OR Spectrum (2021) 43:1–58
https://doi.org/10.1007/s00291-020-00607-8

REGULAR ARTICLE

Last-mile delivery concepts: a survey from an operational research perspective

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Received: 18 May 2020 / Accepted: 4 September 2020 / Published online: 21 September 2020

Abstract
In the wake of e-commerce and its successful diffusion in most commercial activities, last-mile distribution causes more and more trouble in urban areas all around the globe. Growing parcel volumes to be delivered toward customer homes increase the number of delivery vans entering the city centers and thus add to congestion, pollution, and negative health impact. Therefore, it is anything but surprising that in recent years many novel delivery concepts on the last mile have been innovated. Among the most prominent are unmanned aerial vehicles (drones) and autonomous delivery robots taking over parcel delivery. This paper surveys established and novel last-mile concepts and puts special emphasis on the decision problems to be solved when setting up and operating each concept. To do so, we systematically record the alternative delivery concepts in a compact notation scheme, discuss the most important decision problems, and survey existing research on operations research methods solving these problems. Furthermore, we elaborate promising future research avenues.

Keywords Transportation · City logistics · Last-mile delivery · Survey

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1 Introduction

Last-mile delivery, i.e., all logistics activities related to the delivery of shipments to private customer households in urban areas, is a hot topic in cities all over the globe. Its high relevance is mainly triggered by the following general developments and challenges:

- *Increasing volume* Two global mega-trends, in particular, urbanization and e-commerce, are strong drivers for an ever increasing demand for last-mile delivery services. Urbanization denotes the trend that more and more people move into urban areas in general and into "megacities," with 10 million inhabitants and more, in particular. There are estimates that by 2050, 70% of the world's population, approximately 6.3 billion people, will live in major cities (Bretzke 2013). Furthermore, e-commerce is in a steady increase and more and more commercial goods are ordered online. In 2018, e-commerce still showed a worldwide growth rate of 23.3% (Statista 2018). Thus, more geographic concentration and increasing online orders per person lead to a steady increase in parcel volumes to be handled. In Germany, for instance, it is forecasted that by 2023, 4.4 billion shipments will need to be handled per year compared to 1.69 billion in 2000 (Statista 2019).
- *Sustainability* Increasing urban parcel demands induce a much higher number of delivery vans entering the city centers, which additionally burdens the existing infrastructure, adds to congestion, and has negative impacts on health, environment, and safety. As a consequence, increasing customer awareness and novel governmental legislation enforce courier services to intensify the efforts for sustainable and environment-friendly operations (Hu et al. 2019). One example for a public policy directly impacting last-mile deliveries is, for instance, that some regions of the world, e.g., British Columbia (2019), allow (single-person) electric vehicles on their high-occupancy vehicle (HOV) lanes, which are normally reserved for cars with multiple occupants. Such a policy could be an incentive for courier services to electrify their delivery fleet in order to access urban areas faster via uncongested HOV lanes.
- *Costs* Traditional attended home delivery by delivery vans is costly. A simulation study with real-world data from Finland, for instance, indicates that traditional van-based delivery options cause costs between 2 and 6 € depending on customer density (Punakivi et al. 2001). Important drivers for high (especially personnel) costs are traffic jams and missing parking spaces in congested streets as well as customers not at home to receive their parcels. Song et al. (2009) state that first-time delivery failures reported by courier services range between 12 and 60% for different regions of the world. Thus, especially alternative delivery concepts allowing an unattended delivery or customer self-services are a promising alternative to lower costs.
- *Time pressure* The increasing parcel volumes are mainly triggered by increasing e-commerce activities. Most online retailers, however, have made next- or even same-day deliveries to one of their basic service promises (Yaman et al.

2012), so that last-mile deliveries face tight deadlines and considerable time pressure. Moreover, online deliveries vary over the week, with Mondays typically having peak workloads (Poggi et al. 2014), and especially over the year, e.g., due to seasonal sales (Boysen et al. 2019c). Thus, last-mile deliveries also face strongly varying workloads, so that last-mile concepts are required that are easily scalable on short notice.

- *Aging workforce* The aging workforce in many industrialized countries enlarges the problem of employers hiring the required manpower (Otto et al. 2017), especially in a physically demanding environment such as parcel delivery where the press frequently reports on harsh occupational conditions and low payments, e.g., Peterson (2018). In such a work environment, alternative delivery concepts less dependent on human work but on automation seem a promising alternative for the future. On the other hand, the delivery person handing over a parcel is typically the only human interaction for e-commerce customers. Thus, a reliable, responsive, and professional delivery experience influences customer satisfaction both for online retailers and courier services (Li et al. 2006). With self-service concepts based on parcel lockers or automated delivery options based on unmanned aerial vehicles (drones) or autonomous delivery robots, this final human interaction gets lost.

Given these challenges and the recent (and ongoing) technological developments, such as autonomous driving, drones, and delivery robots, it is anything but surprising that plenty of novel last-mile delivery concepts have been promoted during the recent years. These concepts range from already practiced alternatives such as cargo bikes, over evaluated prototypes such as parcel delivery by drones (see Otto et al. 2018), up to ideas for the even farther future such as Amazon's patent for flying warehouses, i.e., airships circling over city centers from where drones are launched (Berg et al. 2016). This paper is dedicated to surveying the literature on established and novel last-mile delivery concepts. Specifically, we take an operational research perspective and survey those papers solving either strategic decision problems when setting up a last-mile concept or short-term problems when operating a specific delivery mode. Further contributions of our paper, in addition to a literature survey, are a compact notation defining the respective process chain of a delivery concept in a concise and systematic manner as well as an overview of promising future research tasks.

The remainder of the paper is structured as follows. First, Sect. 2 precisely defines the scope of our survey. Then, Sect. 3 presents our notation scheme for defining a specific last-mile concept in a compact form. This notation is applied to specify the concepts treated by each surveyed paper. For each concept, long-term configuration problems and short-term operational decision problems are characterized, the relevant literature is surveyed, and future research needs are identified. To do so, we separate the delivery concepts into three classes: status-quo concepts currently operated, near-future concepts where prototypes already exist, and concepts for the farther future where mainly ideas are presented. Each of these concept classes is dedicated a separate section, i.e., Sects. 4 to 6. Finally, Sect. 7 concludes the paper by summarizing our findings and elaborating general future research challenges of the field not directly related to a single delivery concept.

2 Scope of survey

There are quite a few competing definitions of *last-mile delivery*, but a widely agreed understanding is that the term refers to all those logistics activities related to the distribution of shipments, e.g., parcels with goods ordered online, to private customer households in urban areas. According to this understanding, last-mile delivery starts once a shipment has reached a starting point in an urban area, e.g., a central depot after long-haul transportation, and ends once the shipment has successfully reached the final customer's preferred destination point. Further discussions on alternative definitions of last-mile logistics are, for instance, provided by (Gevaers et al. 2011; Lim et al. 2018). Our survey addresses alternative last-mile concepts, which we define as specific process chains applying one or multiple transport vehicles (e.g., a delivery van and/or a drone), storage facilities (e.g., a central depot and/or a postal locker), and handover options (e.g., attended home delivery or self-service by customers) to fulfill the task of last-mile delivery.

In addition to this definition of our survey's scope, we also add a demarcation of related topics not treated:

- There is some overlap with the concept of city logistics (e.g., see Savelsbergh and Van Woensel 2016). We, however, interpret city logistics as the broader concept that addresses all logistics activities in urban areas and, therefore, also refers to people transportation, e.g., by public transport or car sharing. We only address freight transport and disregard people transport; only combined with freight transport, e.g., when transporting parcels with a public tram into the city center (Regué and Bristow 2013), people transport will be an issue (see Sect. 5.4).
- Last-mile delivery is an umbrella term for a broad variety of different shipment services and not only confined to the handover of parcels. In compliance with Allen et al. (2018b), last-mile deliveries can be divided according to the type of handled goods into the following sub-branches: food shopping, ready to eat meals, courier services, large white and brown goods, and parcels transport by parcel carrier. In our survey, we do not explicitly exclude any of those sub-branches, but we focus on the latter aspect of parcel deliveries, which addresses the transport of small- and mid-sized packages (e.g., according to the postal service provider DHL, these are packages with a maximum weight of 31.5 kg and dimensions of at most 120 × 60 ×60 cm (DHL 2019)). However, while the sub-branches all have their own peculiarities, there is a lot of overlap among their urban delivery concepts. Courier services mostly handle smaller and light-weighed items such as letters, documents, newspapers, or advertising mail, e.g., handled by bike couriers. These items allow other transport options (e.g., just a small bag carried over the shoulder) and storage options (e.g., a small container at a street corner). Furthermore, their handover is typically rather unproblematic, since small items fit into letter boxes. Larger and heavy-weighed brown

or weight goods, e.g., handled by less-than-truckload logistics providers, may require two-man handling and larger vehicles (Allen et al. 2018b), so that a lot of transport options of parcel delivery such as cargo bikes and drones are not available. The delivery concepts for home-delivered meals and groceries operate under even higher time pressure (Allen et al. 2018b). Thus, even if we explicitly address the operations of parcel carriers, most of our explanation is also relevant for the other sub-branches of last-mile delivery. If important peculiarities arise, they are addressed within the respective sections.

- The main players in the parcel carrier market are large logistics companies such as UPS, FedEx, or DHL with nation- or even world-wide networks. They organize the complete parcel supply chain starting, e.g., with the pickup of trailers from large online retailers, their initial sorting in a depot (Boysen et al. 2019a), long-haul transport possibly via a central hub to a depot in an urban area, and finally last-mile delivery. Sometimes these larger networks subcontract smaller companies for sub-processes. In the recent years, large online retailers such as Amazon (Amazon 2019) or Alibaba (Cainiao 2018) even try to establish their own parcel delivery networks. We do not cover the complete parcel supply chain, but focus on last-mile delivery.
- Finally, our survey has an operational research focus. We address specific decision problems occurring when setting up or operating last-mile delivery, solved with quantitative methods. Thus, we exclude empirical work, e.g., on customer acceptance of specific delivery concepts (e.g., see De Oliveira et al. 2017; Iwan et al. 2016; Morganti et al. 2014), or the general preferability of specific delivery concepts from an environmental perspective (e.g., see Hu et al. 2019; Ranieri et al. 2018). The specific decision problems focused in this survey are defined in the following.

Given this scope, our survey addresses alternative delivery concepts, which we subdivide (according to our own assessment) into concepts currently already practiced (see Sect. 4), concepts of the near future where the required technology is currently in the evaluation phase (see Sect. 5), and concepts of the farther future where critical technological components are still under development (see Sect. 6). For each last-mile concept falling in one of these categories, we survey the literature with regard to the following decision problems (ordered from long-term strategic to short-term operational):

(i) Setup (or design) of infrastructure (e.g., location and capacity planning of storage facilities),
(ii) staffing and fleet sizing (e.g., workforce planning of delivery persons and fleet sizing of delivery vans), and
(iii) routing and scheduling (e.g., scheduling drone launches from trucks).

For each last-mile concept, each of these three problems is characterized, the relevant literature is surveyed, and future research needs are identified.

There already exist other survey papers dedicated to related topics, so that we have to relate our paper to these existing review papers in order to justify yet another survey. The survey paper of Savelsbergh and Van Woensel (2016) is dedicated to city logistics, which has a similar, yet broader focus on urban logistics (see our definition above). They, however, rather describe the basic trends and challenges in this field, but do not provide a systematic review of the literature according to a classification scheme. Such a systematic literature review on city logistics is provided by Hu et al. (2019). They, however, have a sustainability focus and neither treat decision problems nor solution methods from an operational research perspective. The survey of Browne et al. (2012) also has an environmental focus and, furthermore, specifically addresses policies in some selected cities. Analogously, Lindholm and Behrends (2012) focus on the Baltic region. The survey paper of Lim et al. (2018) on last-mile logistics explicitly excludes operations research papers. A more general perspective on trends in transportation and logistics in general is taken by Taniguchi et al. (2014) and Speranza (2018). Finally, a recent survey article is provided by Mangiaracina and Tumino (2019). They introduce innovative last-mile delivery concepts. In their survey, however, the focus is rather on introducing the concepts and evaluating their impact on delivery costs, than on giving a broad and systematic overview on recent research. It can be concluded that no survey paper with our specific perspective on last-mile delivery concepts yet exists.

Finally, we briefly specify our paper retrieval procedure based on a systematic database search (see, e.g., Hochrein and Glock (2012) for a general description of how to set up a systematic literature retrieval). As keywords specifying the targeted field of logistics we apply “last mile,” “city logistics,” “home delivery,” “B2C distribution,” and “urban logistics.” Further keywords are derived from relevant technological entities playing an important role in last-mile delivery, i.e., “micro-depot,” “mobile depot,” “parcel locker,” “trunk delivery,” “parcel shop,” “delivery van,” “cargo bike,” “unmanned aerial vehicle,” “drone,” “delivery robot,” “crowd-shipping,” and “public transport.” These keywords have been applied as queries in two scholarly databases, namely Business Source Premier and Scopus, and for each identified paper all referencing papers have been identified via Google Scholar. All English-language papers published in peer-reviewed journals that have been retrieved and those cited in their reference lists (snowball approach) were checked for relevance by analyzing their abstracts.

3 A notation scheme for last-mile delivery concepts

To precisely denote a specific last-mile concept in a compact form, this section introduces a notation scheme. Following our definition (see Sect. 2), last-mile delivery starts in a starting point (dubbed depot) where shipments to be delivered in the respective urban area arrive, e.g., after long-haul transportation or after preparing an ordered meal. From there, a process chain is initiated, which consists of one or multiple transport and storage process steps moving the shipments closer to the customer, until, finally, the handover of a parcel to its dedicated customer is processed. The alternatives for these three basic process steps, i.e., storage, transportation, and handover, are listed in Table 1.

Table 1 Classification scheme

Storage		Transport		Handover	
Value	Description	Value	Description	Value	Description
Depot	Central depot	Van	Delivery van	aHome	Attended home delivery
Micro	Micro-depot	Man	Human delivery person	uHome	Unattended home delivery
Mobile	Mobile depot	Bike	Cargo bike	Self	Self-service by customer
Locker	Parcel locker	Drone	Unmanned aerial vehicle		
Shop	Parcel shop	Bot	Autonomous robot		
Trunk	Car trunk	Crowd	Crowdshipping		
		Train	Freight train		
		Vessel	Ship		
		Aircraft	Flying airship		
		aVan	Autonomous van		
		mLocker	Mobile parcel locker		
		Public	Public transportation		
		Loop	Discrete goods pipeline		

Given these basic elements, a specific last-mile delivery concept can now precisely be defined by a chain of storage and transport process steps, where each chain starts at the depot and ends with a handover element. The most widespread delivery concept, for instance, where a human delivery person driving a delivery van on a route toward customer homes who personally take over their shipments in attended home delivery (aHome), can briefly be referred to by the following chain: [depot>van>man>aHome]. To relieve innermost city centers, novel concepts propose to rather deliver parcels with (electric) cargo bikes, which refill their smaller delivery capacities at decentralized micro-hubs. This concept is denoted by [depot>van>micro>bike>aHome]. Another recent concept is parcel delivery by unmanned aerial vehicles, also called drones, which leave their parcels, for instance, on the balcony during unattended home delivery. This last-mile concept can be briefly denoted by the following chain: [depot>drone>uHome]. Due to the short range of current-generation drones, drone delivery from a central distribution center requires a dense and costly depot network, so that another recent last-mile concept rather proposes to apply delivery vans as mobile launching platforms for drones. This alternative drone-based concept is denoted by [depot>van>drone>uHome].

Our compact chain notation is applied in the following sections to denote the alternative last-mile delivery concepts and to briefly define the concept treated by each surveyed paper in our literature review.

4 Today's concepts

This section is dedicated to status-quo concepts that are already established and successfully applied in daily operations. Certainly, this holds true for the traditional and still most important last-mile concept where a human delivery person drives with a van from customer home to customer home (see Sect. 4.1). To relieve urban areas from excessive delivery traffic, quite a few communities already apply and experiment with two-echelon concepts based on decentralized micro-depots and cargo bikes, especially in innermost city centers (see Sect. 4.2). Furthermore, many postal service providers (try to) establish customer self-services to relieve their human delivery personnel from attended home delivery (see Sect. 4.3). These three classes of today's delivery concepts are detailed in the following.

4.1 Human-driven delivery vans

The status-quo delivery concept that is applied all over the world to process the vast majority of shipments is based on delivery vans departing from a central depot, each driven by a human delivery person. On a tour along customer homes, the delivery person stops the van at the roadside, approaches a customer home, and hands over a parcel directly to the customer via attended home delivery. Our compact notation summarizing this delivery concept is [**depot>van>man>aHome**], and in the following, we briefly describe the main process steps of this last-mile concept in detail.

In the parcel carrier industry, shipments arrive at the central depot (see Fig. 1, left) dedicated to an urban area after long-haul transportation by truck, typically from other depots or hubs. Once docked at an unloading dock, trailers are opened, and shipments are successively unloaded onto a conveyor. Many terminals of the postal service industry apply telescope conveyors, which can be extended into a trailer, to reduce the workers' physical unloading effort. The conveyors connect the central sorting system, which is often a loop-shaped conveyor consisting of tilt trays, as displayed in Fig. 1 (middle). Addressees of shipments are automatically recognized, e.g., by OCR software or scanning a barcode, shipments are isolated each onto a separate tray, and circle through the terminal. Alternative sortation technology (e.g., applying cross belts or sliding shoes) is elaborated in Boysen et al.

Fig. 1 Parcel sorting center (left; *Source*: Hermes 2020), tilt-ray sorter (middle; *Source*: Beumer 2007), and delivery van (right, *Source*: Paketda 2020)

(2019a). Once a shipment passes a chute devoted to the shipment's dedicated region, the tray is tilted, and the shipment slides toward a collection point. Here, the delivery person servicing the region can load all collected parcels onto her truck (see Fig. 1, right) parked next to the collection point. Most parcel couriers aim to sort and store all shipments according to the van's delivery tour, such that the driver can conveniently retrieve one shipment after the other from the van's shelves without search effort. Some depots provide their drivers with decision support for tour planning and vehicle loading, but often existing software tools are not flexible enough to consider driver specific knowledge, such as time-dependent travel times, customer preferences, or current road works (Allen et al. 2018a), so that most drivers plan their routes without optimization support. Inner-terminal operations are not within the scope of this survey, so that we refer to the papers of (Fedtke and Boysen 2017) and (Werners and Wülfing 2010) instead, who detail these processes and the main decision problems to be solved. Furthermore, these processes heavily vary for the different sub-branches of last-mile delivery (see Sect. 2). Once a van is loaded, it departs from the depot and subsequently visits the destinations of loaded parcels. Among the main on-tour problems to be solved by the driver are missing curbside parking spaces, which increase the drivers' risk for parking violation tickets or prolonged walks, and failed first-time deliveries, so that either alternative recipients in the neighborhood have to be found or parcels are taken back to the depot for pickup or a later delivery attempt (Nguyen et al. 2019). Some couriers also offer customers the option to hand over product returns to delivery persons, so that also pickup operations may have to be integrated into delivery tours (Allen et al. 2018b). Another variation in the described process chain arises, if large urban areas are not serviced by a single central depot, but have a two-level structure with additional decentralized depots from where the delivery tours depart (Winkenbach et al. 2016). In the following, we only address the decision problems related to the depot where delivery tours start and end. Multi-echelon delivery is treated in more detail in Sect. 4.2.

Note that, some deliverers have the habit (or policy) to simply leave parcels in front of the door or house, ring the bell and leave even if customers are not at home. In this case, the concept is described by the chain [**depot>van>man>uHome**]. However, without explicit permission of the customer, leaving parcels unattended in accessible areas is not allowed and, in case the shipment is lost, will lead to compensation by the logistics service provider. Although this concept may be an appropriate (yet risky) short-term solution for certain situations, e.g., contact-free delivery during a pandemic, the downsides keep the concept from being investigated in depth so far. Hence, an interesting topic for future research would be risk analyses in the last-mile context that take into account that customers (and neighbors) are not at home, unattended shipments are lost, and compensation has to be payed.

Setup of infrastructure Most service providers of last-mile parcel delivery avoid optimizing their delivery tours each day from scratch for the current set of customers to be supplied. They rather partition the territory serviced by a depot into smaller regions, which remain constant for a longer time. Each region is serviced by a repeated delivery pattern, e.g., once per day, by a tour of a single van. The resulting daily delivery tour for a given set of customers of a region is, then, planned either manually, based on specific knowledge of the driver (Allen et al. 2018a), or with the help of computerized decision support. The price for fixed regions, and the simplification of the planning process coming along with this, is a loss of flexibility in the customer-to-tour assignment. Decision support for territory design has a long-lasting tradition in operations research. However, most papers on territory design focus on other applications such as political districting, which is the partitioning of an area into electoral districts avoiding gerrymandering (i.e., an unfair political advantage for a particular party), or commercial districts, where a fair division of potential sales volumes among salesmen is pursued. Surveys on these applications and suited decision support are, for instance, provided by Kalcsics et al. (2005), Kalcsics (2015), and Ríos-Mercado (2020). Territory design for last-mile delivery faces the challenge that regions have to be determined without deterministic knowledge on the varying sets of customers that have to be serviced each day. In such an uncertain environment, the resulting regions should be compact, such that daily delivery tours become not excessively long, the risk that a single van's capacity is exceeded for servicing daily customers should be low, and the daily workload should be balanced among regions. In the following, we briefly summarize some important contributions fitting these requirements. Haugland et al. (2007) introduce a two-stage optimization problem where customers have to be divided into regions first and delivery tours within each district have to be determined afterward. It is assumed, that each district is in response of a single vehicle and that the customer demands are unknown until the decision about the districts is made. A tabu search procedure is applied to minimize the overall routing costs. A similar problem is proposed by Lei et al. (2012), called the vehicle routing and districting problem with stochastic customers. Again, the problem is formulated and solved as a two-stage optimization problem of districting first and routing afterward. However, on contrary to (Haugland et al. 2007) the routing costs are approximated by the Beardwood–Halton–Hammersley formula. For the objective of minimizing a combined cost function of vehicle costs, routing costs, and region compactness, they propose a large neighborhood search metaheuristic. Carlsson (2012) study an uncapacitated version, where customer locations are stochastic but assumed to be distributed according to a known probability density function. Carlsson and Delage (2013) build up on this work, but they do not assume to know the exact distribution. Lei et al. (2015) subdivide a territory into regions, such that over multiple periods with varying deterministic customer sets multiple traveling salesman problems from multiple depots within each region are minimized. Additionally, compactness, route changes among periods, and workload balancing are considered. They apply an adaptive large neighborhood search metaheuristic for solving this problem.

Another long-term decision is related to the delivery pattern per region. To satisfy same-day or even few-hour delivery promises of online retailers, postal service providers may be forced to schedule multiple tours per region each day. On an operational level, multiple tours per region add a shipment-to-tour assignment problem. Non-urgent orders can be added to earlier tours if capacity is still available, but may cause less detour on later tours where, however, at least parts of the customers to be serviced are yet unknown. Decision support tools for this problem and for quantifying potential gains of multiple delivery tours per day, to counterbalance the trade-off with increasing delivery costs, are yet missing.

Staffing and fleet sizing Among the most important labor-related decision problems is the assignment of drivers to regions and their daily tours. Especially short-term adaptions to account for absenteeism or demand peaks, e.g., during end-of-season sales, are important problems that lack scientific decision support. The sizing of a stand-by workforce for these cases and decision support for driver-to-region assignments, e.g., including a (restricted) reassignment of shipments among regions to balance varying experience levels, are challenging fields for future research. To avoid communal access restrictions for vehicles with combustion engines or to promote sustainable delivery services to ecology-minded customers, electric delivery vans become a viable option for many last-mile service providers. Fleet sizing and mix decisions are a prominent research field in the vehicle routing community which has also integrated the peculiarities of electric vehicles, e.g., range limitation and recharging, see (Hiermann et al. 2016; Pelletier et al. 2016). If, however, last-mile service providers partition their territory into regions each operated by a single daily tour, the peculiarities of electric vehicles and how to best mix them with conventional vans should rather be added to the territory design problem discussed above. This is another interesting challenge for future research.

Routing and scheduling Given a region serviced by a single vehicle whose capacity is not exceeded by the current set of customers to be serviced, the basic routing task to be solved is the asymmetric traveling salesman problem (aTSP). In the last-mile context, asymmetric driving distances between a pair of points are caused, for instance, by one-way streets or the no-left-turn policy. Postal service provider UPS advises their drivers to avoid left turns (in countries with right hand driving). Left turns have a higher risk for accidents, and waiting for breaks in the stream of traffic increases travel times and emissions (Fernandez et al. 2017). Survey papers on the aTSP are, for instance, provided by Laporte (1992) and Roberti and Toth (2012). The aTSP addresses, however, merely the basic problem structure, but neglects some important aspects of daily operations, especially relevant when delivering shipments in urban areas:

- *Time windows* To ensure that customers are at home for attended home delivery services, delivery times may be bound to specific time windows agreed with customers. Other common reasons for time windows in an urban context are commercial customers with limited opening hours, or customers residing in access-restricted pedestrian streets only accessible during specific (off-peak) hours. Some recent algorithmic contributions for the aTSP with time windows are provided in (Ascheuer et al. 2000, 2001; Baldacci et al. 2012).
- *Time-dependent travel times* Especially during morning (evening) commute, traffic flows considerably slower into (out of) business districts. Based on real-world data from Stuttgart (Germany), for instance, Ehmke et al. (2012) quantify the variation of tour durations to range between an overall minimum of 70 min (departure on Saturdays, 12:30 a.m.) and a maximum of 100 min (departure on Wednesdays, 9:30 a.m.). Considering these differences of travel times over the day may considerably shorten tour durations. Recent algorithmic developments for the aTSP with time-dependent travel are provided, for instance, in (Albiach et al. 2008; Arigliano et al. 2019; Cordeau et al. 2014).

- *Time-dependent service times* Not only travel may be time-dependent, but also the delivery times for the delivery person once a van is parked. Examples are commercial customers whose sales personnel may be busy in peak hours, so that it takes additional waiting until they can receive shipments, or private customers known to be not at home during specific times, so that a time surplus for finding a willing neighbor arises. A recent contribution to the aTSP with time-dependent service times is (Taş et al. 2016).
- *Electric vehicles* If an electrified van fleet is applied for last-mile deliveries, their limited ranges and the need for recharging have to be integrated into routing problems. Electric vehicles are among the hot topics of the vehicle routing community. We cannot survey the vast body of literature that has accumulated on this topic in the recent years and refer to review papers instead (e.g., Erdelić and Carić 2019; Lin et al. 2014). We only point out the recent algorithmic contributions of Roberti and Wen (2016) and Doppstadt et al. (2016) on the electric TSP with time windows and the TSP for hybrid electric vehicles, respectively, which come pretty close to our setting.
- *Pedestrian subtours* Especially in dense urban areas, finding parking space close to a customer's address can be a cumbersome task, so that larger pedestrian subtours of delivery personnel are rather the norm. An empirical study indicates that an average delivery van remains stationary for more than 60% of daily tour times and delivery persons walk up to 12 km on foot (Allen et al. 2018b). Especially, if shipments are not overly large and heavy (or if the van is equipped with an additional hand truck), a delivery person can carry multiple shipments and subsequently visit multiple customer homes on a pedestrian subtour each starting and ending at the van's parking position. A MIP model for the TSP with time windows and pedestrian subtours is presented and tested by Nguyen et al. (2019).

Region-specific driver knowledge (e.g., with regard to suited parking spaces, time-dependent congestion, and customer preferences) that cannot appropriately be modeled by commercial routing and scheduling software is said to be the main obstacle for the application of optimization-based routing (Allen et al. 2018b; Nguyen et al. 2019). Instead, most last-mile service providers still let the drivers decide on their routes without decision support. Seeing the vast amount of scientific literature published, this cannot be a satisfying result for the vehicle routing community. Therefore, future research should focus on larger solution frameworks integrating all (or at least most) of the above requirements.

For most postal service providers, static routing problems are no shortcoming, because most shipments arrive, e.g., during the early morning hours, from other depots in a concerted manner, often based on fixed delivery schedules (Boysen et al. 2013). These shipments are sorted and separated according to delivery regions, so that static routing problems for each region arise. In other last-mile domains, e.g., express courier services or meal delivery, urgent deliveries rather arrive dynamically over time, so that as additional decision variables the departure times of all tours have to be determined. This problem, also denoted as the wave (or delivery) dispatch problem (Klapp et al. 2018b), has to consider a given set of fixed customers that have already arrived and potential customers which may arrive in the near future.

Whereas the former customers are delayed if the vehicle waits, briefly missing urgent orders arriving just after departure is also cumbersome, because their delivery will have to wait for the return of the vehicle and its next tour. Important contributions for the wave dispatch problem are briefly summarized in the following. Klapp et al. (2018b) define the dynamic dispatch waves problem. Considering a single vehicle and a line on which customer homes are located, the authors focus on the dispatching problem as routing only depends on the farthest customer. They develop a dynamic programming approach to handle the deterministic case and based on that, derive heuristic solution policies to handle the stochastic case. Later, they extended their work to general graphs (Klapp et al. 2018a) to better cope with typical road networks. Closely related, Voccia et al. (2019) formulate a Markov decision process for the same-day delivery problem, i.e., a dynamic pickup and delivery problem on general networks with multiple vehicles. Van Heeswijk et al. (2019) introduce the delivery dispatching problem with time windows and multiple vehicles. Even more flexibility is added to the wave dispatch problem if a vehicle, once departed, is also allowed to prematurely return to the depot in order to pick up urgent orders, although the current tour is not yet completed. This case is, for instance, considered by Ulmer et al. (2019). The wave dispatch problem is also known in the literature as the vehicle routing problem with release dates. For a recent survey, we refer to Mor and Speranza (2020).

A further stream of literature is related to the question how to agree delivery time windows suited to customers without reducing the routing flexibility too much. A first trade-off is related to the size of time windows. Customers prefer short time windows, because this reduces their waiting time (Boyer and Hult 2005). The poll of Gawor and Hoberg (2018), instead, indicates that standard delivery (full day) is preferred over time window delivery (3 h). However, the authors explain this counterintuitive result with unfamiliarity of the surveyed people with the time window concept. For logistics providers, a shorter time window reduces the routing flexibility, so that longer zigzag tours threaten (Macharis and Melo 2011). Another trade-off arises with regard to the number of alternative time windows customers may choose from (Agatz et al. 2008). Naturally, customers prefer more choice, and Van Duin et al. (2016) stress the importance to properly involve customers when arranging time windows. They show that first-time delivery succeeds more often, if customers are not just announced a fixed time window. More choice, however, increases the risk for the logistics provider that customers select time windows that do not fit into short deliver tours. The studies of Campbell and Savelsbergh (2005), Agatz et al. (2011), Boyer et al. (2009), Ehmke and Campbell (2014), and Gevaers et al. (2014) all address a proper time window management employing heuristics (Campbell and Savelsbergh 2005), approximation approaches (Agatz et al. 2011), and simulation studies (Boyer et al. 2009; Ehmke and Campbell 2014; Gevaers et al. 2014). They all confirm the cost-service trade-offs of time window management. An option to deal with this issue is to offer incentives (e.g., a delivery discount) to nudge consumers toward wider or specific time windows preferred by the logistics provider (Campbell and Savelsbergh 2006; Yang et al. 2016). While most studies assume given customer demands, some studies also address uncertainty (Azi et al. 2012; Spliet et al. 2017; Spliet and Desaulniers 2015; Spliet and Gabor 2014). Assuming deterministic demands but stochastic travel times, Jabali et al. (2015) and Vareias et al. (2019) investigate the case of self-imposed time windows in which time slots are offered by the carrier but not the customer.

It can be concluded that, although status-quo delivery concept [depot>van>man>aHome] is successfully operated for decades now, it is astounding how many open research tasks still remain (i.e., especially with regard to the routing problem).

4.2 Cargo bikes

Especially for the inner most city centers where the population density and the burden of traffic are the highest, many communities seek alternative delivery modes. Cargo bikes (see Fig. 2, left) either purely manually or electrically powered or by a mix of both are well-established delivery vehicles, and their successful application in daily operations is, for instance, reported for Antwerp (Belgium) (Arnold et al. 2018), Vienna (Austria) (Anderluh et al. 2017), and Cambridge (UK) (Schliwa et al. 2015). Their main advantage is that they can reach customers residing in areas with access restriction (e.g., pedestrian zones) and where parking space is rare (Anderluh et al. 2017). Since capacities of cargo bikes are much smaller than those of delivery vans, they need to be replenished multiple times with additional shipments during the day. To avoid time-consuming returns to a central depot, cargo bikes are typically replenished via a network of decentralized micro- (also denoted as satellite) depots. A micro-depot can be a garage in a (multi-story) car park, the loading dock of a shop, or a trailer (see Fig. 2, middle). Trailers, in particular, offer the additional option to relocate a mobile depot to another parking position during the day, so that empty return distances for replenishing cargo bikes can be reduced. To deliver shipments toward micro-depots (or to replenish them during the day), delivery vans are applied, so that a two-echelon routing task is to be solved: Vans to micro-depots and, from there, cargo bikes to customers. The main delivery chain discussed in this context is [**depot>van>micro>bike>aHome**].

Note that we evaluate each discussed delivery concept with regard to its potential contribution to the five major challenges of last-mile logistics discussed in Sect. 1. We rate each concept's contribution to each of the challenges in relation to

Fig. 2 Cargo bike (left; *Source*: DPD 2019), Mobile depot (middle; *Source*: Sommer 2018), and evaluation (right)

status-quo concept [depot>van>man>aHome] on a simple binary scale. According to our own subjective evaluation a (green) check icon indicates that this concept contributes to an improvement of the respective challenge. Figure 2 (right), for instance, depicts our evaluation of delivery concepts based on decentralized depots and cargo bikes. Cargo bikes are either manually powered and/or by an electric engine, so that compared to conventional combustion engines of delivery vans they contribute to sustainable last-mile logistics. A (gray) question mark indicates a questionable contribution, which heavily depends on the specific organization of the respective concept. Cargo bikes, for instance, have rather small capacities, so that it remains questionable whether they are scalable for mass markets. Furthermore, it depends on their velocity in which they can move through a city center whether they can lower costs and deliver parcels on time. Finally, cargo bikes tend to increase the demanded level of physical fitness for delivery persons compared to delivery vans, so that an aging workforce may be a major obstacle for a successful mass application of cargo bikes. However, if electrical bikes are used, this negative effect of the concept may be cushioned significantly.

Setup of infrastructure The most long-term and strategic decision is whether to apply cargo bikes at all and how to integrate them into existing delivery networks. In this context, the paper of Arnold et al. (2018) compares cargo bikes with other delivery concepts, namely traditional vans and self-service concepts. A simulation study based on data from Antwerp (Belgium) is applied. Routes of bikes, vans, and people are determined with the Clark–Wright savings algorithm. They also take a certain percentage (i.e., 11%) of failed deliveries into account. The results show that, compared to vans, cargo bikes can lead to a decrease in external costs, i.e., emission, noise, and congestion, by 40% per delivery. Another simulation study is conducted by Fikar et al. (2018) to evaluate the potential of a combined delivery of traditional vans and cargo bikes operating from micro-depots. In an agent-based simulation, vehicle routes are determined via the best insertion heuristic. In this way, impacts of varying storage capacities at micro-depots, maximum delivery times, and the availability of cargo bikes are evaluated.

Once the decision pro cargo bikes is made, the main long-term decision tasks to be taken when setting up this delivery concept are the locations and capacities of micro-depots. Choosing a specific location for a micro-depot may include one-time fixed costs (e.g., long-term rental fees for a garage) and/or daily usage costs (e.g., a parking fee for locating a trailer on a specific parking space). Depending on which of these costs are relevant, selecting micro-depot locations can also become a rather short-term decision problem (see below). Clearly, the micro-depot location problem faces the traditional trade-off of facility location problems: Erecting more micro-depots increases facility costs, but reduces the transport costs toward customers and vice versa. The peculiarity, however, is that we have a two-echelon transportation task. Traditional vans are applied to deliver shipments toward micro-depots and, from there, cargo bikes deliver the shipments toward customers. Thus, the locations of micro-depots constitute the customers (multiple depots) for the former (latter) routing task. Multi-echelon location routing problems, which combine location planning with the routing decisions from the selected locations, have a long-lasting tradition in the vehicle routing community. Instead of trying to summarize the vast number of algorithmic research contributions and problem variants, we refer to the in-depth literature surveys provided in (Cuda et al. 2015; Drexl and Schneider 2015; Prodhon and Prins 2014; Schneider and Drexl 2017). A main challenge when selecting long-term locations for micro-depots is that the customers to be delivered are yet uncertain and bound to daily change. However, there also exist quite a few multi-echelon location routing problems integrating fuzzy or stochastic customer data (see Drexl and Schneider 2015).

Staffing and fleet sizing includes the decisions on an appropriate number of bike-driver tandems to be applied and the truck fleet for supplying the micro-depots. Again, these decisions face the traditional trade-off between these problems: Larger fleets increase delivery services for customers, e.g., a higher rate of on-time deliveries, but increase wage and investment costs. Naturally, these decisions are also impacted by the locations of the micro-depots and the interdependent routing of vans and cargo bikes of our two-echelon environment. Optimizing location routing decisions jointly with fleet sizing combines three challenging decision tasks and is, thus, a great algorithmic challenge. An approach for this optimization task also including different vehicle types and time windows is, for instance, presented by Koç et al. (2016a). They apply a complex hybrid evolutionary algorithm including large neighborhood search. A more application-oriented view also including fuel consumption, emissions, and operational costs is presented by the same authors in Koç et al. (2016b). The only paper of this category explicitly considering the peculiarities of cargo bikes (and not just any multi-echelon routing task) is the paper of Choubassi et al. (2016). They tackle a routing problem with time windows in order to compare different types of cargo bikes, i.e., trikes, e-trikes, bikes, and e-bikes, with delivery vans. Note that a trike has three wheels and can, thus, carry a larger cargo compartment (see Fig. 2, left). The considered optimization problem aims at minimal routing costs, is formulated as a MIP, and solved with a heuristic procedure. Results show, for instance, that e-trikes have the lowest net present value.

Routing and scheduling If the locations of micro-depots are fixedly determined and cannot be altered on short notice (because a given network of garages is applied), the remaining routing problem for a given fleet of cargo bikes resembles a multi-depot vehicle routing problem. An in-depth survey paper on this problem is presented by Montoya-Torres et al. (2015). Further peculiarities that may be relevant are limited capacities of micro-depots (Mirhedayatian et al. 2019), time windows, if the customers are promised specific delivery times, and recharging of electric cargo bikes. The latter problem becomes even more involved if different travel speeds of electric cargo bikes are integrated. Slower travel leads to longer delivery times, but reduces energy consumption and, thus, saves recharging time, and vice versa. A survey on vehicle routing including speed-dependent energy consumption is, for instance, provided by Demir et al. (2014). Furthermore, time-dependent travel times to consider slower travel during rush hours may be relevant in our urban context. For a survey on time-dependent routing see Gendreau et al. (2015). If trailers are applied as micro-depots and there is flexibility to select from a given set of potential locations on short notice for the price of a parking fee, then we still have the two-echelon routing structure discussed above. Routes of trucks delivering micro-depots and of cargo bikes toward customers are interdependent and impacted by the selected micro-depot locations. However, other than in the long-term problem variant, the customers to be delivered are typically known with certainty on a daily basis. Again, we refer to the survey papers on location routing problems (Cuda et al. 2015; Drexl and Schneider 2015; Prodhon and Prins 2014; Schneider and Drexl 2017) for suited solution procedures. Instead, we focus on the routing literature that is specifically dedicated to cargo bikes. Sheth et al. (2019) investigate a problem variation without temporary storage in micro-depots and develop analytical functions to estimate and compare routing costs of traditional vans and cargo bikes. Their results indicate that bikes are more cost efficient for deliveries close to the depots, routes with a high density of customers, and low delivery volumes. Anderluh et al. (2017) treat a two-echelon routing problem for parcel distribution with vans on the first leg and cargo bikes on the second. Hereby, a temporal and spatial synchronization between the two types of vehicles is integrated in the problem. A MIP and a greedy randomized adaptive search procedure (GRASP) with path relinking is presented.

The two-echelon location routing problems relevant for delivery concepts with cargo bikes are among the most challenging optimization problems of the transportation domain. Especially when extending these problems by further aspects of real-world relevance, such as uncertainties with regard to customers, limited capacities, time windows, fleet size and mix decisions, recharging of electric cargo bikes, speed-dependent energy consumption, and time-dependent travel times. The basic two-echelon optimization problem and any of these extensions in isolation have received plenty of scientific attention. However, holistic approaches combining many or even all these aspects in a large algorithmic framework that can be applied to solve real-world data instances are yet missing. Furthermore, there are two other delivery concepts closely related to [depot>van>micro>bike>aHome] that require future research efforts.

[**depot>van>mobile>bike>aHome**] If trailers are applied as micro-depots, they offer an additional flexibility. Trailers can be applied as *mobile depots*, which are relocated toward varying locations during the day. Mobile depots promise a reduction of empty travel for cargo bikes when replenishing their shipment capacities. In addition to the selection of locations, timing decision defining the movement and durations of stay of mobile depots at each selected location need to be taken. Furthermore, these decisions have to be synchronized with the cargo bikes and their movement through the city center. The vehicle routing community investigates similar problems such as the truck and trailer routing problem (Gerdessen 1996) or routing with mobile facilities (Lei et al. 2016), but solution approaches focusing on the peculiarities of mobile micro-hubs supplying cargo bikes are yet missing.

[**depot>van>mobile>man>aHome**] Instead of applying cargo bikes for attended home deliveries, Allen et al. (2018a) introduce the application of so-called pavement porters. Informed via a smartphone app, porters in duty for a specific street segment receive shipments at the curb from a delivery van, and supply parcels via hand carts in their area. This adds even more flexibility with regard to locating mobile micro-depots and, furthermore, requires time synchronization between porters and delivery vans. Suited solution algorithms are yet missing.

4.3 Self-service

Attended home delivery is the most time-consuming and, thus, costly way to hand over packages. The delivery person has to stop at each single customer home, walk to the door, look for the correct doorbell, and hope that somebody is at home. If nobody is there, either the parcel is taken back for another delivery attempt at a later time or for customer pickup at a central facility. Alternatively, the delivery person tries to find a neighbor to deposit the parcel there. All these reactions on unsuccessful delivery attempts cause additional effort and are a potential source of dissatisfied customers. Therefore, many postal service providers try to establish customer self-service. When applying this handover option, multiple parcels for more than a single customer are brought to a decentral facility conveniently reachable by customers. Such a decentralized facility can either be a parcel locker or a shop (see Fig. 3). Note that shop is an umbrella term for a decentral collection unit, where shipments for multiple customers are taken over and handled by a human service person. This can be a tobacco shop or small convenience stores serving as a parcel shop, but also the welcome reception of a large office building or fitness center.

Compared to home delivery, the batched delivery of multiple customers' parcels to a decentralized pickup location saves effort for the postal service provider, which facilitates handling increasing parcel volumes, tends to lower costs, and relieves the (aging) workforce. This, however, is just one side of the trade-off. Self-serving customers give up convenience and have to travel toward their respective pickup locations. This may delay the final receipt of a shipment and may require incentives (e.g., lower postal fares) to convince customers to participate in self-service. Furthermore, the saved travel effort of the postal service provider is to be traded off against the additional travel of customers toward the self-service location. Thus, also from an environmental perspective it is not self-evident that customer self-service reduces travel-induced environmental impact, but depends whether a customer makes an additional drive by car between her home and the self-service station or passes by the pickup location on the way back home anyway. Our evaluation of customer self-service compared to the status-quo delivery option with regard to the five challenges identified in Sect. 1 is summarized in Fig. 3 (right). Especially, the questions on the right incentives and the total environmental impact of self-service are important

Fig. 3 Customer self-service: Parcel locker of the Australian Post (left; *Source*: Worthington 2014), Self-service in a book store (middle; *Source*: Hermes 2016), and evaluation (right)

research topics, but they are beyond the scope of this survey. In the following, we concentrate on the decision problems to be solved when setting up and operating a self-service delivery concept and start with parcel lockers.

[**depot>van>locker>self**] Parcel lockers are applied since many years in more than 20 countries all over the world, including the US, UK, Germany, and Canada (Deutsch and Golany 2018). Figure 3 (left) shows an example from the Australian Post. Lockers, typically positioned in well-frequented areas, are stationary unattended delivery machines operating on a 24/7 basis. They store parcels to be picked up by customers, who have to identify themselves via some integrated terminal, and often also provide the possibility to send parcels. Especially for people often not at home during typical delivery times of traditional courier services, parcel lockers provide a convenient alternative to process mail at a suited time (Iwan et al. 2016).

Setup of infrastructure Quite a few papers on parcel lockers focus on critical factors for their successful diffusion in different example regions, e.g., Brazil (De Oliveira et al. 2017), Australia (Lachapelle et al. 2018), New Zealand (Kedia et al. 2017), Poland (Iwan et al. 2016), the Netherlands (Weltevreden 2008), France (Morganti et al. 2014), and Sweden (Vakulenko et al. 2018). These empirical works reveal that the customers' travel distances toward their designated parcel lockers are among the most important success factors. Thus, location planning of parcel lockers is of utmost importance. This decision faces the typical trade-off of location planning (e.g., Klose and Drexl 2005): The more parcel lockers are erected, the better their reach toward customers, but the higher one-time installation costs (and vice versa). The only paper treating location planning of parcel lockers yet is the one of Deutsch and Golany (2018). Given a set of potential locker locations, they formulate a MIP to choose optimal positions, such that total profit is maximized, where profit considers revenue of customers using the lockers, fixed and operational setup costs for opening a locker, discounts depending on farther customer travel toward lockers, and the loss of potential customers if lockers are placed beyond their accepted walking range. A simplifying assumption they make is that each locker has unlimited capacity for parcels. This neglects another long-term decision problem, which is the question for the right layout of each parcel locker and the sizing of compartments. The larger each single compartment, the larger the probability that some parcel fits. But given limited urban space for parcel lockers and a given total size of a locker, more customers can be serviced if smaller compartments are selected. Faugère and Montreil (2017, 2020) address the design of parcel lockers. They discuss the pros and cons of four different locker designs in the physical internet context (Faugère and Montreil 2017) and apply optimization procedures to size the compartments of a locker (Faugère and Montreil 2020). Future research should consider that location planning of lockers and deciding on their individual layouts are heavily interdependent. The set of potential customers serviced from a locker depends on the position of the locker within walking range and the size and number of compartments. Thus, future research should develop holistic approaches unifying both decisions.

Staffing and fleet sizing the delivery process for a given network of parcel lockers with delivery vans launched from a central depot is rather similar to any one-to-many transportation setting, so that it is not surprising that no literature specifically dedicated to these decisions in a parcel locker context yet exists.

Routing and scheduling On an operational level, a given network of parcel lockers already exists. Thus, the remaining decision tasks are to assign customer parcels to specific compartments of parcel lockers and to schedule their delivery toward the selected lockers, which is typically executed by delivery trucks. In this context, Orenstein et al. (2019) present the so-called flexible parcel delivery problem. They assume that each customer is only willing to accept self-service from a subset of lockers (e.g., those within walking range) and provide a MIP and a metaheuristic to solve the resulting combined assignment and routing problem. They show that the delivery effort is strongly affected by the number of alternative lockers accepted by each customer. A new variant of the TSP with time windows is formulated by Jiang et al. (2019). Whenever a delivery person is not able to deliver a parcel according to the agreed time window at a customer's home, the parcel is redirected into a nearby locker. The developed MIP and heuristics intend to minimize the overall costs consisting of travel costs of the delivery vehicle, (penalty) costs for the customers when retrieving their parcels from a locker, and fixed costs for each applied locker. Hong et al. (2019) also consider a variant of the TSP with time windows. Similar to Orenstein et al. (2019), they seek a solution minimizing costs depending on the customer-to-locker assignment and the route of the delivery truck. They formulate the problem as a MIP and provide an ant colony heuristic. Ulmer and Streng (2019) investigate a dynamic routing problem. Given a depot, a set of lockers, and (autonomous) vehicles, customer orders dynamically arrive over time and have to be serviced both fast and to a nearby locker. To answer the question when to leave the depot, they propose a policy function approximation to decide whether the delivery vehicles should wait for further shipments that potentially arrive in the future or depart now to allow fast deliveries of those shipments that have already arrived. Existing research neglects that most parcel lockers also offer the service to send parcels. Thus, the resulting routing and scheduling problems are rather of the pickup-and-delivery type where the limited capacity of a delivery truck may become a bottleneck, if some lockers have considerably more outgoing than incoming parcels. Extending existing approaches with this property is a valid task for future research.

[**depot>van>shop>self**] Pickup stores, i.e., decentral self-service units denoted as shops, which are operated by human service persons, e.g., mom-and-pop stores or fitness center receptions, are alternative pickup locations. Their main advantage is that no extra network of parcel lockers has to be established. Instead, existing shops offer postal services in addition to their bread-and-butter business. Furthermore, many customers may prefer the human interaction offered by shops. An overview on real-world shop networks for parcel services in Germany and France is provided by Morganti et al. (2014).

From a modeling perspective, the main difference between a shop (see Fig. 3, left) and a parcel locker, is that, compared to the 24/7 services of parcel lockers, most shops have limited opening hours. Depending on the movement patters of customers, this further reduces the set of acceptable pickup locations. Furthermore, a shop has rather a total capacity limit for storable shipments than a restricted compartment size for each single parcel. Both properties may require to slightly vary the constraints of the long-term and operational decision problems discussed for parcel lockers, but keep the general problem structure unaltered. Consequently, Hong et al.

(2019), for instance, speak of delivery centers and do not differentiate whether this is a convenience store or a parcel locker. A difference, however, is that there may be the opportunity to combine parcel logistics to and from a shop with its "normal" logistics activities related to a shop's bread-and-butter business. In this case, service restrictions of two domains have to be combined, which is a challenging task for future research.

5 Near future

This section elaborates on near-future concepts, which have not yet made it into daily operations, but have already successfully been applied in field tests. Whether these concepts will indeed reach a market-ready state is beyond this paper. However, there are quite a few promising concepts based on technological developments and innovations either on the transport or handover stage that are vividly discussed in the professional and scientific literature. Specifically, this section investigates drones, autonomous delivery robots, crowdshipping, and public transport as alternative transport options. Furthermore, deliveries into car trunks and receptions boxes are innovative unattended delivery options to avoid the strains for parcel service providers connected with attended home deliveries.

5.1 Drones

The application of unmanned aerial vehicles (also denoted as drones) for supplying shipments on the last mile, is vividly discussed in the recent years and prototypes have, for instance, successfully been tested by DHL (DHL 2014), Amazon (Amazon 2020), and Alibaba (BBC 2015), to name just a few. Drones applied for last-mile deliveries (see Fig. 4, left) are typically restricted to carry just a single, not too heavy shipment at a time. Depending on the operational concept of drones, processing a considerable amount of shipments may require a significant drone fleet size, so that it remains questionable whether drones can contribute to handling large parcel volumes and reduce costs. On the other hand, they are electrically powered, unobstructed air travel is comparatively fast, and they operate autonomously (except

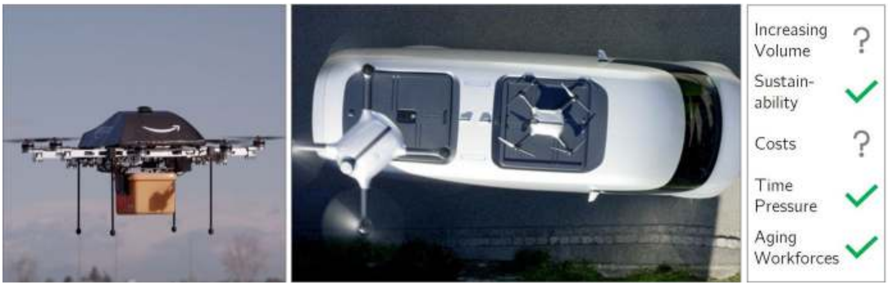

Fig. 4 Drone with a parcel (left; *Source*: Amazon 2013), launched from a van (middle; *Source*: Daimler 2016b), and evaluation (right)

for surveillance personnel), so that drones have the potential to positively impact our other three evaluation criteria, i.e., sustainability, lower costs, and the relief of an aging workforce (see Fig. 4, right). A current implementation in practice, which proofed the concept to be a valid alternative for deliveries, especially in critical times such as a pandemic, was accomplished by Flytrex (2020).

Drones have not only attracted a lot of public interest and press coverage, but also a considerable body of scientific literature has accumulated on this topic in the recent years. The latter is, for instance, documented by the huge number of papers reviewed in the survey paper on drones of Otto et al. (2018). This survey, however, is dedicated to civil applications in general, such as coverage, search, and routing problems, but does not focus on last-mile logistics. Another survey paper on drone-extended traveling salesman and vehicle routing problems is presented by Khoufi et al. (2019). Again, they have a general focus and address drone path optimization problems in general, also including surveillance and monitoring problems. Recently, Rojas Viloria et al. (2020) also survey articles concerning vehicle routing problems with drones for different fields, such as parcel delivery, surveillance and data collection, internal logistics, entertainment, and military. Thus, in the following, we classify and address only those of the papers already surveyed in (Otto et al. 2018), (Khoufi et al. 2019), and (Rojas Viloria et al. 2020), which fall into our scope (see Sect. 2), as well as those articles published since then. Finally, another survey article is provided by Coutinho et al. (2018), but they focus on trajectory optimization. Here, the task is to control a drone according to aspects such as orientation, velocity, altitude, wind, and collision avoidance, such that a given set of predefined waypoints are efficiently visited.

In light of the pros and cons of drone delivery, there are two favorite concepts in particular on how to reasonably apply drones in last-mile delivery, which have originally introduced to the operations research literature by Murray and Chu (2015). Firstly, in concept [depot>drone>uHome] drones are launched directly from the central depot and fly back and forth each leg toward a customer. Given the limited flight range of drones, which according to Agatz et al. (2018) is currently restricted to about 20km, in large urban areas, this concept requires a dense and costly depot network. To overcome this drawback, the second concept [depot>van>drone>uHome] applies delivery vans as mobile launching platforms for drones. We start our survey with the former delivery concept. Note again that all technical and legislative restrictions of drones are beyond our discussion. We only focus on decision problems, and refer the reader to Otto et al. (2018) and the literature cited there for these issues. Further note that we consider drone delivery concepts to always execute unattended delivery (uHome), since parcels can be dropped of at the destination without the recipient being present. This is also applied for papers include deadlines and time windows (e.g., Ham 2018; Ulmer and Thomas 2018), which are more plausible for attended home delivery.

[**depot>drone>uHome**] Launching drones from a depot directly toward customers is the most basic last-mile concept involving drones. On the negative side, however, the limited flight range of drones requires that either the single depot or the network of decentralized depots are erected directly in an urban area, where land is notoriously costly. Thus, among all decision problems related to delivery concept [depot>drone>uHome] discussed in the following, the first one is of considerable importance.

Setup of infrastructure The main question related to this concept to be answered over a long-term planning horizon is where to locate the depots from where the drones are launched. This decision problem faces the classical trade-off of facility location problems (e.g., see Klose and Drexl 2005). Given the limited flight-range of drones, opening more depots increases the reach toward customers and reduces travel distances, but leads to higher investment costs (and vice versa). There are two basic strategies on how to operationalize this trade-off. Either the coverage of drones for a given set of customer locations can be maximized given a limited budget for depots. Alternatively, the number of depots to be erected to cover a given set of customer locations can be minimized. The former problem is considered by Chauhan et al. (2019), who propose a MIP and heuristics to maximize the coverage. The latter is, for instance, pursued by Torabbeigi et al. (2020), who apply a straightforward variant of the set covering problem to this problem. A similar cost-oriented setting, considering depot erection and drone procurement costs, is considered by Shavarani et al. (2020). Considering a competitive environment, where different online retailers compete with each other, Baloch and Gzara (2020) provide a nonlinear mathematical model as well as logic-based benders decomposition approach to decide on which facilities should be opened, so that the overall profitability of the retailer is maximized. While the majority of the literature ignores limitations of drones sharing the same airspace, safety issues are addressed by Sung and Nielsen (2020). They propose a genetic algorithm which decomposes the service area into several disjoint zones each operated by a single drone. To bridge a distance between depot and customer beyond a drone's flight range, recharging stations can be inserted into the distribution network. The resulting location planning problem for recharging stations of drones is, for instance, presented by Hong et al. (2018). They provide a MIP and a heuristic solution approach to maximize the weighted number of covered customers for a limited number of charging stations and a discrete set of potential locations. A similar setting is investigated by Shavarani et al. (2019), who propose a fuzzy approach. The uncertainty with regard to the customer locations that are to be visited, which is typically unknown during long-term location planning, is certainly an aspect that deserves more attention. Finally, Pan et al. (2020) raise the question where to optimally erect drone logistics hubs to support surrounding villages. They do not intend to deliver toward each individual customer but only to local spots within each village. They provide a metaheuristic to handle the problem.

Staffing and fleet sizing Shavarani et al. (2020), Shavarani et al. (2019), and Chauhan et al. (2019) do not only investigate the strategic depot location problem, but simultaneously integrate the tactical drone fleet sizing problem. Liu et al. (2019) propose a two-stage stochastic program to handle uncertain parcel demands. Their approach decides on the drone fleet first and the number of parcels delivered by each drone afterward. Troudi et al. (2018) propose a MIP formulation to minimize the drone fleet considering time windows of customers. Once drone delivery is established and high demands for drones are satisfied by mass production processes, it is to be expected that prices for drones will drop. If this happens, investment costs for a drone fleet will be less of an issue as long as the fleet is generously dimensioned to meet the promised service levels.

Routing and scheduling At the operational planning level, the main question is how to get a given set of parcels to customers given a depot network equipped with drones. Since drones are typically restricted to carry a single shipment at a time, the routing problem in its most basic version reduces to a straightforward assignment of drones to customers. This setting resembles the well-researched parallel machine scheduling problem, where the machines represent drones and jobs their flights to customers. Therefore, drone-related routing research rather treats extended problem versions. One stream, for instance, investigates that trucks and drones operate in parallel, so that a decision is required which kind of transportation device services each customer. In 2015, Murray and Chu (2015) were the first to introduce the parallel drone scheduling TSP (PDSTSP) where a single depot, a truck, and a set of drones are available. The task is to decide which customer should be served by drone and which by truck, so that the makespan is minimized. The drones fly back and forth the depot and selected customers, and the truck services all remaining customers in a single TSP tour without capacity limitation. The authors provide a MIP and a straightforward heuristic. Saleu et al. (2018) and Dell'Amico et al. (2020) build up on their work and propose additional heuristic solution procedures to tackle PDSTSP. Ham (2018) extend the PDSTSP by pickup and delivery options, multiple depots, multiple trucks, and time windows. They apply constraint programming as a solution method. Another extension is investigated by Dorling et al. (2017), who present a MIP and a simulated annealing approach for the case when drones are able to carry multiple packages simultaneously. Torabbeigi et al. (2020) do not only consider the customer-to-drone assignment, but also optimize the corresponding trajectories and provide a MIP as well as bounding methods. While most papers assume a single depot (or a fixed drone-to-depot assignment), Song et al. (2018) and Eun et al. (2019) consider a depot network and allow drones to swap depots. A stochastic and dynamic problem version is proposed by Ulmer and Thomas (2018). They maximize the expected number of serviced customers for trucks and drones operating independently from a single depot. Liu (2019) introduces a rolling horizon approach to handle the dynamic setting for the example of on-demand meal delivery by drones. Finally, Sawadsitang et al. (2019) propose a three-stage stochastic programming formulation to handle uncertainty in terms of takeoffs, e.g., drones may not be allowed to takeoff during stormy weather, and breakdowns, e.g., caused by accidents. Note that trajectory optimization, e.g., minimizing energy consumption given specific weather conditions (see Coutinho et al. 2018), is rather a technical task and thus beyond our scope.

Existing literature on drone routing often ignores recharging drone batteries. This is typically justified by battery swaps, whose time consumption is negligible compared to travel times. Battery swaps, however, require human assistance, and there are other process alternatives to extend flight ranges without human support. One alternative is that a logistics network also contains recharging stations, where drones can recharge their batteries autonomously. Since this takes time and blocks limited charging capacity, integrating autonomous recharging operations could be a valid task for future research. Another alternative is that drones wait at meeting points to be collected by truck. This relieves them from return flights and leaves more energy to reach farther customers, but requires an integrated planning of the drone collection process.

[**depot>van>drone>uHome**] To avoid the costly network of urban depots required by delivery concept [depot>drone>uHome], the other prominent example for applying drones for last-mile logistics proposes the application of delivery vans serving as mobile launching devices. Vans and their higher driving ranges allow to transport drones closer to customers. Drones are loaded en route each with a single shipment stored on the truck, depart to a customer, complete their unattended home delivery, and meet the truck either at the same or a later stop. Alternatively, customers can also be serviced without drone support directly by the driver. The latter is unavoidable whenever customers have no suited landing space for a drone, e.g., because they live in a skyscraper without balcony or openable window. Thus, drones rather extend the options of a given [depot>van>man>aHome] delivery chain, so that when deciding for this concept an existing infrastructure of depots and trucks is typically already available. We thus concentrate on the routing and scheduling tasks to be solved when operating the [depot>van>drone>uHome] concept.

Staffing and fleet sizing As explained above, it is not surprising that the literature on this topic is limited. Specifically, we are only aware of the paper of Salama and Srinivas (2020), who consider the number of drones each truck is equipped with as an additional decision variable. Nonetheless, their focus is also on the routing problem, which is discussed in the following.

Routing and scheduling Recall that Murray and Chu (2015) were the first to introduce concept [depot>van>drone>uHome] to the operations research community. In 2015, they introduced the so-called flying sidekick TSP. Given a single depot and a truck equipped with a single drone, the task is to find a trip with minimum tour completion time (for both devices), so that each customer is served either by truck or drone. The drone is only allowed to depart from and return to the truck at a customer node. Basically the same (single-truck–single-drone) problem is considered by Agatz et al. (2018) called the TSP with drone (TSP-D). Since then, several solutions approaches have been introduced to solve this problem, such as an exact branch-and-bound procedure (Poikonen et al. 2019), an exact dynamic programming (DP) approach for the complete TSP-D (Bouman et al. 2018) and another DP if the customer sequence is given (Agatz et al. 2018), as well as several heuristics (Agatz et al. 2018; Chang and Lee 2018; El-Adle et al. 2019; Ferrandez et al. 2016; Freitas and Penna 2018, 2020; Ha et al. 2020; Murray and Chu 2015; Poikonen et al. 2019; Yurek and Ozmutlu 2018), MIP formulations (Agatz et al. 2018; Dell'Amico et al. 2019; El-Adle et al. 2019; Murray and Chu 2015), and a simulation (Carlsson and Song 2018). Recently, Murray and Raj (2020) have extended the pioneering work of (Murray and Chu 2015) and tackle single-truck–multiple-drone setting with a MIP and a heuristic solution approach.

Analogously to TSP-D, Wang et al. (2017) and Poikonen et al. (2017) introduce the vehicle routing problem with drones (VRPD) considering multiple truck–drone tandems with limited capacity. In addition to the problem formulation, their main contributions are worst-case results. Based on Wang et al. (2017), Schermer et al.

(2019b) develop a MIP and a matheuristic. Wang and Sheu (2019) investigate a problem extension of VRPD where a drone is not forced to return to the same truck it is launched from. They present a MIP and branch-and-price method. Kitjacharoenchai et al. (2019) also abstain from a fixed drone-to-truck assignment, but they abstract from capacity constraints, which results in the multiple traveling salesman problem with drones (mTSPD) solved via MIP and heuristics.

Based on both basic routing tasks, the drone literature investigates a broad variety of problem extensions. Othman et al. (2017) and Boysen et al. (2018a) extract different versions of drone routing problems, when the truck route is already fixed and given. Ha et al. (2018) treat the min-cost TSP-D which considers that drone and truck have different travel costs. Sacramento et al. (2019) also seek for a min-cost solution given multiple trucks each equipped with a single drone. In this context, Wang et al. (2019b) combine both objectives (min-cost and min-time) and introduce the bi-objective version of TSP-D. Further extensions are no-fly zones (Jeong et al. 2019), sustainability aspects (Chiang et al. 2019), and en route operations (Marinelli et al. 2017; Schermer et al. 2019a), where the drone is allowed to depart from/return to the truck on the travel leg between customer nodes. Another problem version is treated by Moshref-Javadi et al. (2020) and Moshref-Javadi et al. (2020), who solve the traveling repairman problem with drones, where the goal is to minimize the cumulated waiting times of all customers. Wang et al. (2019a) mix the concepts [depot>drone>uHome] and [depot>van>drone>uHome] and allow three options simultaneously: Customers are either serviced by a given set of truck–drone tandems, by drones launched from the depot, or trucks without drones. Poikonen and Golden (2020) provide a MIP and heuristic solution approach for the multi-visit drone routing problem, where multiple drones supported by a single truck are each able to carry multiple packages simultaneously. Drones can, thus, visit more than a single customer before returning to the truck. Very similar problem settings are considered by Kitjacharoenchai et al. (2020) and Liu et al. (2020). The peculiarities of pickup and delivery jobs operated by truck-and-drone tandems are investigated by Karak and Abdelghany (2019). Furthermore, related surveillance problems are treated in (Luo et al. 2017; Savuran and Karakaya 2015, 2016), where drones only observe multiple successive target points before returning to the truck.

To conclude, we think that it is fair to say that both drone-based delivery concepts [depot>drone>uHome] and [depot>van>drone>uHome] have received considerable scientific attention. There may be some more elaborate problem versions not yet investigated, but seeing that drones are not yet operating in mass markets and many operational details are still unclear, we think that scientific research should rather concentrate on the identification of the most promising drone-delivery concept, which may vary for different last-mile delivery tasks. Thus, we rather see future research needs for comparing different drone-based delivery concepts. Such a comparison should also integrate the following alternative drone-base concepts which have received much less attention yet:

- [depot>van>micro>drone>uHome] To overcome technical problems when launching drones from delivery vans (and to save the truck's waiting time for drone returns) without having to invest into a costly depot network, Kim and

Moon (2018) investigate the drone station concept. Drone stations are decentralized micro-depots without any further equipment for handling shipments, so that they do not require much costly urban space. The shipments are loaded by a conventional van and delivered toward a drone station where drones can be loaded with shipments, recharge after delivery, and wait for the next truck. Kim and Moon (2018) investigate the TSP with drone stations each utilized by multiple drones, where they seek a truck route through drone stations and customer nodes serviced by the truck itself, such that all customers are serviced in minimum time (with all devices returned).

- [depot>drone>locker>self] A major obstacle for the successful mass application of drone deliveries is that many customers, especially in urban areas, lack suited landing space for a fail-save, secure, and theft-protected unattended delivery. Therefore, drones could rather be applied to deliver shipments toward parcel lockers equipped with a suited landing platform and parcel retrieval mechanism on top. Self-servicing customers without suited landing space can then pick up their shipments at a convenient time from the parcel locker. The only paper addressing this concept yet is provided by Ulmer and Streng (2019). They consider a dynamic dispatching problem, which decides when drones (or earth-bound autonomous vehicles) should depart toward lockers given stochastic knowledge on future arrivals of customer orders.
- [depot>drone>van>man>aHome] Another drone-based delivery concept addressing the lack of suited landing space in urban areas is investigated by Dayarian et al. (2020). They propose to rather apply drones for resupplying trucks en route with urgent orders that have arrived at the depot after their departure. In this way, the flexibility of drones can be utilized to avoid premature vehicle returns to the depot, but attended home delivery is still executed in a conventional manner by a human delivery person.
- [depot>drone>micro>drone>uHome] To reduce the total number of drones and to relieve the airspace, Coelho et al. (2017) propose to rather apply differently sized drones in a two-echelon setting. Larger drones, applying a specific layer of the airspace to avoid interference, transport multiple shipments toward micro-depots, which they call supporting points also used for recharging. From there, small drones applying another layer, each transporting a single shipment, depart toward customers. The authors call the resulting problem the multi-objective green UAV routing problem and apply a matheuristic to solve it.

Seeing the vast amount of operations research literature that has accumulated on drones within just a few years, it will be interesting to see whether the technical development of drones and their market diffusion can live up to these expectations.

5.2 Autonomous delivery robots

Another variant of autonomous delivery devices is earth-bound delivery robots (or simply called bots). An example is depicted in Fig. 5 (left). Quite a few enterprises such as Starship Technologies, Robby, or Amazon Scout are either already

Fig. 5 Autonomous delivery bot (left; *Source*: Starship Technologies 2020) launched from a van (middle; *Source*: Daimler 2016a), and evaluation (right)

selling or currently developing delivery robots. Compared to drones, autonomous delivery bots have different pros and cons: Bots travel in pedestrian speed of about 6km/h on side-walks, which considerably slows down their delivery speed, but allows them to move slightly heavier shipments up to 10kg (Starship Technologies 2015). Whereas a drone has to be supervised by a dedicated flight operator during all time and is not allowed in neuralgic areas, e.g., close to airports (FAA 2018), bots face less security regulations, so that, in different field tests, one operator was allowed to supervise dozens of bots (Bakach et al. 2020). In addition, apart from no-fly zones (e.g., security areas) and obstacles (e.g., large buildings), drones can fly directly from A to B while robots tied to the existing road network. These technical specifications rather influence the input data of decision problem, e.g., cost parameters, operating ranges, and payloads, so that our evaluation of delivery bots with regard to our five challenges of Sect. 1 is similar to that of drones (see Fig. 5, right). The only deviation is that—due to their slow delivery speeds—bots can barely relieve the time pressure of last-mile distribution. However, the bots are already used in practice, e.g., by Hermes in Hamburg and London (Bertram 2017), the German post (T3n 2017), and Amazon (Dormehl 2020) for parcel delivery or for pizza delivery in German and Dutch cities (Starship Technologies 2017).

The main difference of drone- and bot-based delivery concepts, however, that also impacts the structure of the decision problems, is that bots are only suited for attended home delivery. Once a delivery bot has arrived, customers are informed via a smartphone app, have to unlock and open the cargo bay, and have to remove the shipment (Boysen et al. 2018b). Thus, the main drone-based delivery concepts, i.e., either directly from a central depot [depot>drone>uHome] or from a truck as a mobile launching platform [depot>van>drone>uHome], that have also been transferred to earth-bound delivery bots, mainly vary in their handover option. Thus, the main delivery concepts involving delivery bots are: [**depot>bot>aHome**] and [**depot>van>bot>aHome**]. Apart from that, most decision problems and solution approaches of the drone domain can also be applied to delivery bots. Thus, except for some working papers and conference papers, which we do not address in our survey (see Sect. 2), we are only aware of two operations research papers addressing the peculiarities of delivery bots.

Jennings and Figliozzi (2019) consider bots released from trucks [depot>van>bot>aHome] and apply basic continuous approximation methods to evaluate this concept in terms of total delivery time and fleet size. They evaluate under which circumstances this concept can improve traditional delivery concept [depot>van>man>aHome]. Boysen et al. (2018b) consider the routing problem occurring for delivery concept [depot>van>bot>aHome] where, unlike [depot>van>drone>uHome], the robots do not return to the truck but a nearby robot depot. They consider a single truck equipped with shipments and a limited number of bots on board. To avoid long waiting times of the truck for the return of slow bots, they assume that bots return to decentralized bot depots, where they wait to be picked up by the truck. In this setting, they seek a truck route along positions where bots are released and picked up, and to consider the peculiarities of attended home delivery they minimize the number of late deliveries. To solve this problem, the authors propose a MIP and a local search procedure.

As mentioned above, both autonomous delivery devices (i.e., drones and bots) are similar from a mathematical point of view, but mainly vary in specific parameters, such as payload, costs, and operating ranges. Thus, it would be interesting to investigate how customers with different characteristics and requirements should be partitioned among both kinds of autonomous delivery devices and their alternative launching options.

5.3 Crowdshipping

Progress in the fields of technology and digitization enables the involvement of the "crowd" in several business processes. Uber, AirBnb, and Kickstarter are prominent and successful examples in the fields of passenger transport, overnight stays, and funding. Similar concepts have gained attention in the field of freight transport, e.g., by companies as UberRUSH, Cargomatic, Grabr, or Nimber (for a detailed survey of different crowd logistics initiatives see Carbone et al. 2017). Instead of hiring fixedly employed delivery persons, these companies follow the idea of involving many people in the delivery process, professional and non-professional (see Fig. 6, left), who are already on the road, have spare capacity, and are willing to detour to consumer locations (Buldeo Rai et al. 2017; Sampaio et al. 2019). A main characteristic

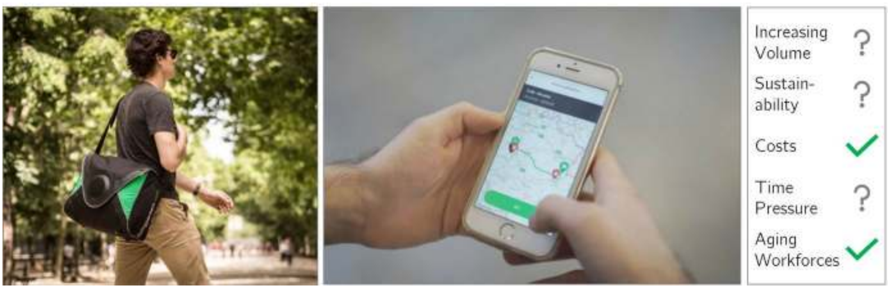

Fig. 6 Non-professional crowdshipper (left; *Source*: LivingPackets 2018), crowdshipping app (middle; *Source*: Hytchers 2018), and evaluation (right)

of crowdshipping is the existence of an online (digital) platform and a related smartphone app (Dablanc et al. 2017). After a delivery request is posted on a platform (for an example, see Fig. 6, middle), they are offered to registered crowdshippers (CS) who can choose one or multiple tasks, pick up the shipments, and deliver them to the recipient (Mladenow et al. 2016). CS receive a compensation for their work, either fixed, based on their travel distance and time, or resulting from a bidding system. Crowdshipping can either be implemented as a stand-alone delivery concept or as a support for traditional van delivery, depending on the business model (Carbone et al. 2017). A current successful implementation of this concept in practice was accomplished by Amazon Flex (2020).

The involvement of CS into the delivery process enables a flexible option to relieve the aging (fixedly employed) workforce of a logistics provider. Once the necessary platform is set up and operating properly, deliveries can be outsourced to the crowd and capacities of postal service providers are freed. Since CS are not employees and only hired for one or multiple deliveries within a short time, the postal service provider has no expenses for long-term salaries, health insurance, gas, and vehicles, which saves costs. The footprint on the environment strongly depends on the vehicles used by the crowd. If deliveries are performed by foot, bike, public, or public transit, emissions can be reduced. However, if deliveries are made by car, the amount of single trips may even increase the negative impacts on environment and society (see, e.g., Buldeo Rai et al. 2018). Since CS are not fixedly employed, reliability and scalability are the main challenges for a logistics provider applying the crowd. Thus, it remains questionable whether increasing parcel volumes can be handled with the necessary reliability and delivery speed.

Crowdshipping has received a lot of scientific attention in the recent years, so that it is not surprising that previous survey papers already address this topic. Sampaio et al. (2019) treat crowdshipping as one part of crowd-based city logistics, so that they have a broader perspective and also include crowd-storage and reverse flows. The surveys of Le et al. (2019), Buldeo Rai et al. (2017), and Dablanc et al. (2017) focus on crowdshipping, but also address empirical and behavioral research. Thus, no previous survey shares our operations research perspective.

Setup of infrastructure A key factor for the successful implementation of a crowdshipping system is a well-functioning platform that matches delivery requests and CS. The setup of such a system, however, is rather an IT challenge, but commonly not substance of operations research literature and therefore not in the scope of this review. Once a functioning platform is available, the main strategic decision to be taken is the design of a suited pricing scheme. This includes a decision on how CS are compensated for their delivery services and, if the platform is provided by a third party offering matching services to multiple shippers, also on the participation fee for shippers. Alternative pricing schemes are listed and discussed with regard to their pros and cons by Le et al. (2019). In an urban context where distances and urgency levels of shipments vary considerably less than in national or even international goods transportation, most examples listed in (Le et al. 2019) apply a fixed pricing scheme where shippers and CS pay and receive a fixed price per shipment, deviating by a fixed commission fee for the platform provider. Distance-based pricing schemes, membership pricing, where a shipper pays a fixed amount for all shipments executed within a certain time span, and bidding systems, where CS bid for shipment offers, are less common in an urban context. However, research on the right pricing scheme and how to appropriately set the parameters (e.g., the fixed compensation fee per shipment) of each scheme is (comparatively) rare. One exception is the paper of Kung and Zhong (2017). They propose an analytical model, which compares different pricing strategies in a system where in-store customers deliver parcels to online shoppers, namely membership-based pricing, fixed pricing, and cross subsidization. Hereby, they aim to maximize the profit of the matching platform. Another study is provided by Ermagun and Stathopoulos (2018), who rather address a pricing based on bids by CS. An integrated view is taken by Yildiz and Savelsbergh (2019). They not only investigate delivery prices and CS compensation of a food delivery network, but also integrate the question how to size the area in which food delivery services are offered. They apply analytical models to maximize profit for a given target service quality level. Further research on pricing schemes related to crowdshipping, although not directly in the scope of this survey, treat topics as pricing for service platforms with incentives during time of lower CS supply (Cachon et al. 2017), pricing for on-demand services (Taylor 2018), and (long-haul) freight pricing (Holguín-Veras 2011).

A main strategic decision for shippers that either participate in a third-party crowdshipping platform or setup their own platform involves the question on how the concept of crowdshipping should be integrated into the delivery process, i.e., as an addition to other delivery methods or as a stand-alone concept with only CS. The papers by Devari et al. (2017), Suh et al. (2012), and Simoni et al. (2019) tackle this issue by comparing different levels of crowdshipping within the delivery process, i.e., no crowdshipping (traditional van-based delivery), combined van and crowd delivery, and pure crowd delivery or self-pickup, by means of costs and emissions. They perform simulation studies with integrated routing algorithms (Devari et al. 2017; Simoni et al. 2019) or evaluate driven distances on routes determined via metaheuristics and simple distance calculations (Suh et al. 2012). CS only have to register at a platform, which is typically free of charge, so that no long-term decisions are to be taken by them. How to generally attract individuals for crowdshipping seems rather a topic for empirical research (e.g., see Le and Ukkusuri 2019; Miller et al. 2017; Punel et al. 2018; Punel and Stathopoulos 2017).

Our decision hierarchy elaborated in Sect. 2 that distinguishes (mid-term) staffing and fleet sizing decisions from (short-term) routing and scheduling decisions is not relevant in the crowdshipping context. Since CS are not fixedly employed and contribute their own delivery vehicle, staffing and fleet sizing decision on a mid-term planning horizon are obsolete. Instead, we have operational matching and routing decisions that are elaborated in the following.

Matching and routing The main service of a crowdshipping platform is the matching of supply and demand. Suppliers offer shipping tasks and CS offer their services and both are brought together by a matching, which decides which shipping offers are executed by which CS. In the most basic form, a crowdshipping platform provides just a list of suited shipping requests (e.g., filtered according to date and geographic positions) CS can choose from manually (Boysen et al. 2019b). More involved solutions are based on optimization-based matchings, which collect shipping offers and CS over a specific time span and optimize their assignment according to some objective function. A general overview on matching problems in the sharing economy and the complexity status of different problem versions is provided by Boysen et al. (2019b). In the crowdshipping domain, however, an optimization-based matching cannot be determined in an isolated manner. Instead, it depends on the pricing scheme whether the shipping offers assigned to a CS meet her minimum wage expectations and the travel costs of each CS, which are determined by routing CS from shipping offer to shipping offer. Thus, the operational decisions to be taken for delivery concept [**depot>crowd>aHome**] constitute a challenging holistic optimization problem involving matching, routing, and pricing tasks. In the following, we review existing research related to these (and further) decision tasks and structure our review according to the respective focus.

- *Combined matching, routing, and pricing* Chen et al. (2018) introduce the multi-hop driver-parcel matching problem with time windows. Given a set of delivery tasks and a set of CS, they aim to determine an assignment with minimal total shipping costs including different types of compensation for the deliveries of CS. The problem includes latest arrival times for shipments and CS, different parcel volumes and CS capacities, as well as maximum detour times for CS. They propose a MIP and two heuristics for solving the problem. Allahviranloo and Baghestani (2019) investigate a similar matching problem in a peer-to-peer network and include a bidding system for CS compensation. Shippers set their maximum willingness to pay for their shipping offers and CS place bids depending on the fit of offers. It is assumed that CS select the tasks with the highest compensation and shippers the CS asking for the lowest compensation. The authors formulate a MIP that aims to minimize the total carrier travel time and the deviation from the original travel route. They apply the MIP in two test cases derived from Los Angeles and Orange County. Akeb et al. (2018) tackle a collaborative crowdshipping variation, in which CS pick up and deliver parcels for their neighbors. To cover as many customers as possible, the authors apply a circle packing algorithm and estimate the number of CS needed for the system. Afterward, they coordinate CS such that the compensation is balanced among them.
- *Leftover shipments* To ensure reliable delivery services, shippers require a backup solution, if not enough CS can be found to deliver all shipments. The typical solution for this problem is to hand leftover shipments over to professional logistics providers, e.g., UPS or DHL. Arslan et al. (2019) address this issue and aim to match delivery requests with CS (called ad hoc drivers) or traditional delivery vans (called backup vehicle drivers) in a rolling horizon approach. While CS are preferred because they demand less compensation than professional drivers, they have given limits on the number of stops, driving time, and driving distance. In this variant of the pickup and delivery problem, each CS can accept multiple delivery tasks, that have to be fulfilled within a given time window. The rather expensive backup vehicle drivers, that all start from a depot, are not subject to any restrictions in the means of time, distance, or number of stops. The platform, that accepts and fulfills all requests, aims for minimal total delivery cost, comprised of compensation for ad hoc and backup driv-

ers. The authors formulate a MIP model for the offline problem and propose an exact label setting algorithm as well as a heuristic reduction. In a similar setting Archetti et al. (2016) introduce the vehicle routing problem with occasional drivers. This concept assumes that a delivery company not only operates a fleet of capacitated vehicles and drivers, but can outsource deliveries to CS that perform requests for a small compensation. The decision problem includes the routing of the company-owned vehicles as well as the assignment of delivery requests to CS aiming for minimum total costs. Hereby, each CS can fulfill at most one request and only if the extra distance traveled does not exceed a given limit. All deliveries start in a single depot and CS are in-store customers that announce their willingness to deliver goods ordered by online customers. A pickup and delivery problem variation with occasional drivers has been studied by Dahle et al. (2019). They also investigate the behavior and compensation of the CS.

- *Combined with item sharing* The problem of matching shipping offers and CS can be extended by integrating the concept of item sharing, as discussed by Behrend and Meisel (2018) and Behrend et al. (2019). Each sharing request involves a certain item (e.g., a do-it-yourself tool) that needs to be delivered from the household owning the item toward another household aiming to use it. The platform matches items, requests, and CS in order to maximize the profit and the number of fulfilled requests. CS have given limits on their flexibility, i.e., travel and detour time, but no time windows to respect. Behrend and Meisel (2018) formulate three MIPs for different implementations of crowdshipping (i.e., home delivery, self-sourcing, and neighborhood delivery). They develop heuristics based on a hierarchical decomposition scheme and a graph-theoretical approach to solve the problem. The premise of single deliveries per CS is abandoned in the work of Behrend et al. (2019), where an exact label setting algorithm and a heuristic reduction are developed.
- *Alternative handover locations* CS do not need to pick up assigned shipping requests from a central depot, but can rather be supplied at decentralized handover locations. A matching problem without time constraints, where CS pick up parcels at lockers, is treated by Wang et al. (2016). While CS can deliver multiple packages per trip, depending on their capacity, the authors aim for matches with minimum travel costs. They present a MIP formulation based on the min-cost network flow problem and develop pruning rules and a network simplex algorithm to obtain good-quality solutions for large-scale instances. Kafle et al. (2017) assume that a truck starts from a single depot and visits several handover locations, where shipments are transferred to CS who perform the second leg of the delivery. CS are subject to capacity and distance limits. The considered system assumes that requests are posted on the platform and CS place bids, including the jobs they are willing to carry out, the compensation for the delivery and potential handover locations. The shipper then selects bids and determines truck routes visiting all necessary handover locations and customers not covered by bids. The objective is to minimize the shipper's total cost, consisting of CS compensation, travel costs, and possible penalties for missing delivery time windows. A similar problem is treated by Huang and Ardiansyah (2019). Here, some delivery requests cannot be outsourced to CS and have to be executed by the van.

Furthermore, the objective function does not include penalties for delays, and CS compensation is split into a fixed and a variable amount.

- *Workload sharing among multiple CS* Previous research assumes that each shipping request is performed by a single CS. Zhang et al. (2017), however, allow a workload sharing among multiple CS executing a shipping request jointly. CS are assumed to pick up parcels at given transfer locations, e.g., parcel lockers in supermarkets, which they pass on their fixed travel routes. They deliver the parcel to another transfer location on their route, e.g., another parcel locker, where another CS can pick it up later on for the next leg. Once the final location, preferably close to the final customer, is reached, the actual addressee can pick it up. In this context, Zhang et al. (2017) optimize the path of parcels along routes of different customers and through several transshipment points. Their optimization model aims for higher profit, lower cost, and higher quality of service in a multi-criteria objective function. The authors develop a routing algorithm based on dynamic mobility and social graphs, which are trained from realistic traces of crowd travel patterns. Gatta et al. (2019a) and Gatta et al. (2019b) investigate the same delivery concept, i.e., crowdshipping based on mass transit networks and automated parcel lockers (see Sect. 5.4). However, their rather behavioral studies observe the willingness of people to participate in such a concept and their preferences. Note that Chen et al. (2018), whose problem setting is elaborated above, also allow workload sharing among multiple CS.

There remains a considerable gap between the status-quo in most real-world crowdshipping platforms and existing research. Whereas most platforms simply present each CS a list of suited and currently available shipping offers to choose from (Boysen et al. 2019b), existing research mainly treats static and deterministic optimization problems. Thus, future research should investigate how to apply these deterministic problems in a dynamic environment, e.g., by planning on rolling horizons, where CS arrive dynamically over time and are impatient to receive their assigned deliveries. Furthermore, benchmark tests with list-based approaches should prove that complex optimization-based procedures combining matching and routing tasks are indeed worth the organizational trouble and lead to considerably better crowdshipping services.

5.4 Combined with people transportation

Another option for last-mile delivery is the usage of free capacity of transport options originally dedicated to moving people. An example is the so-called Tram Fret in Saint-Étienne (France; see Fig. 7, left) where streetcars are applied to move shipment toward urban micro-depots. Another example is elaborated by Gatta et al. (2019a, b). Here, crowdshippers take shipments along on their own travel with the metro system and leave parcels in parcel lockers (see Fig. 7, middle) within range of the actual addressee. Since this delivery options reuse unused capacity of people transportation, it certainly adds to a sustainable last-mile distribution (see Fig. 7, right). The contributions to all our other challenges elaborated in Sect. 1, however,

Fig. 7 Tram Fret in Saint-Étienne (left; *Source*: Danard 2020), parcel lockers in a Seoul subway station (middle; *Source*: HistSystem Co. 2019), and evaluation (right)

remain questionable. The need for a close synchronization of multiple delivery modes increases planning complexity, and it depends how efficiently this planning task can be resolved whether a combination of goods and people transport can meet the high demands of today's last-mile logistics.

The existing literature on different last-mile delivery concepts applying unused capacity of people transportation mainly addresses two transport options:

- *Taxis* Li et al. (2014) investigate the combined transport of people and parcels in the same taxi network: [depot>public>aHome]. Taxi drivers are allowed to carry customers and shipments simultaneously. The introduced share-a-ride problem aims for efficient taxi routes and assignments of customers and parcels to taxis. Hereby, the goal is to maximize the profit of the whole network, which consists of profit received for delivering customers and parcels minus the cost for additional travel distances and times. The problem, including time windows for the deliveries, detour limits, and limited taxi capacity, is formulated as a MIP. Furthermore, the authors introduce a subproblem where the assignments of passengers to taxis and sequences of their services are given. In order to solve the problem, a greedy insertion algorithm and a neighborhood search procedure are presented. Chen and Pan (2016) also discuss parcel delivery via taxis. In their setting (i.e., [depot>van>locker>public>locker>self]), taxis pick up packages at parcel lockers and transport them to other ones, closer to final customers. With a given set of deliveries and dynamically incoming taxi requests, the objective is to minimize the total parcel delivery time. Chen et al. (2017b) approach this problem in a similar manner. Here, the parcel lockers are not only used for initial pickup and final drop-off, but also for temporary parcel storage in order to interchange taxis. Furthermore, taxis are only allowed to pick up or drop-off packages, if no passenger is on board. Chen et al. (2017b) provide an experimental study for this setting based on real-world data from the city of Hangzhou (China), and Chen et al. (2017a) integrate reverse flows from customers back to the depot.
- *Public transport* such as buses, subways, or trams, rather operate on fixed schedules along given lines. Thus, last-mile delivery applying these people transport options has to adapt to given timetables. In this context, Ghilas et al. (2016c)

investigate multi-modal transport chains, where traditional delivery vans and scheduled lines of public transport are combined: [depot>van>public>van>man >aHome]. The presented problem, namely the pickup and delivery problem with time windows and scheduled lines, is a modification of the well-known pickup and delivery problem. In the considered system, a delivery van starts from a depot, picks up parcels at different locations, and delivers them to a transfer point, called station-hub, where the shipments are transferred to a scheduled line. The line service then moves the packages to another station-hub on their fixed path, where, again, shipments are transferred to a van and, hereafter, delivered to the final customers. An important aspect, besides van routing, is the synchronization between the line service and the delivery trucks, while regarding time windows, traveling and service times, as well as capacities. The authors formulate an arc-based MIP with the objective of minimizing total costs, consisting of travel costs for the van and the use of the scheduled line service. They apply commercial solver CPLEX to conduct a sensitivity analysis and investigate the impact of time windows, the number of lines, and the line frequency on the operating costs. The same problem is tackled by Ghilas et al. (2016a) and Ghilas et al. (2019), where an adaptive large neighborhood search heuristic and a branch-and-price algorithm are applied, respectively. Ghilas et al. (2016b) extend the problem by considering stochastic demands. While the expected demands are known ahead, the actual demands are only revealed with certainty upon the vehicles' arrival. The authors propose a scenario-based sample average approximation approach for the problem to generate good-quality solutions. Masson et al. (2017) tackle a similar problem where parcels are transported by city buses from a depot toward bus stations in the city center, transferred to environment-friendly transport options, e.g., cargo bikes, and then distributed among customers (i.e., [depot> public>micro>bike>aHome]). The authors propose an adaptive large neighborhood search heuristic and assess the algorithm on instances derived from a field study in La Rochelle (France).

Existing research has not yet explored all delivery paths when combining goods and people transport on the last mile. For instance, moving shipments via scheduled lines either used by crowdshippers or by consolidated services (see Fig. 7, left) toward parcel lockers in direct vicinity of public transport (see Fig. 7, middle), where customers applying public transport by themselves can conveniently pick up their shipments on their way back from work, widely reuses existing infrastructure. Scheduling this delivery mode remains an interesting field for future research.

5.5 Alternative handover options

There are several innovative ideas to overcome the curse of attended home delivery and the risk for the logistics provider that customers are not at home to receive their shipments. Self-service options (see Sect. 4.3) try to shift the burden of parcel pickup to the customers. However, there are other ideas to handover parcels into the private area of customers during unattended home delivery. Examples are parcel

Fig. 8 Reception box PinPod (left; *Source*: PinPod 2020), trunk delivery by DHL (middle; *Source*: DHL Paket 2015), and evaluation (right)

reception boxes, e.g., at the home yard or the garage (see Fig. 8, left), smart door locks that allow the delivery person to open the front door of a private home with a smartphone app (Amazon 2020), and delivery into the trunks of private cars (see Fig. 8, middle). The latter, for example, was successfully implemented in a cooperation between DHL and Volkswagen (DHL 2017).

Whether these alternative handover options will handle a fair share of future shipment volumes mainly depends on customer acceptance. The recent poll of Felch et al. (2019), for instance, shows that many customers have severe reservations about access systems and trunk delivery, because they fear violation of privacy and theft. However, alternative unattended delivery options have the potential to reduce the number of secondary delivery attempts, which positively impacts all our other challenges (see Fig. 8, right). To substantiate our subjective evaluation is certainly a challenging and important task for future research. First attempts comparing reception boxes with attended home delivery are, for instance, provided by Punakivi et al. (2001) and Wang et al. (2014). From a modeling perspective, however, reception boxes and smart door locks barely add any peculiarities to traditional home delivery (see Sect. 4.1). Therefore, we concentrate our survey on trunk delivery and delivery option [**depot>van>trunk>self**].

From an operational research perspective, the delivery into the trunk of a private car is nothing but attended home delivery with alternative delivery options and time windows following the changing whereabouts of customers during the day. Thus, the resulting optimization problems are rather operational and we concentrate our survey on *routing and scheduling*. Reyes et al. (2017) investigate the vehicle routing problem with roaming delivery locations (dubbed VRPRDL). The introduced model seeks for a solution of minimum costs, such that each customer is served within one of its available time windows at the corresponding location given a set of delivery vans with limited capacity. Next to the MIP formulation, they propose heuristic solution approaches. Ozbaygin et al. (2017) reformulate the VRPRDL as a set-covering problem and develop a branch-and-price algorithm. An alternative branch-and-price algorithm and Lagrangian decomposition for a similar problem setting are presented by Gambella et al. (2018). Ozbaygin and Savelsbergh (2019) address the dynamic version of VRPRDL and present an iterative re-optimization framework based on branch-and-price. Stochastic travel times are considered by Lombard et al. (2018).

The current literature is focused on routing tasks, so that there are plenty of extensions left to investigate. For instance, current research does not consider incentives to convince the customers to allow foreigners access to their cars and provide information about their whereabouts.

6 Farther future

In this section, we address ideas for future last-mile delivery concepts where elementary system components are not yet readily developed. Specifically, we elaborate on delivery concepts based on alternative drone launching platforms, autonomous driving, and tunnel-based cargo transport in the following.

Alternative drone launching platforms To avoid the high investment costs of a dense depot network for launching drones with restricted operating range (see Sect. 5.1), not only trucks can be applied as mobile launching platforms. Instead, there are patent specifications that suggest to rather apply trains, vessels (Beckman and Bjone 2017), and airships (see Fig. 9, left). From a modeling perspective, these alternative mobile launching platforms do not add much peculiarities and the resulting decision models share a lot of similarities with those where drones are launched from trucks (see Sect. 5.1). Mainly the movement of the launching platform, however, alters the existing routing and scheduling problems.

Compared to the road network utilized by trucks, trains moving on railway tracks or vessels traveling along inner-city waterways face a much sparser network. In the most restricted case, the mobile launching platforms applied by delivery concept [**depot>train>drone>uHome**] (or [depot>vessel>drone>uHome]) move merely along a single railway track (river or canal). In this case, it has to be considered that once a drone has departed the launching platform steadily moves onward, so that a triangular motion when moving from launching platform to customer and back to the platform arises. The speed of the launching platform has to be jointly planned with the launching schedule of drones (and their assignment to customers). This challenging optimization problem has not been addressed by existing research.

If an aircraft moving through the sky (or a vessel traveling on open sea) is applied as a mobile launching platform, this leads to delivery concepts [**depot>aircraft>drone>uHome**] (or [depot>vessel>drone>uHome]). In this case,

Fig. 9 Patent drawing for flying warehouse (left; *Source*: Berg et al. 2016), mobile parcel locker called Hannah (middle; *Source*: Teague 2020), and tunnel-based cargo transport with an automated guided vehicle (right; *Source*: CST 2020)

the movement of the launching platform is not bound to a restricted network, but it can freely move in Euclidean space. Poikonen and Golden (2019) call the resulting optimization problem the mothership and drone routing problem. The task is to find a route of the mothership through Euclidean space, such that a drone launched from the mothership visits each customer location exactly once and the total duration is minimized. Furthermore, the drone has a limited operating range and is only allowed to visit a single customer before it has to return to the mothership. To solve the resulting problem, the authors propose an exact branch-and-bound method and a set of heuristics.

In the patent of Berg et al. (2016) for a flying warehouse won by Amazon in 2016 (see Fig. 9, left), however, the airship applied as the drone launching platform is assumed to hover over a city center. Once a customer places an online order, a drone is loaded with the shipment and launched from the airship. A major advantage of drones launched from high altitude, is that the drones only have to stabilize their flights and even far away customers can be reached without excessive energy demand. Once a drone has delivered its parcel it is assumed to not return to the airship but to an earth-bound depot. The drones' flight legs back to the depot are not burdened with payloads, which further adds to extended operating ranges of the [**depot>aircraft>drone>uHome**] delivery concept. Once enough drones have gathered at the depot, they are brought back to the airship with a shuttle aircraft, along with goods and workers. In such a setting, it is not only the interdependent routing of mothership and drones that has to be planned, but they have to be synchronized with the flight schedule of the shuttle. A challenging multi-echelon routing problem arises, which has not yet been addressed in the existing literature.

Autonomous vehicles It seems fair to project that autonomous driving, once realized, will not only have a disruptive impact on people transportation, but it also has the potential to streamline last-mile deliveries. The small and light-weighed autonomous delivery bots discussed in Sect. 5.2 are much less dangerous for passersby, so that they seem much closer to being allowed in public space. This section discusses larger autonomous vehicles with capacity for more than a single shipment where the public interest for a fail-safe and secure autonomous delivery is much higher. Thus, it is to be expected that their realization will take some more time. The following three examples are last-mile delivery concepts based on (larger) autonomous vehicles that are discussed in scientific and non-scientific literature:

- [**depot>aVan>man>aHome**] Instead of a conventional van driven by a human delivery person from customer home to customer home, an autonomous delivery van could be applied in the future. This concept is, for instance, promoted by German automotive supplier ZF (2018). The delivery person can quickly be released from the autonomous van directly next to a customer's home, and the van can find a suited parking space while parcel handover. Furthermore, on a pedestrian subtour, where the delivery person walks with more than a single shipment toward multiple nearby customers before returning to the van (see Sect. 4.1), the start and end of such a subtour need not be identical. Future research should quantify the potential gains of autonomous delivery vans supporting a human delivery person and should provide routing problems addressing the resulting peculiarities.

- [**depot>mLocker>self**] Other than their stationary counterparts (see Fig. 3, left), mobile parcel lockers are equipped with an autonomous drive, so that they can alter their location during the day. An example for a pilot study of a mobile locker is depicted in Fig. 9 (middle). The ability to change locations increases their reach toward customers, which may also move around in the city center during the day. From a modeling perspective, the main difference toward trunk delivery and the resulting vehicle routing problems with roaming delivery locations (see Sect. 5.5) is that mobile lockers have to wait for the pickups, once customers are informed on the arrival of a nearby mobile locker via a smartphone app. Thus, mobile parcel lockers are not that agile and (probably) remain for a longer period of time (e.g., an hour) at a specific location before moving onward. Schwerdfeger and Boysen (2020) were the first to investigate the resulting dynamic facility location problem of mobile parcel lockers. They conclude that mobile lockers have the potential to considerably reduce the fleet size compared to their stationary counterparts.
- [**depot>aVan>locker>self**] Due to safety issues, a direct contact of autonomous delivery vehicles and customers may remain problematic for quite some time. Thus, autonomous delivery vans equipped with an automated handover mechanism could rather be applied to resupply self-service facilities such as parcel lockers. Ulmer and Streng (2019) investigate this case. They consider the dispatching decision of the autonomous vehicles toward lockers given customer orders arriving dynamically over time.

Thus, deriving suited decision support for novel last-mile concepts based on autonomous driving and comparing their potential gains offers plenty of interesting future research tasks.

Cargo tunnels Finally, there are also ideas to apply automated guided vehicles (see Fig. 9, right) or rail-bound cargo vehicles to transport shipments from a central depot outside the city center via cargo tunnels toward inner-city micro-hubs. Once arrived at a micro-hub, cargo bikes can, for instance, be applied to deliver shipments toward customer homes. The resulting delivery concept [**depot>loop>micro>bike>aHome**] comes by without conventional delivery vans, so that the problems associated with these vehicles (i.e., congestion and emissions, see Sect. 1) are reduced. On the negative side, there are the huge digging and investment costs for the tunnel. Concepts based on cargo tunnels are, for instance, promoted by Smart City Loop (Germany) and Cargo Sous Terrain (Switzerland; see Fig. 9, right). We were not able to find any scientific operations research literature on tunnel-based last-mile concepts. However, this concept gives rise to very interesting decision problems on all planning levels. For instance, the positions of micro-hubs have to be coordinated with feasible tunnel corridors, and limited capacities in the micro-hubs require a close coordination of delivery schedules via the tunnel with cargo bike tours. Again, this innovative concept leaves plenty room for future research.

7 Future research and conclusions

The large overview table that specifies the delivery concept investigated, the decision problem treated, and the solution method applied by each surveyed paper is given in "Appendix." In spite of the large number of papers listed there, it can be concluded that the multitude of alternative last-mile delivery concepts still requires a lot of additional research effort. Specifically, our table reports on 27 distinct last-mile delivery concepts treated by existing research. Many of these concepts, especially those of the near and farther future treated in Sects. 5 and 6, respectively, demand not only a lot of additional R&D effort to technically develop them to a market-ready state, but also a lot of research on operations research methods to support an efficient application of these delivery concepts. Critics may say that, first, future last-mile concepts such as drones or autonomous delivery bots should prove their capability, before operational decision tasks such as routing issues have to be resolved. Without sophisticated optimization approaches provided by operations research, however, simulation studies evaluating the economic viability of a novel delivery concepts can only be based on simple decisions rules. This, however, bears the risk of underestimating some novel last-mile concepts, so that R&D money is misdirected to the wrong concepts. Thus, already in an early phase of an innovative last-mile concept research of the operations research community seems highly welcome. In the previous sections, our literature survey has identified multiple future research tasks associated with each single concept. However, we also see some important future research tasks not related to a single delivery option, but on a general level:

- Our survey reveals that existing last-mile research is particularly routing-focused. Since routing is a vital task for most last-mile concepts, such a focus seems well justified. However, there are also other important decision areas that should be addressed by future research. Territory design, for instance, where a large territory is to be partitioned into smaller regions each covered by a dedicated tour (see Sect. 4.1), is a well-researched problem for traditional van-based delivery. However, whether and how existing approaches can be adapted if alternative delivery concepts, e.g., truck–drone tandems, are applied, remains a challenging field for future research. Analogously, time window management and the question how to agree suited delivery time windows with customers (see Sect. 4.1) has not yet been treated for non-traditional delivery modes. Thus, also the problem tasks beyond routing are a valid field for future research.
- Many papers addressing a specific decision problem of a non-standard last-mile delivery concept benchmark their approach with an alternative delivery mode, e.g., the status-quo applying traditional delivery vans. Unfortunately, these benchmark tests remain isolated and are not sufficient to systematically compare all (most important) novel and traditional delivery concepts. This rather requires a concerted effort of the research community. For a systematic benchmark test, a

unique data set gained from real-world data is required, which is publicly available and contains all detailed information on street networks, parking spaces, footways, access restrictions, recharging opportunities, exact customer locations, etc. Once such a general data set is available each new delivery concept could be tested on the same data. In this way, a systematic benchmark of many alternative concepts with regard to KPIs derived from the challenges discussed in Sect. 1 could be gained. This would support the identification of the right delivery concepts for different customer segments, an efficient allocation of R&D money, and informed decisions on public legislation and rules related to city access and last-mile logistics.

- Finally, we see a dire need to answer the following research question: What is the right mix of delivery concepts? Each last-mile delivery mode has different strengths and weaknesses, so that the right choice will most likely be a combination of multiple concepts each focusing on different customer segments. For instance, delivery vans equipped with drones could rather be an option for rural areas where back yards provide appropriate landing space for drones, cargo bikes and autonomous delivery bots could be the right choice for urban areas, and especially non-urgent deliveries for price-sensitive customers could be candidates for self-service options. Investigating an appropriate customer segmentation and their assignment to the most suited delivery modes remains a valid task for future research.

Seeing the huge challenges related to last-mile logistics in urban areas, the multitude of novel technological developments, and the manifold research opportunities identified in this paper, it seems fair to project that last-mile logistics will remain a fruitful field of research with major practical relevance in the years to come.

Funding Open Access funding provided by Projekt DEAL.

Appendix: Summary of literature survey

This section provides a tabular summary of the literature related to last-mile concepts. Table 2 contains all the abbreviations used in the overview in the means of problem type and solution procedure. Applying these shortcuts, Table 3 lists the

Table 2 Symbols

Shortcut	Description
(1)	Setup of infrastructure
(2)	Staffing and fleet sizing
(3)	Routing and scheduling
A	Analytical model and/or cost analysis
C	Constraint programming
E	Exact solution approach
H	Heuristic solution approach
I	Iterative sampling approach
M	Metaheuristic
MA	Matheuristic
MAR	Markov decision process + policy function approximation
MIP	Mixed integer program or integer linear program
S	Simulation
W	Worst case analysis

papers related to the last-mile delivery concepts discussed in this paper. For the sake of clarity and simplicity, we set the following guidelines for this table:

- For every article, we provide the delivery concept (2nd column), the considered problem (3rd column), and the solution approach(es) described (4th column). If the authors tackle a problem that combines different delivery concepts (e.g., the problem setting includes a choice whether each shipment is transported by a delivery van or a crowdshipper), we list both concepts in the same entry. If a paper investigates multiple separate delivery concepts subsequently in the same paper, we list the paper multiple times, once for each concept.
- The term “heuristic” comprises all heuristic procedures excluding matheuristics and metaheuristics, which receive their own shortcut (see Table 2).
- Drone delivery concepts are always considered as unattended delivery (uHome), because a direct customer interaction seems problematic due to safety issues.
- Literature on crowdshipping, especially on matching problems, often assume multiple decentral pickup locations at customer homes. Nonetheless, we speak of a depot as the starting point. Furthermore, if a crowdshipping problem involves pricing decisions, which we consider a long-term decision, we add (1) to the problem column, even if it is part of, e.g., a routing problem.

Table 3 Literature overview

Paper	Delivery concept	Problem*	Method**
Agatz et al. (2018)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, H, W
Akeb et al. (2018)	[depot>crowd>uHome]	2	E
Allahviranloo and Baghestani (2019)	[depot>crowd>aHome]	3	MIP
Anderluh et al. (2017)	[depot>van>micro>bike>uhome]	3	MIP, M
Archetti et al. (2016)	[depot>crowd>uHome], [depot>van>man>uHome]	3	MIP, M
Arnold et al. (2018)	[depot>van>micro>bike>uHome], [depot>van>micro>bike>shop>self]	1	S
Arslan et al. (2019)	[depot>crowd>aHome], [depot>van>man>aHome]	3	MIP, E, H
Baloch and Gzara (2020)	[depot>drone>uHome]	1	MIP, E
Behrend and Meisel (2018)	[depot>crowd>uHome]	3	MIP, H
Behrend et al. (2019)	[depot>crowd>uHome]	3	MIP, E, H
Bouman et al. (2018)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	E
Boysen et al. (2018a)	[depot>van>drone>uHome]	3	MIP, M
Boysen et al. (2018b)	[depot>van>bot>aHome]	3	MIP, M
Carlsson and Song (2018)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	A
Chang and Lee (2018)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	H
Chauhan et al. (2019)	[depot>drone>uHome]	1, 2	MIP, H
Chen et al. (2018)	[depot>crowd>aHome]	3	MIP, H
Chen and Pan (2016)	[depot>van>locker>public>locker>self]	3	–
Chen et al. (2017b)	[depot>van>locker>public>locker>self]	3	H
Chiang et al. (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Choubassi et al. (2016)	[depot>van>micro>bike>ahome]	2	MIP, H
Coelho et al. (2017)	[depot>drone>micro>drone>uHome]	3	MIP, MA
Dayarian et al. (2020)	[depot>drone>van>man>aHome]	3	MIP, H
Dell'Amico et al. (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP
Dell'Amico et al. (2020)	[depot>drone>uHome], [depot>van>man>aHome]	3	MIP, MA
Deutsch and Golany (2018)	[depot>van>locker>self]	1	MIP
Devari et al. (2017)	[depot>crowd>uHome]	1	S
Dorling et al. (2017)	[depot>drone>uHome]	3	MIP, M
El-Adle et al. (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, H
Ermagun and Stathopoulos (2018)	[depot>crowd>uHome]	1	A

Table 3 (continued)

Paper	Delivery concept	Problem*	Method**
Eun et al. (2019)	[depot>drone>uHome]	3	MIP
Faugère and Montreil (2020)	[depot>van>locker>self]	1	MIP
Ferrandez et al. (2016)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	M
Fikar et al. (2018)	[depot>van>micro>bike>aHome]	1	S
Freitas and Penna (2018)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	M
Freitas and Penna (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	M
Gambella et al. (2018)	[depot>van>trunk>self]	3	MIP, E, H
Ghilas et al. (2019)	[depot>van>public>van>man>aHome]	3	MIP, E
Ghilas et al. (2016a)	[depot>van>public>van>man>aHome]	3	MIP, M
Ghilas et al. (2016b)	[depot>van>public>van>man>aHome]	3	MIP, I, M
Ghilas et al. (2016c)	[depot>van>public>van>man>aHome]	3	MIP
Ha et al. (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	M
Ha et al. (2018)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M, H
Ham (2018)	[depot>drone>uHome], [depot>van>man>aHome]	3	C
Hong et al. (2018)	[depot>drone>uHome]	1	MIP, H
Hong et al. (2019)	[depot>van>locker>self]	3	MIP, M
Huang and Ardiansyah (2019)	[depot>van>crowd>aHome], [depot>van>man>aHome]	3	MIP, H, M
Jennings and Figliozzi (2019)	[depot>van>bot>aHome]	1	A
Jeong et al. (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Jiang et al. (2019)	[depot>van>locker>self], [depot>van>man>aHome]	3	MIP, M
Kafle et al. (2017)	[depot>van>crowd>aHome]	1, 3	MIP, M
Karak and Abdelghany (2019)	[depot>van>drone>uHome]	3	MIP, H
Kim and Moon (2018)	[depot>van>micro>drone>uHome], [depot>van>man>aHome]	3	MIP, E
Kitjacharoenchai et al. (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Kitjacharoenchai et al. (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, H
Koç et al. (2016a)	[depot>van>bike>aHome]	2	MIP, MH
Koç et al. (2016b)	[depot>van>bike>uHome]	2	MIP, MH

Table 3 (continued)

Paper	Delivery concept	Problem*	Method**
Kung and Zhong (2017)	[depot>crowd>uHome]	1	A
Li et al. (2014)	[depot>public>aHome]	3	MIP, AH, H
Liu (2019)	[depot>drone>uHome]	3	MIP, MA
Liu et al. (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	M
Liu et al. (2019)	[depot>drone>uHome]	2, 3	MIP, M
Lombard et al. (2018)	[depot>van>trunk>self]	3	S, M
Marinelli et al. (2017)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	M
Masson et al. (2017)	[depot>public>micro>bike>aHome]	3	MIP, M
Moshref-Javadi et al. (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Moshref-Javadi et al. (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Murray and Chu (2015)	[depot>drone>uHome], [depot>van>man>aHome]	3	MIP, H
Murray and Chu (2015)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, H
Murray and Raj (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, MA
Orenstein et al. (2019)	[depot>van>locker>self]	3	MIP, MA, M
Othman et al. (2017)	[depot>van>drone>uHome]	3	H
Ozbaygin et al. (2017)	[depot>van>trunk>self]	3	MIP, E
Ozbaygin and Savelsbergh (2019)	[depot>van>trunk>self]	3	E
Pan et al. (2020)	[depot>drone>uHome]	3	M
Poikonen and Golden (2019)	[depot>aircraft>drone>uHome]	3	E, H
Poikonen and Golden (2020)	[depot>van>drone>uHome]	3	MIP, H
Poikonen et al. (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	E, H
Poikonen et al. (2017)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	W
Reyes et al. (2017)	[depot>van>trunk>self]	3	MIP, H
Sacramento et al. (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Saleu et al. (2018)	[depot>drone>uHome], [depot>van>man>aHome]	3	MIP, H
Salama and Srinivas (2020)	[depot>van>drone>uHome], [depot>van>man>aHome]	2, 3	MIP, H
Sawadsitang et al. (2019)	[depot>drone>uHome], [depot>van>man>aHome]	3	MIP, E
Schermer et al. (2019a)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M

Table 3 (continued)

Paper	Delivery concept	Problem*	Method**
Schermer et al. (2019b)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, MA
Schwerdfeger and Boysen (2020)	[depot>mLocker>self]	3	MIP, H
Shavarani et al. (2020)	[depot>drone>uHome]	1, 2	MIP, M
Shavarani et al. (2019)	[depot>drone>uHome]	1, 2	MIP, M
Sheth et al. (2019)	[depot>van>micro>bike>uHome]	3	A
Simoni et al. (2019)	[depot>crowd>uHome]	1	S
Song et al. (2018)	[depot>drone>uHome]	3	MIP, H
Suh et al. (2012)	[depot>crowd>aHome]	1	H, M
Sung and Nielsen (2020)	[depot>drone>uHome]	1	M
Torabbeigi et al. (2020)	[depot>drone>uHome]	1, 3	MIP
Troudi et al. (2018)	[depot>drone>uHome]	2	MIP
Ulmer and Streng (2019)	[depot>aVan>locker>self]	3	MAR
Ulmer and Thomas (2018)	[depot>drone>uHome], [depot>van>man>aHome]	3	MAR
Wang et al. (2019b)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Wang et al. (2017)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	W
Wang and Sheu (2019)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MIP, E
Wang et al. (2019a)	[depot>van>drone>uHome], [depot>drone>uHome], [depot>van>man>aHome]	3	MIP, M
Wang et al. (2016)	[depot>van>locker>crowd>uHome]	3	MIP
Yildiz and Savelsbergh (2019)	[depot>crowd>uHome], [depot>van>man>uHome]	1	A
Yurek and Ozmutlu (2018)	[depot>van>drone>uHome], [depot>van>man>aHome]	3	MA
Zhang et al. (2017)	[depot>van>locker>crowd>locker> self]	3	MIP, H

*(1) Setup of infrastructure, (2) Staffing and fleet sizing, (3) Routing and scheduling

**(A)nalytical, (C)onstraint programming, (E)xact, (H)euristic, (I)terative sampling, (MA)theuristic, (MAR)kov decision process + policy function approximation, (M)etaheuristic, MIP, (S)imulation, (W)orst case

- Within our notation scheme, shortcut “man” exclusively denotes a transport process. If, however, a human delivery person only puts parcels into a parcel locker, loads a drone, or hands a parcel over after parking a cargo bike directly in front a customer home, but does not transport a parcel on foot (over a considerable distance), we do not add the “man” shortcut to the respective delivery concept.

- We do not list the literature related to status-quo delivery concept [depot>van>man>aHome]. Due to the vast amount of research papers that, for instance, treat some general routing problem, but are also relevant for last-mile delivery, it seems impossible to achieve some level of completeness.

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