Sect. 2.3 provides an infrastructural perspective, concentrating on the characteristics of different types of OOHD facilities.

2.1. Providers

Businesses employ OOHD with the aim to make the delivery process more efficient. As part of the cost-intensive last mile is carried out by the recipients themselves, routing costs are lowered. Specifically, OOHD enables the consolidation of recipients and drastically reduces the number of failed deliveries. This results in shorter travel distances, travel times, as well as potentially lower service times.

In the context of OOHD, three types of business models prevail. **Facility providers** offer OOHD infrastructure, but do not themselves deliver. Businesses that offer OOHD as part of a parcel delivery concept face the strategic decision whether to use third-party OOHD facilities or to set up their own infrastructure instead. We use the term **delivery service providers** for those who utilize third-party OOHD facilities, and the term **logistics service providers** for those who build and use their own OOHD infrastructure. Fig. 1 locates the business models of selected companies in the OOHD landscape.

OOHD encompasses four major tasks, which are order capture, transport, storage, and parcel pickup. The interfaces with recipients are located at the beginning (order capture) and at the end (parcel pickup) of the overall procedure. Transport and storage take place without recipient contact. During order capture, recipients and service providers agree on delivery modalities, e.g., under which conditions a recipient accepts OOHD. Last-mile parcel delivery operations then start from a regional depot. Orders are deposited at publicly accessible facilities. As soon as the parcels are dropped off at such a facility, the recipients are informed and can retrieve them at a convenient time.

This survey focuses on the last mile, as OOHD primarily impacts this part of the delivery process. We also omit the discussion of business models that are integrated even further (e.g., Amazon). Note that multiple process steps occur between order capture and last-mile delivery, such as order assembly and long-haul shipping. As these do not involve recipient interaction, they are out of the scope of this review.

Depending on the business model pursued, different decisions arise at various planning levels.

Delivery service providers, on the daily operational level, construct route plans for the delivery vehicles and determine final delivery locations for the day's recipients. The basis for efficient delivery is established on the tactical planning level. Here, the delivery service providers face several decisions affecting the scope of operational decision making. First, they need to specify a delivery concept, i.e., a set of delivery modes. These delivery modes may encompass traditional home delivery (HD), out-of-home delivery (OOHD), attended home delivery (AHD) as well as less established delivery modes such as crowdshipping and delivery to the trunks of the recipients' cars. Second, delivery service providers need to set up a network of third-party OOHD facilities. These cooperations may be arranged with individual business owners (e.g., kiosks, florists), chains (e.g., gas stations), or dedicated providers of OOHD infrastructure (facility providers). Usually, monetary compensations are paid to the third-party companies. Third, delivery service providers need to incentivize recipients to opt for delivery products that include the possibility of OOHD. Apart from configuring an attractive OOHD network, this can be implemented through appropriate pricing and marketing of the respective products (e.g., discounts on OOHD products). Last, delivery service providers need to supply a fleet of delivery vehicles and delivery staff. Of course, these four major aspects are highly interrelated, such that the alignment of these decisions is paramount. Examples of delivery service providers are, as shown in Fig. 1, UPS and FedEx.

Facility providers do not transport parcels themselves but take an auxiliary role in the delivery process by supplying and maintaining a network of storage facilities that enables pickup by the recipients. Consequently, the business model of facility providers consists in selling storage capacity to delivery service providers or local retailers. While OOHD storage facilities come in two forms, i.e., automated parcel lockers and manned parcel shops (cf. Sect. 2.4), the term facility provider refers to a business that manages a network of parcel lockers. Examples include Pick in Singapore and the Chinese facility provider Hive Box. Parcel shops, instead, are usually either operated by individual third-party businesses or by the delivering company itself. Facility providers face many challenging decisions. First, they need to allocate capacities to users (i.e., delivery service providers). This can take place on either the tactical or the operational (daily) planning level. Second, facility providers need to make their networks of lockers attractive to the recipients, because only then will delivery service providers have an interest in using the infrastructure. As the attractiveness of a locker in large part depends on the distance to the recipients, it is sensible to set up a dense locker network. Here, a central tradeoff between the number of recipients attracted and the setup costs for each additional locker must be evaluated. Third, facility providers need to establish contracts with delivery service providers and other users. Revenue can be generated through variable usage fees for compartments as well as long-term rentals and collaborations. Fourth, facility providers need to design the locker layout, i.e., determine a configuration of different types of compartments.

Logistics service providers combine the business models presented so far by delivering parcels and using a self-built OOHD infrastructure. These are mostly larger logistic companies like DHL, GLS, and DPD or national postal services like Australia Post and Poczta Polska from Poland, since the setup and maintenance costs of a proprietary locker network are only worthwhile for larger parcel volumes. Logistic service providers face many of the challenges already discussed. In short, they need to set up a network of OOHD facilities, and, if applicable, design locker layouts, they need to establish a delivery concept, and incentivize recipients to accept OOHD. Furthermore, they need to take care of route

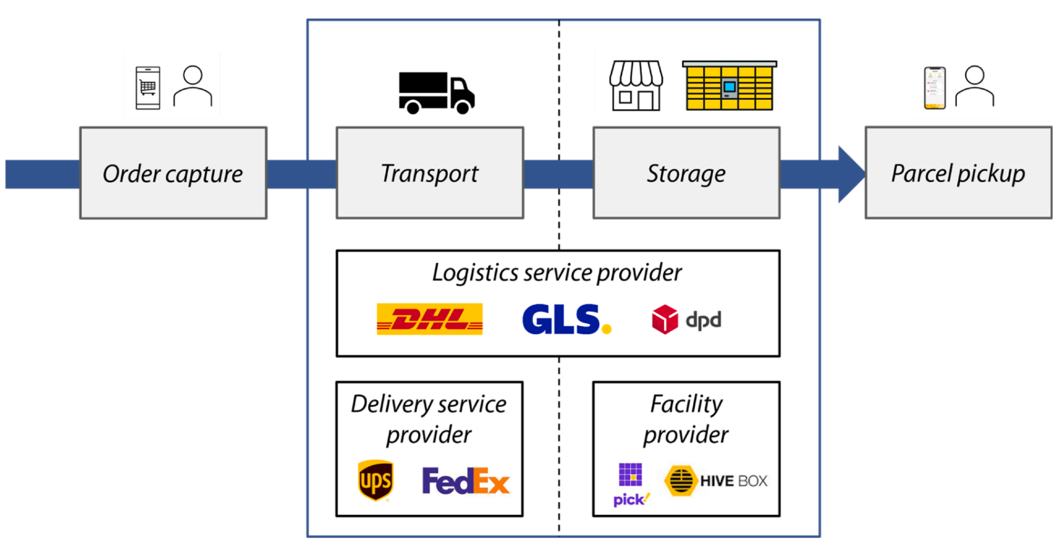

Fig. 1. OOHD business models.

plans as well as delivery vehicles and delivery staff. As the location decisions reside on a strategic planning level, they have massive repercussions for the routing decisions on the tactical and operational levels. For example, it is not straightforward to weigh up the advantages and disadvantages of a dense locker network (high setup cost, large number of recipients attracted, large potential routing savings), as they take hold on different planning levels.

2.2. Recipients

Recipients expect a fast, affordable, and reliable delivery of their orders. OOHD can contribute to make this possible through a) a generally improved efficiency on the last mile and b) a reduction in delivery failures, which are expensive and delay-inducing. However, recipients also value convenience. As OOHD requires the recipients' cooperation in the pickup process, it may be perceived as inconvenient.

The integration of recipient behavior in the delivery process therefore plays a major role for OOHD service providers. Recipient behavior influences the OOHD process in two ways: First, recipients select a delivery mode during order capture and thus determine possible delivery locations. Second, the recipients' time of parcel retrieval is uncertain, causing capacity availabilities to fluctuate.

The recipients' preferences regarding OOHD are diverse and depend largely on their daily routines. There are recipients who want to be supplied exclusively at home or exclusively at an OOHD facility as well as recipients who generally or under certain conditions consider both delivery modes. Recipients who might only accept HD are, for example, businesses which expect large delivery quantities and generally exhibit a reduced chance of failed delivery, as well as elderly people for whom the process of picking up a parcel from an OOHD facility involves greater effort. On the other end of the spectrum are private recipients who are often off to work during the day and, consequently, experience failed deliveries at a high rate. These recipients might insist on OOHD, as they want to pick up the parcel during their lunch break or on their way home. Lastly, a third group of recipients considers both forms of delivery, taking into account the specific delivery modalities. In the case of HD, this could be a guaranteed time window within which the delivery takes place. Regarding OOHD, recipients usually have a maximum willingness to walk or expect monetary compensation.

From a service provider perspective, recipients that consider delivery modes based on OOHD are advantageous, as they enable the consolidation of multiple recipients at a single delivery location. Furthermore, recipients possibly exhibit up to two types of location flexibility. Some recipients may be visited either at an OOHD location or at their home location. For others, multiple OOHD facilities may constitute feasible delivery locations (cf. Sect. 3.3).

Note that, in real-world applications, the customer of a provider of last-mile delivery and storage services is often not the recipient but the sender. We will nevertheless use the term 'customer' to describe the parcel recipients (end consumers) from Sect. 3 onward, as the overwhelming majority of publications uses the term in this way.

2.3. Infrastructure

The backbone of any OOHD business model are publicly accessible facilities which serve as drop-off points for the delivery service providers, as temporary storage facilities, and as pickup points for the recipients. We refer to these facilities as OOHD facilities. In practice and in the scientific literature, many different terms are used to describe OOHD facilities (e.g., pickup stations, shared delivery locations, collection-and-delivery points, automated parcel lockers, etc.). This variety and a lack of clearly defined characteristics make it difficult to distinguish between different types of OOHD facilities and their applications and requirements.

In real-world applications, a distinction is made primarily between parcel shops and parcel lockers. Typical parcel shops are postal stations, gas stations, or retail stores, whereas the term parcel locker refers to an unmanned storage unit consisting of several lockable compartments. Recipients get one-time access via mobile applications or access codes. Table 1 summarizes the main differences between the two types of facility:

The capacity of a parcel locker is strictly limited by the number and size of installed compartments. If a compartment is larger than the parcels to be stored, it is conceivable to place several parcels in one compartment. However, to ensure that recipients only have access to their own parcels, it is not possible to place parcels of multiple recipients into a single compartment. Therefore, at a given point in time it is impossible to supply more recipients than compartments available. Furthermore, some parcels may be prohibitively large or unwieldy to fit any compartment. In contrast, the capacity of parcel shops is typically not defined by the number of parcels, but by the space needed to store them. In fact, the storage area is sometimes large enough to render capacity limits irrelevant for most practical applications. Basically, the available capacity of parcel lockers and shops is not static but changes dynamically due to the influence of recipient pickup and possible returns.

The pickup experience at a parcel locker is completely contactless. Recipients have access authorization for their parcel, for example, in the form of an alphanumerical password or a QR code. Parcel lockers verify the recipients' identity and automatically open the corresponding compartments so that the parcels can be retrieved. In a parcel shop, the recipient interacts with an employee instead of a machine. Employees check the recipients' identity and hand over the parcels. This process might be preferred by non-tech-savvy recipients. However, parcel shops may experience waiting times as several tasks need to be handled by human employees.

Parcel shops and parcel lockers also differ in their availability, i.e., in the time interval in which recipients can pick up their parcels. In the case of parcel shops, an employee must be on site to hand over the parcel. The possible time of collection is therefore usually limited to the opening hours of the shop. In the case of parcel lockers, the location of the locker is decisive for its availability. If this place is unrestrictedly accessible, recipients can pick up their parcel 24/7. In both cases, service providers may limit the total storage time, forcing recipients to retrieve their parcels within a span of a certain number of days. If the recipients fail to pick up their parcels in time, they are returned to the sender.

The location of OOHD facilities is a critical success factor of an OOHD network, as it influences the number of recipients interested in using it. Places like public transport stations and shopping centers, which have a high number of visitors, therefore constitute ideal locations for OOHD facilities. However, it is usually more difficult and expensive to establish OOHD facilities at such attractive locations. Parcel shops are most often integrated into existing local offices of the service provider or into third-party businesses. Consequently, a network

Table 1
Differences between parcel shops and parcel lockers.

	parcel shop	parcel locker
capacity restrictions	(limited) storage area	limited number, compartments
pickup experience	human interaction	machine interaction
temporal accessibility	opening hours	24/7
facility placement	existing (third-party) businesses	purpose-built
arising costs	salaries/fees, rental	setup, maintenance, rent

of parcel shop cooperations needs to be established. Parcel lockers are purpose-built in public or semi-public spaces. However, not every location is adequate, since parcel lockers require power, internet access, and sufficient space.

There are also differences between parcel lockers and shops in terms of the costs incurred, which must be taken into account when setting up or planning to use an OOHD infrastructure. In particular, parcel lockers require high initial investments for acquisition and installation as well as periodically occurring expenditures for maintenance and rent if the lockers are not on the property of the locker owner. With parcel shops, on the other hand, the running costs are dominant. When operating own shops, salaries for employees and other operational costs are incurred. In the case of integrating the parcel shop into an existing third-party business, the owner must be paid a compensation. This compensation may be designed in many ways. For example, fixed or volume-based payments are conceivable.

Due to a lack of a widely accepted definition, the existing OR literature on OOHD does not distinguish clearly between parcel shops and parcel lockers. Also, for reasons of generalization and tractability, most papers only consider a subset of the characteristics relevant in practice. Therefore, we will refrain from categorizing publications as dealing with either parcel lockers or parcel shops. Instead, we refer to both variants as OOHD facilities and point out specific characteristics if necessary.

3. General problem characteristics

The scientific community has put forward a great variety of OR problems in the context of OOHD. To avoid repetitions in the following sections, this section provides an overview of general problem aspects regardless of the specific problem type. It lays the foundation for the discussion and classification of the scientific literature in Sect. 4. Specifically, Sect. 3.1 introduces the types of objective and types of decisions. The subsequent sections present common assumptions regarding facilities (3.2), customers (3.3), and the stochasticity and dynamism of the studied problems (3.4). Sect. 3.5 defines categories for the central managerial research questions pursued. Sect. 3.6 gives an overview over the terminology and categories used in Sect. 4.

3.1. Decisions and objectives

Optimization in the context of OOHD comprises three major decisions, which we will refer to as location, routing, and assignment decisions. The location decision describes the selection of suitable locations for OOHD facilities. Routing decisions concern the determination of route plans, i.e., sequences of delivery locations to be visited by delivery vehicles. Assignment decisions, i.e., the selection of final delivery locations for all customers, enable the exploitation of the customers' location flexibility. Note that not all three decisions are necessarily present in every problem formulation, but any problem discussed henceforth has decision variables pertaining to at least one of these decision types.

The literature review in Sect. 4 is divided into three sections according to the types of decision made in the publications. Sect. 4.1 discusses publications dealing with location decisions, Sect. 4.2 deals with papers focusing on routing decisions, and Sect. 4.3 looks at publications with both location and routing decisions. Assignment decisions may occur in any of the three sections. The division into three sections also mirrors the three major types of business models (cf. Sect. 2.1), with facility providers facing a pure location decision, delivery service providers solving routing problems, and logistics service providers making both location and routing decisions.

The three types of decisions are, of course, closely interlinked. Otherwise, they could be separated into multiple optimization problems without loss of solution quality. For example, the assignment possibilities depend on the locations of OOHD facilities, as does the routing of vehicles. In turn, the location decisions are guided by their consequences for assignments and routing. Decisions in the OOHD literature are not limited to the three major types. In problem formulations with a focus on the OOHD facilities, the level of detail sometimes exceeds that of a mere location decision, as locker configurations and capacities are subject to optimization. Different compartment characteristics, in turn, entail decisions assigning customers to specific compartments. Diverse delivery concepts often bring with them further decisions, such as decisions on opening satellite delivery locations and outsourcing decisions. Lastly, a small number of papers include a product-based view of OOHD, with decisions on product design, offer sets, and pricing.

The objectives pursued reflect the perspectives of the different business models. Like in the vehicle routing literature, the minimization of costs is the most common objective, although the costs are not limited to routing related costs. Especially in location routing problems, the objective includes both routing costs and costs pertaining to the opening of facilities. Emphasizing the central role of customers, many authors also include costs based on the assignment decision. A smaller group of papers, particularly in the group of facility location planners, take this a step further and incorporate revenues for customers served through the OOHD infrastructure.

3.2. Facilities

A central aspect of OOHD is the temporary storage of parcels in OOHD facilities. Depending on the type of facility and the specific problem setting, the storage capacity and parcel compatibility may be restricted. We divide the existing literature into three groups. The first group assumes uncapacitated facilities, the second group takes capacity into account on an aggregated level, and for the third group, the detailed consideration of capacity limits is in the focus of the publication.

Neglecting OOHD facilities is justified in some cases. For example, some papers work on the premise that all final delivery locations are determined prior to optimization and therefore automatically adhere to capacity restrictions. Other authors investigate last-mile settings in which OOHD takes an auxiliary function and assume that the small number of out-of-home deliveries is easily managed by the OOHD facilities.

Aggregated capacity constraints are typically expressed in terms of a maximum total volume, total weight, or a maximum number of parcels that can be stored. Typically, authors imposing a limit on the number of parcels have parcel lockers in mind, while papers implicitly or explicitly focusing on parcel shops use restrictions on the total volume or weight.

Models that consider individual parcel compartments exhibit the highest level of complexity with regard to capacity, as this often implies an assignment decision (parcel to compartment). Compartments may differ in size and number. Some papers go even further and take detailed compartment specifications, such as cooled compartments for perishable goods, into account. If compartments are considered, a distinction must be made as to whether only one parcel may be delivered to a compartment or whether several parcels from the same customer may share a compartment. Note that the modeling of unit size compartments, in which only one package may be stored at a time, is equivalent to a restriction on the maximum number of parcels. Moreover, the availability of facility capacities depends on the customers' pickup behavior, which will be discussed in Sect. 3.4.

In addition to the capacity of a facility, the publications differ in their assumptions about facility-usage, i.e., who owns the facility and which actors use it. If the facility is owned and used exclusively by the decision maker, we refer to them as proprietary OOHD facilities. Furthermore, a group of authors considers the collaborative use of facilities by multiple service providers. This assumption occurs frequently when the optimization problem is formulated from the perspective of a pure facility provider who is not involved in the operational delivery process. From the point of view of a delivery service provider that does not have its own facilities, there is also the possibility of using facilities of a third-party provider. Typically, monetary compensation must be paid to the facility provider for the use of third-party facilities. This facility provider compensation is usually modelled as a uniform fee per customer or as a function of the shipments' size.

3.3. Services and customers

As the cooperation of customers is essential for OOHD, optimization problems rely heavily on assumptions concerning customer preferences and customer behavior. In particular, the feasible delivery locations for each customer must be determined.

To this end, each customer is assumed to belong to one of three groups limiting which types of delivery service (HD or OOHD) are conceivable:

- **Only HD** service: Only the customer's home location may be a feasible delivery location.
- **Only OOHD** service: Only OOHD facilities may be feasible delivery locations.
- **Either** service: Both the customer's home location and OOHD facilities may be feasible delivery locations.

Authors employ this preselection of delivery locations for two reasons. First, as discussed in Sect. 2.2, customers may be predisposed toward different delivery services, e.g., due to their age or their daily routine. Second, the grouping of customers may be problem-driven. Examples include the case of a facility provider aiming to maximize the demand captured by the OOHD network, where OOHD is the only relevant service type. Therefore, solely the customer group 'only OOHD' is considered here. In the case of a delivery service provider using OOHD facilities with compartments, some packages might be excessively heavy and bulky to be suitable for OOHD. Hence, some customers are classified as 'only HD', while others with small shipments may receive delivery at either their home location or an OOHD facility ('either').

Resulting from this distinction of customer groups, Table 2 lists six types of settings representing all relevant combinations of customer groups.

Moreover, if customers consider OOHD, it is generally assumed that delivery cannot take place at an arbitrary OOHD facility, since customers may not be willing to travel large distances. Thus, it is important to establish which of the OOHD facilities qualify as feasible delivery locations for each customer of the groups 'only OOHD' and 'either'. Beyond the initial preselection, there exist manifold ways in the literature to take customer behavior into account when determining a set of feasible delivery locations. While some publications focus on this aspect and model customer choice explicitly, others make simplifying assumptions. We differentiate between the following broad categories of **determining feasible delivery locations** with respect to customer behavior:

1. The set of feasible delivery locations is prespecified.
   a) There are multiple feasible OOHD facilities per customer.
   b) The final delivery location of each customer is fixed.
2. The set of feasible delivery locations is determined according to a rule.
   a) Customers accept OOHD to a facility within a certain radius.
   b) Customers accept OOHD to the facility closest to them.
3. Customer choice behavior is modelled explicitly.

Table 2
Settings.

Setting type	only HD	only OOHD	either
1		✓	
2	✓	✓	
3			✓
4	✓		✓
5		✓	✓
6	✓	✓	✓

In the first group of papers, the set of feasible facilities for a customer has already been determined prior to optimization in an unspecified way. We refer to this as a **prespecified** set of OOHD facilities for a customer. This set can consist of one or more facilities. If there are multiple OOHD facilities to choose from, the service provider can decide to which of the permitted facilities the parcel will be delivered. In principle, the service provider also has a choice where to deliver the parcel if HD is a possible delivery mode for a customer in addition to OOHD. In a setting in which a customer only wants OOHD and only one facility is permitted due to preprocessing, the delivery location is already fixed and not part of the optimization.

The second group of papers determines the set of feasible delivery locations endogenously by applying predefined **rules**. We refer to this as rule-based determination. The most frequently used criterion when assessing if a facility is suitable for a customer is the distance the customer has to travel to pick up the parcel. The assumption here is that customers accept OOHD to all facilities that are located within a certain maximum distance (radius) of their home address (rule-based-radius). The second common rule is the assumption that a customer accepts only the OOHD facility closest to his home address as a possible delivery location (rule-based-closest). Note that rule-based sets of OOHD facilities do not differ from prespecified sets if the locations of OOHD facilities are not part of the optimization problem. Also, some authors who decide on facility locations strictly enforce OOHD for customers within the radius.

The third group of papers uses discrete **choice models** to account for the customers' preferences. Given an offer set which encompasses all options (modes) a customer may choose from, discrete choice models predict the probability that a specific option is selected from this offer set. Often, an outside option is included allowing customers to choose none of the other options. Discrete choice models capture uncertainty in the customer's behavior, making them the most sophisticated approach among those discussed in this section. For a comprehensive overview and a detailed description of the most prominent models, we refer the interested reader to the survey by Strauss et al. (2018). In the existing OOHD literature, parametric models rooted in random utility theory prevail. In parametric models, the utility customers associate with a specific option is decomposed into a deterministic and random component. The deterministic component is expressed as a function of different option attributes that act as explanatory variables and influence the choice probabilities, e.g., the distance between the customer and the OOHD facility.

A subset of the publications does not factor in the behavior of individual customers but instead considers the customers on an aggregated level, e.g., in the form of demand clusters. This facilitates the solution of large-scale problems but also excludes customer-specific characteristics. In these publications, customer choice is sometimes integrated through demand shifts: Depending on the distance between a demand cluster and an OOHD facility, the percentage of the demand that can be delivered to OOHD facilities varies.

Lastly, in some model formulations, the assignment of a customer to an OOHD facility incurs a payment from the service provider to the customer. This customer **compensation** is most often uniform or dependent on the distance customers must travel to pick up their parcels. Note that compensation payments are often combined with the rules presented above (e.g., OOHD is only possible to the OOHD facility closest to a customer, and if OOHD takes place, a customer compensation is paid).

3.4. Stochasticity and dynamism

Delivery processes are subject to various influences of stochastic nature. However, most papers treat the considered problems as deterministic for reasons of tractability. For those authors that do account for it, the primary source of stochasticity is the uncertainty about customer behavior. This can be divided into four major categories with direct implications for OOHD.

- First, there is an uncertainty pertaining to the **presence of the customers** themselves. At the time of planning, it might not be clear which customers are to be served on a given delivery day. This is particularly relevant for problems dealing with strategic decisions like facility location.
- Second, the decision maker might have to reckon with uncertain **customer preferences**. For example, the set of acceptable OOHD facilities might be determined through discrete choice models (cf. Sect. 3.3).
- Third, the **pickup behavior** of the customers is also of critical importance for a service provider who supplies the facilities with parcels. Due to customer pickup, a delivery service provider does not have complete information at the time of operational delivery planning as to how many or which of the previously occupied compartments have become available at the time of arrival at a facility. This results in a stochastic availability of location capacities.
- Fourth, some publications consider **failed deliveries**. OOHD and failed deliveries are closely connected, since one of the main purposes of OOHD is the elimination of failed deliveries. Failed deliveries are inherently stochastic, as they only occur because the customer's absence is unknown.

If the decision maker may react or adapt to the stochastic information revealed over time, a dynamic problem arises where decisions are made in a sequential fashion. Otherwise, the problem is of static nature. In both cases, it is crucial to anticipate potential effects of a decision that materialize once the random information becomes known.

3.5. Managerial focus

OOHD is highly relevant for parcel delivery operations on the last mile. Most publications seek to answer a variety of research questions related to business models. However, as evident throughout Sect. 3, optimization problems in the context of OOHD exhibit a high level of heterogeneity and complexity. This not only applies to the distinction between the three major types of problems (facility location, vehicle routing, location routing), but also to each of these problem classes individually, as we will discuss in Sect. 4. Due to the heterogeneity, general statements quantifying the impact of OOHD cannot be made. For example, while all studies report cost savings from the usage of OOHD, the percentage of routing cost saved varies widely depending on the delivery concepts, the delivery infrastructure, and the customer behavior under investigation. Nevertheless, we provide an overview of the central inquiries by identifying different research foci and key parameters.

It is self-explanatory that facility location and location routing problems highlight infrastructural aspects and that vehicle routing problems put an emphasis on routing modalities. The classification of further research foci encompasses eight categories, that are not mutually exclusive. Their purpose is to give the reader an impression at first glance, as to which aspects are highlighted in the specific publication. Publications might be uncategorized if they have no managerial focus (emphasizing mathematical properties or solution procedures only) or if the focus is on infrastructure and/or routing aspects.

- Comparison (Co): focus on the assessment of the solution of an optimization problem with and without OOHD, thereby setting up a comparison of delivery concepts, e.g., HD vs. OOHD.
- Configuration (Con): focus on locker layout/configurations.
- Customer (Cu): focus on intricate customer choice behavior or service level restrictions.
- Environmental (Eco): focus on environmental impact of OOHD or eco-friendly delivery concept.
- Innovative delivery concept (IC): focus on non-traditional delivery modes (apart from OOHD), such as crowdshipping.
- Long-term (LT): focus on long-term view of OOHD networks.
- Product (Pro): focus on the integration of different delivery product specifications, pricing considerations.
- Real world (RW): focus on cooperations with businesses, large-scale application.

In addition to the managerial focus of the studies, we point out the investigation into the following crucial parameters and assumptions of OOHD optimization problems: number of OOHD facilities (N), determination of feasible delivery locations (L), compensation/assignment cost (A), facility opening cost (F), capacities and/or configurations (C), pickup behavior (P).

3.6. Overview

In this section, we summarize the distinctions of the Sects. 3.1 through 3.4. The section serves as an overview of the entries used in the classification tables in Sect. 4. For the objective function (column **Obj.**), we distinguish between routing costs (R; including distance-based costs and other routing-related costs such as vehicle fix costs), costs for the setup and operation of facilities (F; OOHD facilities, satellite facilities, etc.), costs depending on a customer's final delivery location (customer compensation (CC), facility owner compensation (FOC), unspecified assignment costs (A), compensation for crowdshippers (CS)), revenues (Rev), demand captured (D), externalities (Ext), service level/customer satisfaction measures (S), and penalties (P; e.g., for failed deliveries, non-deliveries, and late deliveries). OOHD facilities are characterized through their **capacities** and the usage model considered. A checkmark (✓) indicates whether capacities are taken into account. Some papers go into greater detail by differentiating between different compartment characteristics (C). Concerning the usage/ownership model, we distinguish between proprietary (P), collaborative (C), and third-party (3P).

The groups of customers and the determination of feasible delivery locations (particularly, their eligibility for OOHD) are of great significance. The **setting** types correspond to the ones introduced in Table 2. An asterisk indicates that customers are not considered individually. Regarding the determination of feasible delivery locations (column **Loc.**), we distinguish between rule-based approaches (radius (R-R), closest (R-C)), prespecified sets of possible delivery locations (PS), and fixed locations (Fix), as well as the integration of discrete choice modelling (DC). Papers without the modelling of individual customers might include demand shifts (DS), signaling that the percentage of OOHD demand varies depending on the location of OOHD facilities. Some publications impose no restrictions (NR) on location feasibility, instead evaluating assignment decisions in the objective function. In the context of location routing, forced OOHD (Fc) for customers in the vicinity of an opened facility is a further category.

The types of stochasticity are tracked in the column '**Stoch.**', with possible entries for preferences (Pr), customer pickup (P), demand (D), failed deliveries (FD), and travel times (TT). The column '**Dyn.**' indicates whether some decisions are made dynamically.

The tables of Sect. 4 also briefly state the type of **solution procedure** applied. We use the following abbreviations in alphabetical order: ABS (agent-based simulation), ACO (ant colony optimization), ALNS (adaptive large neighborhood search), ASA (active set algorithm), BBO (biogeography-based optimization), BP&C (branch-price-and-cut), B&B (branch-and-bound), B&C (branch-and-cut), B&P (branch-and-price), BD (Benders decomposition), BPP (bin-packing problem), CA (continuum approximation), C&W (Clarke & Wright savings algorithm), CLP (constraint logic programming), DP (dynamic programming), FP (fixed policies), GA (genetic algorithm), GMM (Gaussian mixture model), GS (greedy search), ILS (iterated local search), KT (kernel transformation), LS (local search), MH (matheuristic), MIP (exact solution of mixed integer program), ML (machine learning), PFA (policy function approximation), PSO (particle swarm optimization), QP (quadratic program), SA (simulated annealing), SC (set covering, set partitioning), SO (simulation–optimization), TS (tabu search), VND (variable neighborhood descent), VNS (variable neighborhood search).

In addition to these general characteristics, we identified three problem-specific columns that will be discussed in-depth in the respective sections. For the sake of completeness, we briefly list these columns and their abbreviations in the following:

- The OOHD infrastructure problems in Sect. 4.1 can be categorized into three groups (column **Problem type**): The first group examines the tradeoff between system costs and coverage (C vs. C). The second group aims to maximize the demand captured under budget constraints (D vs. B). Lastly, the third group considers the profit resulting from the subtraction of system costs from the revenues obtained (Profit).
- Routing characteristics are only relevant for the VRPs and LRPs discussed in Sects. 4.2 and 4.3, respectively. The corresponding column (**Rout.**) shows common variations of the classic capacitated vehicle routing problem, including problems with a two-echelon (2E) and three-echelon (3E) network structure, time windows for home delivery (TW), multiple depots (MD), and multiple trips per vehicle (MT). Furthermore, the column indicates whether a pickup-and-delivery problem (PDP) is studied, whether roaming delivery locations (RDL) are considered, whether split delivery (SD) may occur at OOHD facilities, whether OOHD facilities may possess customer-specific time windows (OTW), whether the routing for HD and OOHD is separated (Sep), whether electric vehicles are used (EV), and whether a single vehicle (TSP) case is investigated.
- Lastly, we highlight distinctive problem aspects in all three sections (column **Spec. features**). This includes capacity decisions for OOHD facilities (CD), the configuration of OOHD facilities without a location decision (NLD), the location planning of facilities not specific to OOHD (OF), the possibility to adapt the delivery network over time (NA), the explicit differentiation between parcel lockers and shops (Fac), and a minimum utilization of facilities (U). Moreover, there are publications that consider cancellations (Canc), failed deliveries (FD), crowdshipping (CS), the dispatching of vehicles (Disp), returns (Ret), or demand-dependent service times (ST). Focusing on the customer interface, some papers deal with differentiated services (S), offer sets (OS), pricing (Pric), or preference lists (Prio). A handful of problems work in a multi-period setting (MP).

4. Literature review

Last-mile delivery concepts incorporating OOHD involve three major types of decisions concerning a) the location of OOHD facilities, b) the routing of delivery vehicles, and c) the assignment of customers to delivery locations. We broadly group the literature review according to the first two types of decisions. Sect. 4.1 addresses publications that focus on the placement and layout of facilities to establish a customer-attracting OOHD network. Sect. 4.2 reviews publications that formulate routing problems, aiming to capture the potential of OOHD. Sect. 4.3 presents works that integrate the strategic location decision and the operational routing decision and discusses approaches of dealing with the complexity resulting from the entanglement of different planning levels. This trichotomy mirrors the perspectives of the different business models (facility providers, delivery service providers, logistics service providers). Sect. 4.3 further includes a short summary of the literature on the novel technology of mobile parcel lockers.

Following established frameworks in the literature, our survey is a narrative (Snyder, 2019) and scoping (Schryen and Sperling, 2023) review. To identify relevant publications, we employed the scientific databases Google Scholar and Web of Science. As OOHD is an emerging research topic, we did not impose any temporal restrictions and considered work starting from the earliest relevant publication dating back to 2014 up to and including January 2024. We selected keywords such as ‘out-of-home deliver*’, ‘delivery option*’, or ‘parcel locker*’ along with its synonyms (cf. Sect. 1), further refining the search with ‘optimi?ation’ or ‘last-mile’ if necessary. Using wildcards and asterisks, we hedged against different spelling variants and account for both singular and plural forms of words. In addition, we performed backward and forward searches. Regarding formal inclusion criteria, our survey only encompasses work available in English. Furthermore, we mostly limited the discussion to journal articles, but, recognizing that OOHD is a rapidly evolving literature stream, we made exceptions for highly relevant conference proceedings and working papers that put forward a novel perspective or problem. We assessed the relevance of publications through a manual screening process based on four criteria: Our survey covers publications on 1) optimization problems in the context of 2) parcel delivery featuring 3) dedicated OOHD infrastructure, with which 4) recipients interact to receive their parcel (cf. Sect. 1).

In total, the publications stem from 39 different journals, with ‘Transportation Research Part E: Logistics and Transportation Review’ (10 publications), ‘Computers & Operations Research’ (6) and ‘European Journal of Operational Research’ (4) the only journals with more than three relevant OOHD publications. Fig. 2 shows the temporal distribution of publications regarding the three major problem types: facility location, vehicle routing, and location routing (including mobile lockers).

The publications in this survey posit a great plurality of optimization problems. While the publications focusing on facility location problems (4.1) can be divided into three broad groups according to key modelling choices, the variety of delivery modes and network structures make such a classification impossible for the other groups of publications (4.2, 4.3). To ease readability, the structures of the three sections follow a similar pattern. In a first subsection, we outline main research themes and describe the perspective taken by the authors. In a second subsection, we then discuss key aspects of each problem type, including the underlying OOHD infrastructure, stochastic influences, and the most common class of solution procedure. Furthermore, we highlight distinctive, problem-specific features.

We acknowledge that our style of presentation comes at the expense of a detailed description of each individual paper. To mitigate this, each section includes a tabular overview where the characteristics introduced in Sects. 3.1 to 3.5 are represented in corresponding columns. Additionally, each table contains a column for the solution procedure and special features of individual publications respectively. Lastly, the table in Sect. 4.1 features a column classifying the publications according to their problem type, whereas the tables of Sects. 4.2 and 4.2 include a column on routing characteristics. This approach allows us to dedicate

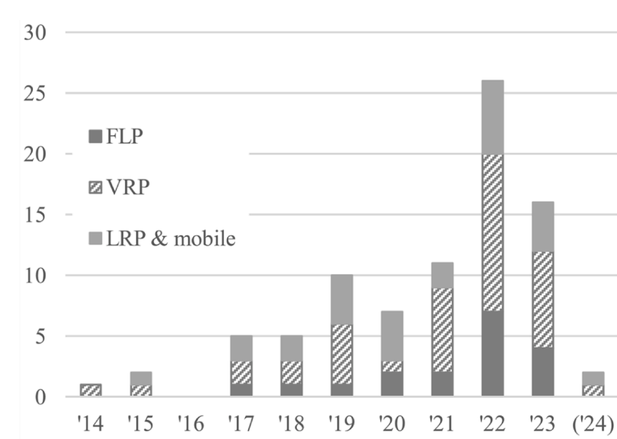

Fig. 2. Number of publications per year *Note:* The decline in 2024 is due to the fact that our review only covers publications up to and including January 2024.

the discussion in the main body of the text to insights attained through the comprehensive study of the literature while conveying the central components and assumptions of the individual publications in tabular form.

4.1. OOHD infrastructure problems

In the first group of problems, the focus is on the OOHD infrastructure. These problems do not have routing components and therefore abstract from a concrete delivery process. Their purpose is to determine a setup (most often a set of locations) of OOHD facilities so as to create an attractive OOHD network. As the setup of lockers requires a lot of preplanning and high initial investments, these are usually long-term, strategic decisions. For a detailed characterization of the individual publications in this section, we refer the reader to Table 3.

4.1.1. Research focus

A fundamental characteristic of OOHD infrastructure problems is that the location decisions influence the customers' demand behavior. Opening or not opening a specific OOHD facility leads to demand 'moving' from one location to another or to demand being lost altogether (with customers choosing the 'outside option'). Hence, the primary driver of the location decisions are the ensuing demand consequences, making this group of papers generally customer-centric. This manifests itself in different ways, including the types of problem under investigation which can be grouped into the following three broad categories:

- The first group are problems minimizing the system cost. This type always occurs in combination with constraints ensuring that a minimum percentage (in some cases: all) of the customers must be covered, i.e., served by an OOHD facility. Otherwise, no facilities would be opened keeping the costs at 0. Examples of papers investigating the tradeoff between system costs and coverage include Ottaviani et al. (2023) and Xu et al. (2021). Every customer must be assigned in, e.g., Lee et al. (2019) and Wang et al. (2022c).
- The second group consists of problems that aim to maximize the demand captured. Likewise, this is only sensible in the presence of additional restrictions, i.e., a maximum number of OOHD facilities or a maximum budget (e.g., Wu et al., 2015; Kahr, 2022; Tadić et al., 2023).
- The third group of papers contrasts revenues for customers served and facility opening (or other) costs. No additional constraints are required in this case, as the optimization automatically aims to strike a balance between the two components of the objective function by maximizing profit (e.g., Deutsch and Golany, 2018; Sweidan et al., 2022; Lin et al., 2022).

Fitting for problems without routing components, almost all publications assume customers that can exclusively be served out-of-home (i. e., customer setting 1 in Table 2). Some authors start from the premise that all customers must be served by the OOHD network, others assume that the location decision determines a subset of customers that are served. Herein lies a difference to the routing-related problems of Sects. 4.2 and 4.3, which – with a few exceptions – require every customer to be served.

Since no routing is performed, the perspective taken is usually that of

Table 3
Facility location problems.

	Obj.	Facilities		Customers		Stoch.	Dyn.	Problem type	Spec. Features	Sol. Proc.	Managerial	
		Cap.	Usage	Setting	Loc.						Param.	Focus
Deutsch and Golany (2018)	F, Rev, CC		C	1*	DS, R-C			Profit		MIP		
Faugère and Montreuil (2020)	F, Rev, A	C	C	1*	NR	D		Profit	NLD	MIP	C, F	Con, Cu
Kahr (2022)	D	C	C	1	R-R	D		D vs. B		BD	C, F, L, N, P	Con, Cu
Lee et al. (2019)	A		C	1	R-R, R-C			C vs. C		MIP	L	
Lin et al. (2020)	D		C	1*	DC	Pr		D vs. B	NA	MIP, PSO	L, N	Cu
Lin et al. (2022)	F, Rev		P	1	DC	Pr		Profit	OS	QP	L	Cu, Pro
Luo et al. (2022)	F, S	C	C	1*	R-R			C vs. C		ML, GA	L, P	Con, RW
Lyu and Teo (2022)	D		C	3	DC	Pr		D vs. B		MIP	N	Cu, RW
Mancini et al. (2023)	D, A	✓	P	1	R-R	D, P		D vs. B		ILS, MH	L, P	Cu
Ottaviani et al. (2023)	F	✓	P	1	R-R, R-C	D		C vs. C	CD	GS	L, N	
Rabe et al. (2021)	F, A	✓	C	1*	NR	D		C vs. C	NA, U	SO (MIP)	N	LT
Raviv (2023)	F, P	✓	P	1*	R-R, R-C	D, P		C vs. C	CD	MIP		
Sawik et al. (2022)	F, A	✓	P	1	NR	D	✓	C vs. C	NA, U	ABS		LT
Sweidan et al. (2022)	F, Rev, CC	✓	C	1*	DS			Profit		MIP	C	
Tadić et al. (2023)	A		C	1	R-C			D vs. B		SA	N	
Wang et al., (2022c)	F	C	C	1	R-R, R-C	D, P		C vs. C	CD, Ret	MIP		Cu
Wu et al. (2015)	D, A		C	1	R-R, R-C			D vs. B		GMM, KT		Cu
Xu et al. (2021)	F	✓	P/3P	1	R-R	D	✓	C vs. C	Fac, NA	MIP	N	

(cf. Sect. 3 for explanations of abbreviations. *Objective:* assignment (A), customer compensation (CC), demand (D), facilities (F), penalties (P), revenue (Rev), customer satisfaction (S) | *Capacity:* capacity of OOHD locations considered (✓), compartments (C) | *Usage:* collaborative (C), proprietary (P), third-party (3P) | *Setting:* Table 2, Sect. 3.3 (1–6), customers not modelled individually (*) | *Location (determination of feasible delivery locations):* discrete choice (DC), demand shift (DS), no restriction (NR), rule-based 'closest' (R-C), rule-based 'radius' (R-R) | *Stochasticity:* demand (D), customer pickup (P), preferences (Pr) | *Problem type:* cost vs. coverage constraints (C vs. C), demand vs. budget constraints (D vs. B) | *Special features:* capacity decision (CD), locker vs. shop (Fac), network adaption (NA), no location decision (NLD), offer sets (OS), returns (Ret), minimum facility utilization (U) | *Solution procedure:* agent-based simulation (ABS), Benders decomposition (BD), genetic algorithm (GA), Gaussian mixture model (GMM), greedy search (GS), iterated local search (ILS), kernel transformation (KT), matheuristic (MH), mixed integer program (MIP), machine learning (ML), particle swarm optimization (PSO), quadratic program (QP), simulated annealing (SA), simulation optimization (SO) | *Parameters investigated:* facility capacity/compartments (C), facility opening cost (F), determination of feasible delivery locations (L), number of OOHD facilities (N), pickup behavior (P) | *Managerial focus:* configuration (Con), customer (Cu), long-term (LT), product (Pro), real world (RW)).

a facility provider aiming to attract customers. Nevertheless, some papers implicitly or explicitly solve an optimization problem of a logistics service provider, i.e., a company that not only provides OOHD facilities, but uses them itself (cf., e.g., Mancini et al., 2023). Although no explicit routing costs are considered, in these cases, the optimization of the OOHD network is used as a proxy. This relies on the assumption that a higher number of customers served out-of-home leads to a greater reduction in routing costs.

4.1.2. Selected problem characteristics

The general emphasis on the customers described in Sect. 4.1.1 is also evident in the high number of papers studying **stochastic influences,** all of them relating to customer behavior.

- First, some authors explore the stochastic relationship between the open facilities and the customers' location choice. Lin et al. (2020), Lin et al. (2022), and Lyu and Teo (2022) all employ discrete choice modeling to capture the impact of OOHD network design on the customers' decision making. In this way, the location decision is closely tied to the customers' location choice. The most important explanatory variable in their choice models is a customer's distance to the nearest locker. Lyu and Teo (2022) also find a significant effect of the type of locker location, i.e., the locker's proximity to a shopping mall and a metro station. Going beyond influencing customer choice through facility placement, Lin et al. (2022) actively restrict a customer's offer set (choice of delivery options). Due to the intricacy and the computational consequences of discrete choice modeling, most authors, however, opt for a deterministic modeling of customer preferences, implementing the assignment of customers to lockers within a prespecified radius or to the nearest locker.
- The second and most common stochastic influence is the makeup of the set of customers. As the problems discussed in this section are of strategic nature most authors do not assume perfect knowledge about which customers are present (e.g., Kahr, 2022; Ottaviani et al., 2023). Related to this is another aspect exclusively seen with this problem type: long-term design of the locker network. Both Rabe et al. (2021) and Sawik et al. (2022) use simulation–optimization techniques to investigate a multi-year development of the OOHD infrastructure in a growing e-commerce market. Xu et al. (2021) also regard long-term location decisions. In their problem formulation, the facility provider periodically solves a facility location problem in order to react to dynamically arising customer demand.
- A third type of stochasticity is introduced through customer pickup behavior. Since slow pickups use up storage capacity, they have consequences for the efficiency of the OOHD system, e.g., other parcels may need to be rerouted to other OOHD facilities or cannot be handled at all. Mancini et al. (2023) integrate such stochastic capacities. Wang et al. (2022c) propose a robust optimization model to deal with uncertain demand (including returns) as well as customer pickup behavior.

In addition to the selection of a suitable location, the **configuration** of an OOHD facility should not be neglected.

- A group of authors makes decisions on the capacity of OOHD facilities (Raviv, 2023; Wang et al., 2022c; Ottaviani et al., 2023). Luo et al. (2022) differentiate between two types of locker compartments and investigate a multi-objective problem, in which they directly contrast the lockers' ability to serve customer demand (of both types) and the network setup cost in the objective function.
- On a more granular level, Faugère and Montreuil (2020) focus on the detailed composition of parcel lockers consisting of different sized compartments with the goal of serving as many customers as possible under diverse demand scenarios. Kahr (2022) jointly optimizes the location and configuration of parcel lockers, maximizing the expected demand captured by the locker network.
- Concentrating on the facilities' layout, a few papers do not include a location decision (Faugère and Montreuil, 2020).

While most authors address the initial problem of a facility provider, i.e., the creation of a new network of facilities, others include the adaption of an existing OOHD infrastructure (e.g., Lin et al., 2020; Sawik et al., 2022). **Adapting a network** can involve building new facilities as well as closing or replacing existing ones. Often, adapting a network is part of long-term infrastructure considerations and subject to additional constraints like a minimum level of locker utilization.

Generally, facility location problems exhibit lower complexity when compared with the other major groups of problems due to the exclusion of vehicle routing. This enables the widespread use of exact **solution procedures** (see Table 3) and the examination of other problem aspects at a level of detail rarely seen with other problem types. For example, this is apparent in the work of Lyu and Teo (2022), who expand on the estimation of customer choice behavior and the calibration of the corresponding choice model. Also, the fine-grained planning of locker module configurations, as incorporated in Faugère and Montreuil (2020) and Kahr (2022), is hardly ever present in problems with vehicle routing.

Nearly all papers work under the (implicit) assumption that the decision maker (most often a facility provider) opens the facilities for **collaborative** use by multiple delivery service providers and/or local business owners. However, to our knowledge, no research has yet gone into the nature and design of the contracts between facility providers and facility users and this aspect is not taken into account in the papers listed here (cf. Sect. 5). The designation of facility usage as collaborative or proprietary has little consequence, as in all papers a general group of customers and locations is considered, without apparent influences from possible businesses using the lockers.

4.2. Vehicle routing problems

Due to the large number of stops, the considerable distance covered, and a high number of failed delivery attempts, the conventional delivery process on the last mile is particularly cost-intensive. Delivery concepts centered on OOHD can enhance last-mile efficiency by consolidating orders, i.e., by grouping nearby customers into a single delivery location. As the delivery process involves no direct handover from the delivery person to the customer, failed deliveries can be avoided almost completely. Capturing the potential of these operational advantages, a second group of papers focuses on vehicle routing aspects. Basis of this planning is a given network of OOHD facilities, which can either be used proprietarily or rented from a third-party provider in exchange for monetary compensation. Table 4 review the individual publications in depth.

4.2.1. Research focus

The authors of papers in this subsection mostly take the perspective of a delivery service provider or logistics service provider with an established OOHD network. Focusing on short planning horizons (e.g., a single delivery day), they consider operational planning problems. The decisions to be made typically consist of the assignment of customers to a delivery location and the resulting routing decision. The objective is usually to supply all customers at minimum total cost. In addition to routing costs, the assignment of a customer to an OOHD facility can entail various costs, such as compensation to customers or facility owners (if authors consider a third-party facility network). These costs are mostly taken as given and their influence on the allocation and resulting route plans is examined.

With the aim of quantifying the savings potential of OOHD regarding costs on the operational level, most authors compare concepts that include the possibility of OOHD with other, more traditional, delivery concepts. They are therefore contrasted to home delivery (e.g., Janinhoff et al., 2023), attended home delivery (e.g., Dumez et al., 2021),

Table 4
Vehicle routing problems.

	Obj.	Facilities		Customers		Stoch.	Dyn.	Rout.	Spec. features	Sol. proc.	Managerial	
		Cap.	Usage	Setting	Loc.						Param.	Focus
Akkerman et al. (2023)	R, CC, Rev, P		P	3	DC	D, Pr	✓	SD	FD, Pric	ML	L, A, N	Co, Cu, Pro
Arnold et al. (2018)	R, Ext		P/3P	2	Fix			2E	FD	C&W	A, N	Co, Eco, RW
Boschetti and Novellani (2023)	R, CC	✓	P	3	PS			TSP		B&C	A, N	Co, IC
Buzzega and Novellani (2022)	R, A	✓	P	3	R-R			TW		B&C	N	Co
Dell'Amico et al. (2022)	R, CC	✓	P	6	PS			OTW, TW	Ret	B&C		Co
dos Santos et al. (2022)	R, CS	✓	P	2	Fix	P	✓	2E	CS	MIP	C, P	IC
Dragomir et al. (2022)	R		P	3	R-R			PDP, RDL, TW		ALNS, VND		Co, IC
Du et al. (2021)	R, Rev, P	✓	P	2	Fix	P	✓	MT, SD, TSP	Ret	ML	P	Cu
Dumez et al. (2021)	R	✓	P	6	PS			TW	Prio, ST	ALNS, SC		Co, Cu
Escudero-Santana et al. (2022)	R, S		P	6	PS			RDL, TW	Prio	GA, SA, TS		Co, Cu, IC
Galiullina et al. (2024)	R, CC		P	3	R-C	Pr	✓	TSP	Pric	B&B		Pro
Grabenschweiger et al. (2021)	R, CC	C	P	3	PS			TW		ALNS, BPP	C	Con
Gutenschwager et al. (2023)	R, A		P	1	R-C					C&W, LS	N	Cu, Eco
He et al. (2020)	R		P	2	Fix	D	✓	TW	Canc	DP, MH	L	Co, Cu
Janinhoff et al. (2023)	R, FOC	✓	3P	6	R-R			MT	ST	ALNS, TSP, BPP	L	Co, Pro, RW
Jiang et al. (2019)	R, CC, FOC	✓	3P	3	R-R			TSP, TW		VNS	A, N	Co
Jiang et al., (2022a)	Rev, FOC	✓	3P	3	R-R			TSP		VNS	C, L, N	
Jiang et al., (2022b)	R, FOC		3P	6	R-R			TSP		BBO, LS		
Leung et al. (2022)	R, S		P	2	Fix	D	✓		Disp	FP, TS		Cu, IC
Mancini and Gansterer (2021)	R, CC	✓	P	6	R-R			TW		MH, ILS	A, L	Co, Cu
Orenstein and Raviv (2022)	D, S	✓	P	1	Fix	D, P		PDP, SD	MP	MIP		Cu, IC
Orenstein et al. (2019)	R, P	C	P	1	PS	P	✓		ST	C&W, MIP, TS	L, N	Cu
Pahwa and Jaller (2023)	R, F, Ext	✓	3P	3*	NR	D	✓		OF	CA, MIP		LT
Pourmohammadreza and Jokar (2023)	R, CC	✓	P	6	PS				Prio, Ret	MIP	A, L	Co, Cu
Sitek and Wikarek (2019)	R, A	✓	P	6	PS				Ret	CLP, MIP		
Sitek et al. (2021)	R, A	✓	P	6	PS			TW	Ret	CLP, MIP, GA		
Tilk et al. (2021)	R	✓	P	6	PS			TW	Prio, ST	BP&C	C	Cu
Ulmer and Streng (2019)	S	✓	P	1	R-R	D, P, Pr	✓		Disp	PFA	C, L, P	Cu
Vukićević et al. (2023)	R		P	3	R-R			EV, TSP		VNS	L	Eco, IC
Wang et al. (2014)	R		3P	1	Fix					GA	F	Co
Yu et al., (2022a)	R, CS		P	6	R-C			SD, TW	CS, ST	ALNS	L, N	Co, IC
Yu et al., (2022b)	R	✓	P	6	PS			TW	Ret	SA		
Yu et al., (2022c)	R	✓	P	6	R-C			SD, TW		SA		
Yu et al. (2023)	R, A, CS	✓	P	4	R-R			2E, SD, TW	CS	ALNS	C, L	IC
Yu et al., (2021b)	R		3P	3	PS			TSP	FD	MIP	A, L	Co, Pro
Zahedi-Anaraki et al. (2022)	R, CC, FOC	✓	3P	6	PS			TW		BD, VNS	A	Pro
Zang et al. (2023)	R, A		P	6	R-R			TW		B&C	L, N	Co
Zhang and Lee (2016)	R		P	2	Fix			TW		ACO	L	Co
Zhou et al., (2019a)	R		P	2	Fix	TT		OTW, TW		GS, LS	L	Co
Zhou et al. (2018)	R, A		P	6	PS			2E, MD, SD	ST	LS, GA	A	Co, RW

(cf. Sect. 3 for explanations of abbreviations. *Objective:* assignment (A), customer compensation (CC), crowdshipping compensation (CS), demand (D), externalities (Ext), facilities (F), facility owner compensation (FOC), penalties (P), routing (R), revenue (Rev), customer satisfaction (S) | *Capacity:* capacity of OOHD locations considered (✓), compartments (C) | *Usage:* proprietary (P), third-party (3P) | *Setting:* Table 2, Sect. 3.3 (1–6), customers not modelled individually (*) | *Location (determination of feasible delivery locations):* discrete choice (DC), fixed location (Fix), no restriction (NR), prespecified set (PS), rule-based 'closest' (R-C), rule-based 'radius' (R-R) | *Stochasticity:* demand (D), customer pickup (P), preferences (Pr), travel time (TT) | *Routing:* two-echelon network (2E), elective vehicles (EV), multitrip (MT), multi-depot (MD), customer-specific time windows at OOHD facilities (OTW), pickup-and-delivery problem (PDP), roaming delivery locations (RDL), split delivery at OOHD facilities (SD), single vehicle (TSP), time windows (TW) | *Special features:* cancellations (Canc), crowdshipping (CS), dispatching (Disp), failed deliveries (FD), multiperiod (MP), other facilities (OF), pricing (Pric), customer priorities (Prio), returns (Ret), demand-dependent service times (ST) | *Solution procedure:* ant colony optimization (ACO), adaptive large neighborhood search (ALNS), biogeography-based optimization (BBO), branch-price-and-cut (BP&C), branch-and-bound (B&B), branch-and-cut (B&C), Benders decomposition (BD), bin packing problem (BPP), continuum approximation (CA), Clarke & Wright savings algorithm (CW), constraint logic programming (CLP), dynamic programming (DP), fixed policy (FP), genetic algorithm (GA), greedy search (GS), iterated local search (ILS), local search (LS), matheuristic (MH), mixed integer program (MIP), machine learning (ML), policy function approximation (PFA), simulated annealing (SA), set covering/set partitioning (SC), tabu search (TS), variable neighborhood descent (VND), variable neighborhood search (VNS) | *Parameters investigated:* assignment cost/compensation (A), facility capacity/compartments (C), facility opening cost (F), determination of feasible delivery locations (L), number of OOHD facilities (N), pickup behavior (P) | *Managerial focus:* comparison (Co), configuration (Con), customer (Cu), environmental (Eco), innovative delivery concept (IC), long-term (LT), product (Pro), real world (RW)).

and further concepts, including ones with multiple delivery modes (e.g., Dragomir et al., 2022). The early publications of Wang et al. (2014) and Zhang and Lee (2016) also deal with the evaluation of delivery modes and the associated savings potential on the last mile.

The publications exhibit a large variety not only in the concepts under investigation, but also concerning the problem environment, including configuration and usage of OOHD facilities, routing properties, and customer characteristics. Before we delve into the numerous settings examined by the authors, it should be noted that the potential of OOHD depends in large part on the delivery concept employed as well as the properties of the instances investigated. Generally, the cost savings attainable through OOHD are higher in concepts that otherwise heavily restrict the service provider's decision making. For example, they are higher when OOHD is contrasted with AHD instead of HD, since the presence of time windows significantly reduces the solution space. Similarly, the efficiency of last-mile logistics is higher for instances of greater location density, irrespective of the delivery mode. Hence, the expected savings enabled through OOHD tend to be smaller.

As discussed in Sects. 2.2 and 3.3, OOHD can only fully develop its potential if the service provider succeeds in integrating customers and their preferences into the design of the delivery concept. This often includes the gradual introduction of OOHD into an existing delivery concept and a slowly increasing familiarity of customers with OOHD as a new delivery mode. The authors thus manipulate the percentage of customers considering OOHD as well as the rules to determine feasible delivery locations. Abstracting from customer preferences to highlight the performance of delivery modes, some authors (e.g., He et al., 2020) fix the final delivery locations in advance. These papers therefore do not contain assignment decisions and concentrate on the design of delivery routes.

4.2.2. Selected problem characteristics

In the evaluation of the potential of OOHD, the **alternative delivery modes** that are offered along with OOHD play a major role.

- About half of the papers consider attended home delivery as an alternative delivery mode. The narrower the time windows are selected, the more attractive the use of OOHD facilities tends to be from the point of view of a delivery service provider, since these usually have no or very wide time windows (e.g., opening hours). Exploiting this feature, Zang et al. (2023) investigate the potential of OOHD in the extreme case of conflicting home delivery time windows. While most publications assume no temporal restrictions on OOHD, some papers consider customer-specific time windows at OOHD facilities (cf. Dell'Amico et al., 2022; Zhou et al., 2019a).
- The routing literature also contains numerous delivery modes that, like OOHD, aim to make the last-mile delivery process more efficient. Some of these modes have also been researched in combination with OOHD. Crowdshipping, i.e., the outsourcing of individual delivery requests, is integrated as another delivery mode by dos Santos et al. (2022), Yu et al. (2022a), and Yu et al. (2023). Dragomir et al. (2022) and Escudero-Santana et al. (2022) examine OOHD in the context of roaming delivery locations (e.g., delivery to the trunk of a car). Boschetti and Novellani (2023) permit both OOHD and delivery via drones. All three concepts resemble OOHD in that it is possible to avoid direct delivery at some of the customers' home locations, e.g., those that would require a sizeable detour.

In order to fully reap the benefits of OOHD, the service provider may adjust the **specification of routing modalities**.

- Some authors (e.g., Du et al., 2021; Yu et al., 2022c) allow for split delivery at OOHD facilities. While split delivery can have a negative effect on customer satisfaction in the context of home delivery, this is much less problematic with OOHD, especially in the case of unmanned facilities. As the aggregated demand of a facility is split up, not the demand of an individual customer, the split delivery is not noticeable to the customers.
- Furthermore, in an OOHD network, vehicles need to make fewer stops to serve the same number of customers, thereby saving time. However, it might not be possible to serve more customers in the same trip due to vehicle capacity restrictions, limiting cost saving opportunities. Allowing multiple trips per vehicle (cf. Janinhoff et al., 2023; Du et al., 2021) can thus lead to further savings.

In contrast to Sect. 4.1, the focus here is not on the **OOHD infrastructure** and its configuration. Only two publications (Grabenschweiger et al., 2021; Orenstein et al., 2019) consider OOHD facilities with compartments of different sizes. Nonetheless, some authors perform sensitivity analyses with respect to the existing infrastructure. In the effort to capture the potential of OOHD, they vary the number of OOHD facilities as well as their capacity (e.g., Buzzega and Novellani, 2022; Jiang et al., 2022a). The authors consider a range of different delivery networks. This includes problems with just one vehicle resulting in a TSP (e.g., Jiang et al., 2019; Jiang et al., 2022b), to multi-echelon networks (e.g., Zhou et al., 2018), in which OOHD facilities are sometimes used not only for customer pickup but also as satellites (e.g., dos Santos et al., 2022).

In addition to last mile delivery, several authors include aspects of **first mile logistics** in their problem settings, employing OOHD facilities to capture shipments from local businesses and customer returns (e.g., Sitek et al., 2021; Sitek and Wikarek, 2019; Yu et al., 2022b). In this case, the customer deposits the package, which is later collected by the service provider. With a concept that includes both deliveries and returns, aspects such as the capacity of facilities and vehicles gain additional importance. Other authors (e.g., Dragomir et al., 2022; Orenstein and Raviv, 2022) combine first and last mile operations by examining pickup and delivery formulations.

Unlike many other applications of vehicle routing problems, in an OOHD context, an emphasis is put on **customer satisfaction**. While the determination of feasible delivery location is mostly rule-based or assumed to be prespecified, the assumptions regarding the customer settings introduced in Sect. 3.3 are heterogeneous. To ensure customer satisfaction, some authors introduce customer priorities for delivery locations. Here, customers specify an ordered list of all possible delivery locations. Customer satisfaction with the final delivery location must then either meet a predefined level (e.g., 80 percent of customers must be assigned to one of their first two priorities; cf. Dumez et al., 2021; Tilk et al., 2021) or is part of the optimization (Escudero-Santana et al., 2022). It should be noted that this only addresses customer satisfaction on a global level; individual customers may still be supplied at locations that are inconvenient for them.

One of the most studied aspects in terms of OOHD profitability is the value of **customer flexibility**. Two types of flexibility are under investigation: the flexibility to be served at home and out-of-home, and the flexibility in the composition of the set of feasible OOHD facilities. The authors therefore vary the proportions of customer groups as well as the rules to determine feasible delivery locations. Some authors in this context define customer flexibility in terms of delivery product conditions. For example, Janinhoff et al. (2023) examine different products that incorporate the possibility of OOHD with varying degrees of customer flexibility and derive insights for product line pricing from the cost savings attainable.

Furthermore, several authors (e.g., Mancini and Gansterer, 2021; Pourmohammadreza and Jokar, 2023) investigate the effects of manipulating compensations that arise when customers are assigned to an OOHD facility. The **compensation schemes** affect either the customers (compensation for pickup) or the facility owners (compensation for storage and handling). However, the relationship between compensation payments to customers and their willingness to agree to OOHD to different facilities is not explicitly addressed. Further, Zahedi-Anaraki et al. (2022) implement customer compensations which directly depend on the degree of flexibility exhibited by the individual customer, irrespective of the eventual delivery location. Yu et al. (2021b) retroactively infer compensations from the cost differences between delivery modes. Actively steering customer demand, Akkerman et al. (2023) dynamically control the availability and prices of delivery options presented to each individual customer. Similarly, Galiullina et al. (2024) offer monetary incentives for OOHD to selected customers during the fulfillment planning phase, leaving it up to the incentivized customers to decide on the final delivery location.

Last-mile delivery processes are subject to various **stochastic influences**:

- Regarding OOHD, the pickup behavior (e.g., dos Santos et al., 2022; Orenstein et al., 2019) of the customers, which results in a dynamic capacity of the facilities, stands out.
- Other stochastic influences examined in the context of VRPs are demand (e.g., Leung et al., 2022), travel times (Zhou et al., 2019a) or customer preferences (e.g., Galiullina et al., 2024). He et al. (2020) account for customer cancellations by dynamically reoptimizing the routing plan. Ulmer and Streng (2019) consider a dynamic problem setting under stochastic demand, stochastic customer pickup, and customer preferences. With the goal of minimizing the time span between order capture and delivery, autonomous vehicles are dispatched dynamically to parcel lockers.
- Taking on a longer-term perspective, Pahwa and Jaller (2023) investigate OOHD along with outsourcing as a strategy to cope with uncertainty due to large-scale demand disruptions. Similarly, Orenstein and Raviv (2022) develop vehicle schedules and a corresponding parcel routing policy to address uncertainty in demand and pickups on a tactical level.

Another advantage of OOHD compared to home delivery is the potentially shorter **service time**, i.e., the time needed for parking, unloading, and handing over the parcel at a delivery location. Among other factors, e.g., the availability of on-site parking, the service time depends on the number of parcels handled. This is especially relevant for parcel lockers, as each parcel is stored individually. Several authors take this characteristic – which we label demand-dependent service times – into account (e.g., Dumez et al., 2021; Orenstein et al., 2019).

OOHD can contribute to a reduction of **emissions** on the last mile if the savings from consolidation and prevented failed deliveries outweigh the additional emissions from customer pickup. In this way, OOHD can also be part of holistic, eco-friendly delivery concepts. Putting their emphasis on this aspect, Arnold et al. (2018) examine various delivery modes, which include OOHD facilities and cargo bikes, also with regard to the externalities caused. Vukićević et al. (2023) investigate the use of electric vehicles to further reduce emissions. Gutenschwager et al. (2023) place a particular focus on emissions that are attributable to customer pickup behavior.

The papers in this section examine numerous variants of the vehicle routing problem, which is known to be NP-hard. Since the majority of models presented in this section have to be solved frequently and for large instances in order to be applied to real-world problems, most authors resort to heuristics as **solution procedures**.

Table 5
Location routing problems.

	Obj.	Facilities		Customers		Stoch.	Dyn.	Rout.	Spec. features	Sol. proc.	Managerial	
		Cap.	Usage	Sett.	Loc.						Param.	Focus
Enthoven et al. (2020)	R, A		P	6	R-R			2E	OF	ALNS	A, L, N	IC
Grabenschweiger et al. (2022)	R, F, CC	✓	P	3	R-R			TW	MP	ALNS		
Guerrero-Lorente et al. (2020)	R, F, CC, P	✓	P	3*	DS, R-R			2E	CD, OF, Ret	CA, MIP	F, L	Cu, RW
Hong et al. (2019)	R, F, CC, P	✓	P	1	R-R			OTW, TSP		SC, ACO	C, L	
Huang et al. (2019)	R, F		P	3	R-R, Fc			EV, Sep	OF	C&W, TS	L	Co, Eco, IC
Janinhoff and Klein (2023)	R	✓	P	4	DC	D, Pr		MT	OS	MIP, ALNS	L, N	Cu, Pro, RW
Janjevic et al. (2019)	R, F		P	3*	DS			2E, SD	OF	CA, heur. B&P	L, N	RW
Janjevic et al. (2021)	R, F	✓	P	3*	DS			3E, SD, TW	CS, OF, S	CA, MIP		IC, Pro, RW
Leyerer et al. (2020)	R, F	C	P	2	R-R			2E, EV, SD, TW	CD, ST	MIP	L	Co, Eco, RW
Peppel and Spinler (2022)	R, F, Ext	✓	P	3	DC	Pr		EV		MIP	C, F, L, N	Eco, LT
Rautela et al. (2022)	R, F		P	3*	DS	FD		2E, MT	Ret, ST	CA, MIP	L	Co, Cu, RW
Veenstra et al. (2018)	R, F		P	3	R-R, Fc			Sep		VNS	F, L, N	
Wang et al., (2022a)	R, F	✓	P	3	R-R			EV, Sep		B&P	C, F, L	Eco
Wang et al., (2022b)	R		C, P	3	DC	D, Pr		Sep, TSP		CA, MIP	L	Co, Cu, RW
Wang et al. (2018)	R, F, A, S	✓	P	3	R-R			MD, TW	OF, Ret	TS		Co
Yu et al., (2021a)	R, A, CS		P	4	R-R			2E, SD, TW	CS, OF	ALNS	A, L	IC
Zhang et al. (2023)	R, F, Rev		P	3*	DC	Pr		2E	Pric	CA, ASA	L	Co, Cu, Pro
Zhou et al. (2016)	R, F, P	✓	P	3*	R-R			MD	FD	GA	L	Co
Zhou et al., (2019b)	R, F, P	✓	P	4*	DS			Sep	CD, FD	CA, GA	C, L	

(cf. Sect. 3 for explanations of abbreviations. *Objective:* assignment (A), customer compensation (CC), crowdshipping compensation (CS), externalities (Ext), facilities (F), penalties (P), routing (R), revenue (Rev), customer satisfaction (S) | *Capacity:* capacity of OOHD locations considered (✓), compartments (C) | *Usage:* collaborative (C), proprietary (P) | *Setting:* Table 2, Sect. 3.3 (1–6), customers not modelled individually (*) | *Location (determination of feasible delivery locations):* discrete choice (DC), demand shift (DS), forced OOHD by facility (Fc), rule-based 'radius' (R-R) | *Stochasticity:* demand (D), failed deliveries (FD), preferences (Pr) | *Routing:* two-echelon network (2E), three-echelon network (3E), elective vehicles (EV), multitrip (MT), multi-depot (MD), customer-specific time windows at OOHD facilities (OTW), split delivery at OOHD facilities (SD), separated routing for OOHD facilities (Sep), single vehicle (TSP), time windows (TW) | *Special features:* capacity decision (CD), crowdshipping (CS), failed deliveries (FD), multiperiod (MP), other facilities (OF), offer sets (OS), pricing (Pric), returns (Ret), differentiated services (S), demand-dependent service times (ST) | *Solution procedure:* ant colony optimization (ACO), adaptive large neighborhood search (ALNS), active set algorithm (ASA), branch-and-price (B&P), continuum approximation (CA), Clarke & Wright savings algorithm (CW), genetic algorithm (GA), mixed integer program (MIP), set covering/set partitioning (SC) tabu search (TS), variable neighborhood search (VNS) | *Parameters investigated:* assignment cost/compensation (A), facility capacity/compartments (C), facility opening cost (F), determination of feasible delivery locations (L), number of OOHD facilities (N) | *Managerial focus:* comparison (Co), customer (Cu), environmental (Eco), innovative delivery concept (IC), long-term (LT), product (Pro), real world (RW)).

4.3. Location-routing problems

With decisions on both the placement of OOHD facilities as well as routing, location routing problems combine the aspects discussed in the two previous sections. We therefore shorten the discussion and only go into detail on a problem aspect if it was not previously mentioned, or if it is particularly important in the context of location routing. Table 5 provides the corresponding detailed analysis of the publications in this section.

4.3.1. Research focus

Taking the view of a logistics service provider who manages both last-mile delivery and the operation of proprietary OOHD facilities, location routing problems (LRPs) in the context of OOHD often aim to assess entire delivery networks. They are more comprehensive than the VRPs portrayed in the previous section, as they additionally incorporate the installment and operation of facilities. LRPs feature location decisions which include but may not be limited to the positioning of OOHD facilities. Here, the decision maker actively interferes with the underlying delivery infrastructure and thereby heavily influences the (subsequent) location assignment and routing decisions. Simultaneously, the facilities' locations shape the vehicle routes by consolidating the demand in the vicinity of the OOHD facility.

While for vehicle routing problems the assignment decision for one customer (i.e., the determination of the final delivery location) was largely independent from the assignment decision for another customer (or only restricted through facility capacity), the decision maker in an LRP context establishes the set of delivery options through the location decision. As the location decision impacts the set of feasible delivery locations of multiple customers at once, the assignment decisions of the customers are indirectly linked to each other. Authors dealing with location routing problems often assume customer setting 3, i.e., all customers that accept OOHD also accept HD. Feasibility is guaranteed even if no suitable OOHD facility is opened for a certain customer, since the customer can be served at the home location instead.

As the locations of OOHD facilities are not predefined, the method of determining feasible delivery locations is even more pivotal than in VRPs. These eligibility considerations govern the location decision. Prior to optimization, the set of feasible delivery locations for a customer is unknown. Through the placement of OOHD facilities the decision maker either directly controls its makeup (in the case of rule-based determination) or influences the customer's preferences (in the case of discrete choice behavior). The most common approach is to use a radius-based rule, i.e., assuming that all customers within a maximum distance of an OOHD facility may be visited there.

Due to the high degree of interrelation between facility location, assignment, and vehicle routing decisions, the complexity of LRPs is even higher than the complexity of the problems discussed in the previous sections. Hence, authors often need to compromise to keep the problems somewhat tractable, i.e., they often make less detailed assumptions, use approximations, or employ multi-phase heuristic approaches. A complicating factor in the decision making is the fact that the two types of decisions belong to different planning levels. While the placement of OOHD facilities is of strategic or tactical nature, the routing of vehicles and the assignment of customers to final delivery locations takes place daily on the operational level. The location decision therefore influences not only one, but many subsequent routing problems.

4.3.2. Selected problem characteristics

The OOHD-LRPs formulated in the scientific literature differ to a large extent. One reason for this is the different level of abstraction chosen for individual problem aspects. This is evident in the varying degrees of detail regarding the planning of the **OOHD infrastructure**. While most publications decide on suitable locations only, a small subset of authors integrate capacity decisions for the OOHD facilities (e.g., Leyerer et al., 2020; Zhou et al., 2019b).

Another reason for the variety of optimization models is the plurality of delivery concepts they reflect. This comes to the foreground in LRPs, as an emphasis is put on the entire **delivery network**. For example, there are papers studying multi-echelon networks (e.g., Janjevic et al., 2021; Yu et al., 2021a) and delivery networks with separate routing for OOHD facilities and customer home locations (e.g., Veenstra et al., 2018; Huang et al., 2019). Expanding the location decisions to other facilities that do not act as pickup points for customers, some authors optimize highly complex networks. This includes, for example, the opening and placement of depots (Guerrero-Lorente et al., 2020; Wang et al., 2018) or satellites (e.g., Janjevic et al., 2019; Rautela et al., 2022).

The interplay of OOHD infrastructure, customers, and the design of specific **OOHD services** or prices is investigated in several papers. Zhang et al. (2023) influence customer behavior through the placement of OOHD facilities and the pricing of home delivery. While maximizing the delivery service provider's profit, these decisions shape equilibria of customer behavior. Janjevic et al. (2021) differentiate between standard, express, and instant delivery service and design a multi-tier distribution network that accommodates all three service levels. Janinhoff and Klein (2023) examine the effect of different specifications of OOHD service on the optimal design and the resulting efficiency of OOHD facility networks.

Not only do OOHD-LRPs involve various types of decisions, they also often exhibit **objective** functions with multiple components. Alongside routing-related costs, setup and operational costs of OOHD facilities are considered. Although not as prevalent as in VRPs, a few papers include costs based on the assignment of customers to OOHD facilities, such as customer compensations (Grabenschweiger et al., 2022) and indirect measures of service quality in the form of penalties for failed deliveries (e.g., Zhou et al., 2016), late deliveries (e.g., Hong et al., 2019), and non-deliveries (e.g., Guerrero-Lorente et al., 2020).

A group of authors investigates how OOHD may contribute to a more sustainable last mile by cutting **emissions**. Similar to Sect. 4.2, some publications, especially those dealing with multi-echelon networks, work with diverse vehicle fleets including cargo bikes (Enthoven et al., 2020) and electric vehicles (e.g., Peppel and Spinler, 2022; Wang et al., 2022a). Going beyond the operational level, Huang et al. (2019) consider the joint location planning for OOHD facilities and charging stations for electric vehicles.

In general, authors dealing with LRPs seldom incorporate **stochastic influences**. This stark contrast to the problems discussed in Sect. 4.1 is again due to the computational complexity, not because of a lack of necessity.

- First, we already described the close connection between customer preferences and the selection of adequate OOHD locations. To make these decisions accurately, it is sensible to consider stochastic customer choice behavior. Wang et al. (2022b) and Peppel and Spinler (2022) are among the publications that include probabilistic discrete choice modeling.
- Second, there might also be significant uncertainty with respect to the presence of customers. The abovementioned incongruency of planning levels (multiple operational routing problems based on a single strategic location decision) implies a need to account for stochastic variations of daily demands. While Janinhoff and Klein (2023) is the only publication that tackles a problem variant with stochastic customer demands, Grabenschweiger et al. (2022) address the same issue by solving a multi-period location routing problem.

As mentioned above, the complexity of the OOHD environment necessitates simplifications for reasons of tractability, which is also reflected in the **solution procedures**.

- For obvious reasons, the solution procedures in this section include only very few exact approaches, with most papers relying on

heuristics and/or approximations. Particularly noticeable is the large number of papers using continuum approximation (CA). CA describes a group of techniques that aim to estimate routing costs, without solving the corresponding routing problem.
- In close relation to this, several papers do not model each customer individually but group the customers into demand clusters prior to optimization (e.g., Janjevic et al., 2019). As a consequence, problems of real-world size become tractable, while other assumptions (e.g., with respect to customer choice behavior and routing) might lose accuracy.

4.3.3. Mobile lockers

Finally, a problem setting in which both locations and routing are considered, is the case of mobile lockers. In contrast to all papers discussed until now, the OOHD facilities are not static in their position, but can be moved, or, in the case of autonomous vehicles, even move themselves. The idea is that fewer lockers are needed, as movable lockers can cover multiple areas of the delivery region. Customers announce their whereabouts as a set of time–space tuples and are visited at any of the locations during the delivery day. Once the mobile locker is placed in their vicinity, they are informed and have a (limited) time window to retrieve their parcel before the locker moves on. In optimization problems with mobile lockers, all three major decisions (i.e., location, routing, assignment) coincide. Obviously, the location decision here is not strategic but operational and might even be adjusted dynamically.

As opposed to lockers with fixed locations, mobile lockers are not (yet) in widespread use. Unsurprisingly, the number of papers on this topic is quite low. Schwerdfeger and Boysen (2020) formulate a mobile locker delivery problem and investigate numerous central parameters including customer walking ranges, locker velocities, and the width of pickup time windows. In a further study (Schwerdfeger and Boysen, 2022), the same authors illustrate and benchmark a wide array of mobile locker concepts, contrasting autonomous and human locker transport, as well as discussing differences between lockers built into vehicles and lockers loaded on to vehicles to be deposited individually. Kötschau et al. (2023) are also among the first to study mobile lockers. Maximizing the number of customers served, they compare various delivery modes with fixed lockers, mobile lockers, attended home delivery, and the combination of these modes. Liu et al. (2023) determine stopover locations and dynamically plan routes including parcel resupply for mobile lockers.

5. Further research directions

Service providers involved in last-mile delivery that use OOHD or consider expanding their services to include OOHD face many questions. Most importantly, service providers need to assess the profitability of OOHD. For multiple reasons, this is quite challenging. First, the underlying optimization problems exhibit a high degree of computational complexity, often combining multiple NP-hard problems. Second, in contrast to many other logistical optimization problems (warehouse location problems, capacitated vehicle routing problems, etc.), optimization in the context of OOHD can hardly be useful without the integration of (complex) customer behavior. Third, as the problems arise in last-mile parcel delivery, they naturally deal with very large problem sizes. OR scientists dealing with such complex optimization environments are forced to make assumptions and therefore run the risk of excessive simplification. For example, none of the LRPs formulated account for parcel lockers with heterogeneous compartments, only very few papers integrate complex customer choice behavior etc. Some techniques exist to reduce problem size, e.g., reducing the number of customer locations through approximations and clustering. However, this may impact the accuracy of the model, as individual aspects (for example in the context of choice behavior) are disregarded.

The existence of potential cost savings attainable through OOHD under various assumptions has been well documented, with multiple studies confirming significant improvements of routing costs and other key performance indicators, such as the number of vehicles in use. Apart from the general challenge of handling the problems' complexity, many other business-relevant questions remain unanswered. Reverting to the central aspects of OOHD presented in Sect. 2, we identify the following six areas of future research (Fig. 3).

Parcel shops vs. parcel lockers (1): For OOHD facilities, we can distinguish parcel shops (manned) and parcel lockers (unmanned). While their purpose is largely identical, they have numerous differences. Particularly, they differ with respect to the storage possibilities, cost structure, and in their appeal to different customer segments (cf. Sect. 2.3). This raises the question which type of facility is suitable under which circumstances. The existing publications often focus on only one of the above aspects and/or simplify their assumptions, such that the two types become indistinguishable. Hence, the studies may fall short in their assessment of the OOHD infrastructure. To our knowledge, there are no studies evaluating under which circumstances lockers (shops) are preferable. It might further be sensible to utilize networks with both types of facility. Specifically, differences in cost structure and pickup behavior between shops and lockers have potentially large ramifications

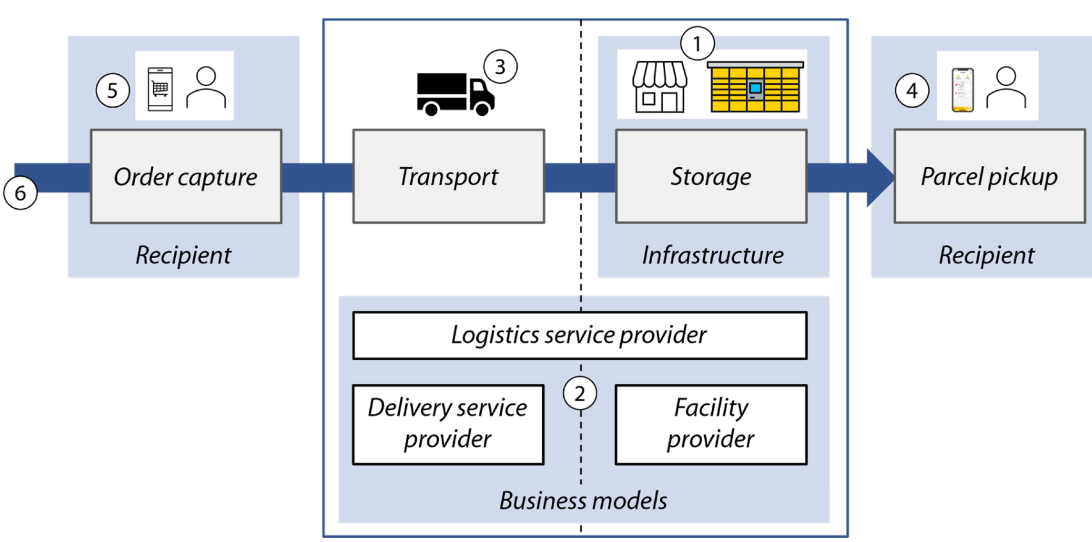

Fig. 3. Research gaps.

for logistics service providers and facility providers, resulting in a need to research corresponding location routing and facility location problems.

When the OOHD infrastructure is to be based on parcel lockers, the layout of the lockers is subject to decision making. Service providers need to determine suitable sizes and types of compartments. While several papers from a facility provider's perspective include this aspect (cf. Sect. 4.1), the only papers integrating layout considerations and routing decisions are Grabenschweiger et al. (2022) and Orenstein et al. (2019).

Business strategy (2): As discussed earlier, three types of business models prevail in the OOHD landscape. When introducing delivery concepts based on OOHD, delivery service providers face the decision whether to integrate vertically, i.e., whether to become (in our terminology) a logistics service provider. Here, the advantages and disadvantages of owning the OOHD infrastructure have not yet been thoroughly investigated. Furthermore, it is unclear how long it takes to recoup the potentially large initial investments of building an OOHD infrastructure. It would therefore be sensible to investigate (long-term, stochastic) location routing problems.

It is further remarkable that the optimization problems posed from the perspective of a facility provider and those from the perspective of a delivery service provider cooperating with a facility provider are often not fully compatible. On the one hand, as detailed in Sect. 4.1, the type of problems that mimic a facility provider's perspective usually assume a collaborative use of facilities. There is typically no distinction between customers of different users (i.e., cooperating delivery service providers). The papers instead work with a single set of customers (representing the entire population) as a proxy, maximizing demand captured or revenue without differentiation between the user companies. On the other hand, papers dealing with delivery service providers (cf. Sect. 4.2) predominantly assume fixed storage capacities (reserved for them). Whether reserving storage capacities for specific users impacts the solution has not been subject to research. More specifically, the design of contracts between facility providers and delivery service providers and its implications for their daily operations warrants further research, e.g., viewing capacity allocation through the lens of two-stage stochastic programming.

Related to this aspect is the collaboration between multiple delivery service providers who collectively decide on OOHD facility locations. Focusing on game-theoretic aspects and radically simplifying vehicle routing, this problem has been posited by Mercurio et al. (2023). In general, the intersection of collaborative vehicle routing (cf. Gansterer and Hartl, 2018) and OOHD contains many research opportunities, as both components can play a major part in the design of efficient last-mile processes.

Failed deliveries (3): One of the major advantages of OOHD is the much-reduced risk of failed deliveries, which contribute to the costliness of last-mile delivery. Nevertheless, this aspect has been explored very sparingly, with almost all papers focusing on the benefits of customer consolidation and customer location flexibility. When considered, failed deliveries are often subject to rather rough assumptions, such as fixed costs incurred upon delivery failure. This stands in contrast to more sophisticated approaches proposed by the AHD literature. As an example, Voigt et al. (2023) construct customer availability profiles, thereby modeling the probability of delivery failure on a more granular, time-dependent level. Also working with availability profiles, Özarık et al. (2023) tackle failed deliveries with two-stage stochastic programming by tentatively planning multiple visits to selected customers. To properly quantify the potential cost savings resulting from employing OOHD instead of HD, it would be sensible, similar to Özarık et al. (2023), to model possible fallback procedures in case of delivery failure explicitly and to solve corresponding stochastic, multi-period optimization problems.

Customer pickup (4): A large discrepancy between real-world applications and the optimization problems discussed pertains to the customers' pickup behavior. Almost all papers investigate a single-period setting, working on the premise that storage capacity is either not a limiting resource or remains stable. The latter assumption relies on the observation that a known percentage of packages are picked up within 24 h after delivery to the OOHD facility (e.g., 75 %; Lyu and Teo, 2022). However, many publications consider contexts in which customers can either be served at home or at an OOHD facility. Through the resulting location assignment, the decision maker actively manages the storage capacities, which in turn should affect the availability of storage capacity in the following delivery periods, even when assuming high rates of prompt pickup. Explicitly incorporating customer pickup means that problems can no longer be fully decomposed into individual delivery days, leading to sequential decision problems with a long, multi-period time horizon. Investigating these problems hence necessitates solution methodology tractable for extensive planning horizons, such as proposed by Ulmer et al. (2018) for a dynamic service routing problem.

The close relationship between customer pickup behavior and available storage capacities also raises the question how service providers should deal with the uncertainty in the available storage capacity. A conservative approach would be to only assign parcels if there is known vacant capacity. This may lead to less efficient operations, as the capacities would tend to be underused. Assigning parcels to OOHD facilities without knowledge about free capacity, on the other hand, runs the risk of unsuccessful delivery attempts at OOHD facilities. In this case, parcels would need to be reassigned and rerouted, possibly with negative repercussions for the customer. To evaluate the efficiency of such diverse policies, more research into (dynamic) assignment and routing problems is required.

Demand management (5): As a consequence of the potential efficiency gains through OOHD, service providers are interested in incentivizing customers toward selecting delivery products that allow for consolidation and location flexibility. For example, a delivery service provider prefers if a higher percentage of customers can be visited either at home or at an OOHD facility, instead of only at home (the solution space of the corresponding optimization problem gets larger, ensuring non-increasing routing costs). The perceived attractiveness of delivery products incorporating OOHD hinges on two decisions: the products' design and the products' pricing. Following Ma et al. (2022), future work will have to place emphasis on developing adequate models to represent customer choice, building on insights from empirical research, and incorporating customer behavior efficiently into OOHD optimization problems. As of yet, little research has been done on the interplay of product design, product pricing, and customer choice behavior. Notably, only three publications consider demand management on an operational level, dynamically controlling the availability of delivery options (Sethuraman et al., 2023), offering incentives through pricing (Galiullina et al., 2024), or both (Akkerman et al., 2023). This lack of research is contrasted starkly by other real-world problems, in which demand management and routing decisions are similarly intertwined, such as attended home delivery and mobility-on-demand. For these applications a rich body of literature has amassed in the past two decades (Fleckenstein et al., 2023; Waßmuth et al., 2023).

The above considerations regarding product design and demand management also apply to the case of mobile lockers. The existing problem formulations hinge on the reliability of the customers, often assuming near-immediate customer pickup and the willingness to fully disclose their itinerary. Through product and price differentiation and the resulting customer choice behavior, these assumptions may be more appropriate.

Anticipatory decision making (6): In an OOHD context, there are numerous types of stochasticity related to the interaction with customers (cf. Sect. 3.4). Service providers might seek to react to realizations of the corresponding random variables, revealing the need for decision support in dynamic environments. On the one hand, customers may be steered during order capture by dynamic pricing of delivery products and/or dynamic changes of the offer set (cf. Agatz et al. (2013)

for a classification in an AHD context). On the other hand, in applications like same-day delivery, routing and assignment decisions are of dynamic nature themselves. While some publications already consider dynamic settings, especially in the context of vehicle routing (c.f. Sect. 4.2), most of the developed solution approaches are myopic. Consequently, immediate costs serve as the only criterion for decision making, whereas the potential impact on future decisions and costs is neglected. As of now, Akkerman et al. (2023), Du et al. (2021), Galiullina et al. (2024), Sethuraman et al. (2023), and Ulmer and Streng (2019) are the only publications proposing anticipatory solution methods in the OOHD literature. Future work will require solution concepts capable of scaling to the vast combinatorial decision spaces arising from routing or demand management while adequately anticipating the downstream effects of a decision. As observed by Hildebrandt et al. (2023), a promising avenue for future research points toward combining operations research methods, which excel at searching large decision spaces, with machine learning to evaluate decisions.

6. Summary and outlook

In this survey, we systematically compartmentalized the practice of out-of-home delivery (OOHD) and identified optimization problems considering different types of business models and services. The focus was on provider-specific challenges as well as their interplay with recipients and OOHD infrastructure.

We highlighted important real-world aspects and showed how the existing literature transfers them into components of optimization models. We discussed three main groups of models: First, papers in which the location decision with the aim of building attractive facility networks is in the foreground, second, papers that focus on routing problems, and third, papers that make an integrated location and routing decision. For each group, we provided comprehensive tables enabling the reader to quickly access the content and characteristics of publications.

Drawing on the practice-relevant problems established in Sect. 2, we pointed out gaps in the research as well as future research directions. Among others, these include the influence of failed deliveries and their impact on the assessment of OOHD-enabled savings potentials, as well as the consideration of customer behavior, especially regarding pickup behavior and the integration of demand management.

Due to the identified research gaps, which represent the starting point of promising research, a further increase in the literature investigating OOHD is to be expected. The use of OOHD is also growing in practice. In addition to the expansion of the OOHD infrastructure, new technologies such as mobile lockers emerge, which in turn provide new opportunities and challenges to be investigated.

CRediT authorship contribution statement

Lukas Janinhoff: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Robert Klein:** Writing – review & editing, Supervision, Conceptualization. **Daniela Sailer:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Jim Morten Schoppa:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

Data availability

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

Appendix 1

Objective			
A	assignment	FOC	facility owner compensation
CC	customer compensation	P	penalties
CS	crowdshipping compensation	R	routing
D	demand	Rev	revenue
Ext	externalities	S	customer satisfaction
F	facilities		
Capacity			
✓	capacity of OOHD locations considered		
C	compartments		
Usage			
C	collaborative		
P	proprietary		
3P	third-party		
Settings			
1–6	cf. Table 2, Sect. 3.3		
*	customers not modelled individually		
Loc (determination of feasible delivery locations)			
DC	discrete choice	NR	no restriction
DS	demand shift	PS	prespecified set
Fix	fixed location	R-C	rule-based ‘closest’
Fc	forced OOHD by facility	R-R	rule-based ‘radius’
Stochasticity			
D	demand		
FD	failed deliveries		
P	customer pickup		
Pr	preferences		
TT	travel time		
Problem type			
C vs. C	cost vs. coverage constraints		
D vs. B	demand vs. budget constraints		
Profit	revenue − costs		
Routing			
2E	two-echelon network	PDP	pickup-and-delivery problem
3E	three-echelon network	RDL	roaming delivery locations
EV	electric vehicles	SD	split delivery @ OOHD facilities
MT	multitrip	Sep	separated routing for OOHD facilities

(continued on next page)

(*continued*)

MD	multi-depot	TSP	traveling salesman problem = single vehicle
OTW	customer-specific time windows @ OOHD facilities	TW	time windows
Special features			
Canc	cancellations	OF	other facilities
CD	capacity decision	OS	offer sets
CS	crowdshipping	Pric	pricing
Disp	dispatching	Prio	customer priorities
Fac	facility (locker vs. shop)	Ret	returns
FD	failed deliveries	S	differentiated services
MP	multiperiod	ST	demand-dependent service times
NA	network adaption	U	minimum facility utilization
NLD	no location decision		

Solution procedure			
ABS	agent-based simulation	GMM	Gaussian mixture model
ACO	ant colony optimization	GS	greedy search
ALNS	adaptive large neighborhood search	ILS	iterated local search
ASA	active set algorithm	KT	kernel transformation
BBO	biogeography-based optimization	LS	local search
BP&B	branch-price-and-cut	MH	matheuristic
B&B	branch-and-bound	MIP	mixed integer program
B&C	branch- −and-cut	ML	machine learning
B&P	branch-and-price	PFA	policy function approximation
BD	Benders decomposition	PSO	particle swarm optimization
BPP	bin-packing problem	QP	quadratic program
CA	continuum approximation	SA	simulated annealing
C&W	Clarke & Wright savings algorithm	SC	set covering, set partitioning
CLP	constraint logic programming	SO	simulation–optimization
DP	dynamic programming	TS	tabu search
FP	fixed policy	VND	variable neighborhood descent
GA	genetic algorithm	VNS	variable neighborhood search
Parameters investigated			
A	assignment cost/compensation	L	determination of feasible delivery locations
C	facility capacity/compartments	N	number of OOHD facilities
F	facility opening cost	P	pickup behavior
Managerial focus			
Co	comparison	IC	innovative delivery concept
Con	configuration	LT	long-term
Cu	customer	Pro	product
Eco	environmental	RW	real world

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