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Review

Autonomous Delivery Solutions for Last-Mile Logistics Operations: A Literature Review and Research Agenda

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Abstract: The implementation of autonomous delivery solutions in last-mile logistics operations is considered promising. Autonomous delivery solutions can help in tackling urban challenges related to last-mile logistics operations. Urbanization creates higher mobility and transportation demand, which contributes to increased congestion levels, traffic, air pollution, and accident rates. Moreover, mega-trends, such as e-commerce, demand that logistics companies react to increased customer expectations in terms of delivery time and service. Concerning service, electrified autonomous delivery solutions have the potential to operate 24/7 and can help to overcome driver shortages. This paper conducts a systematic literature review. Based on the literature set, a snowballing procedure was applied. Complementary gray literature was included. This work discusses different autonomous delivery solutions such as Autonomous Delivery Robots (ADRs), Unmanned Aerial Vehicles (UAVs), two- or multi-tiered systems, and the concept of passenger and freight integration. The work presents advantages and disadvantages, enabling the comparison of solutions. Furthermore, a research agenda is provided, from which practical-managerial and theoretical implications can be derived. The research agenda can help researchers, manufacturers, businesses, and governmental institutions to prepare for the arrival and subsequent implementation of autonomous delivery services. Various implications related to energy demand, legislation, implementation strategy, training, and risk and safety are presented. The outcome of this work calls for collaboration among various stakeholders, encourages mutual learning, and hints at the importance of national and international development projects.

Keywords: autonomous delivery robots; unmanned aerial vehicles; two-tiered system; passenger and freight integration; last-mile delivery

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Citation: Engesser, V.; Rombaut, E.; Vanhaverbeke, L.; Lebeau, P. Autonomous Delivery Solutions for Last-Mile Logistics Operations: A Literature Review and Research Agenda. *Sustainability* **2023**, *15*, 2774. https://doi.org/10.3390/su15032774

Academic Editor: António Abreu

Received: 23 December 2022
Revised: 16 January 2023
Accepted: 27 January 2023
Published: 3 February 2023

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1. Introduction

Urbanization, with an additional 2.5 billion people living in cities by 2050, land scarcity, and mega-trends such as e-commerce demand have improved transport services and infrastructure [1,2]. New transport and mobility demands including freight movement will negatively impact, among other factors, parking and congestion in cities if current road infrastructure remains as it is [3]. Safety is particularly important, considering the number of accidents in traffic [4]. Furthermore, road transport in general is a major contributor to economy-wide greenhouse gas emissions, which result in climate change. Therefore, the European Commission has set emission targets in order to reach net-zero greenhouse gas emissions concerning all sectors by 2050 [5]. Emissions caused by freight movements during the last mile currently result in 158.4 g CO_2 per km and per order (from light vehicles, cars, and motorbikes). Target emissions per km and per order were set at 0.147 g CO_2 by the European Commission in 2019 [6]. Freight transport represents a growing sector driven

by new trends such as e-commerce. Increasing consumer demands [7], coupled with the desire for faster delivery or even instant delivery [8], puts pressure on logistics service providers to act. It is assumed that new trends will increase shipments by a factor of 10, due to the shift from multi-package shipments to individual shipments, while retail numbers remain the same [2]. Autonomous delivery solutions can help in overcoming current logistics challenges, including ecological footprint, cost, accessibility, and traffic. Solutions can include unmanned aerial vehicles also known as drones, autonomous delivery cars and trucks, and autonomous delivery robots [9]. In terms of sustainability, autonomous vehicle technologies promise to positively contribute to the environment by producing less pollutants and greenhouse gas emissions, and consuming fewer natural resources [10]. Economically, autonomous solutions can help logistics companies to reduce external cost and offer greater service [11]. Moreover, Industry 4.0 and artificial intelligence developments are fostering the development of autonomous vehicle technologies [12]. However, negative economic effects might occur due to increased maintenance and operation infrastructure costs [10]. Concerning the social pillar of sustainability, autonomous solutions have an enormous advantage in terms of safety, considering that 90% of road accidents are caused by humans [4]. Time-saving aspects may further contribute to positive social impacts [10]. It must be noted that, due to the low maturity levels of autonomous vehicle technologies, evaluating their impact on sustainability presents difficulties, as represented by limitations in the literature [10].

Over the past decades, automation has been applied in industry for repetitive and predictable tasks in controlled environments such as fully automated warehouses. However, growing logistics operations and demand, together with emerging automation technologies, will foster the development of innovative and automated delivery vehicles operating on road networks [13]. Autonomous solutions can help overcome the urban challenges of last-mile deliveries (Frost and Sullivan, 2018 in [14,15]). Faster delivery services and reduced costs achieved by using autonomous vehicles can lead to improved customer satisfaction [16]. To achieve short delivery times and low-cost services, Chinese companies have introduced consumer-centric logistics solutions guaranteeing deliveries within 24 h in China and within 72 h worldwide [2]. Along with time and cost, optimization of traffic flows can be achieved through the software programming of the autonomous technology. This, in turn, can lead to decreased fuel emissions, positively impacting the environment. Concerning safety, most road accidents are caused by driver error; thus, autonomous solutions can help to drastically reduce crashes [4]. Interest in autonomous delivery solutions is growing, particularly for logistics service providers. For instance, driving bans issued in some cities forbidding certain internal-combustion-engine cars to enter may affect deliveries that are usually performed by conventional vans, resulting in the need for alternative delivery solutions [17] (p. 1781).

However, despite the promising advantages of autonomous delivery solutions in terms of environmental, economic, and societal aspects, some researchers state that congestion problems will remain a challenge or even increase. This could occur if autonomous delivery vehicles are added to the existing transport networks without replacing vehicles [4]. Concerning employment, [18] mentions that implementing autonomous solutions in last-mile delivery processes might affect or even replace current work tasks, thus leading to job loss. On the other hand, autonomous delivery solutions can help in overcoming driver shortages (see Verlinde, 2018 in [16]).

In order to tackle the challenges faced by last-mile logistics operations in cities with regards to population density, congestion, the environment, and quality of life, the objective of this work is to identify autonomous delivery solutions that are suitable to be integrated in last-mile urban logistics operations. Solutions are discussed and comprehensively presented, allowing them to be compared. As a result, this work provides a research agenda stating the research areas and topics that require further investigation. The research agenda presents practical implications for researchers, manufacturers, companies, and governmental institutions to prepare for the arrival and subsequent implementation of

the presented autonomous delivery solutions. Additionally, theoretical implications are provided to address researcher and cross-functional collaborations. For reaching the research objective, a literature review is conducted using both scientific journal articles and gray literature. This work considers Autonomous Delivery Robots (ADRs), Unmanned Aerial Vehicles (UAVs), two-tiered systems, and passenger and freight integration.

This work focuses on autonomous delivery solutions of automation level 5, which represents full automation. Automation level 5 implies that a vehicle is 'capable of performing all driving functions under all conditions', while a driver or operator optionally can control the vehicle [19] Throughout the literature and referring to [20], the terms automated and autonomous have been used in different ways. The Society of Automotive Engineers, for instance, refers to "highly automated driving systems" for applications of automation level 3 and higher [20] (p. 255), which implies that the term 'automated' can be valid for applications below level 5. In line with [20] and in order to avoid confusion, the term 'autonomous' is used throughout this work. The work's focus is on urban areas and goods delivery. 'Last mile' considers the section from when a parcel is picked up from a consolidated logistics depot, for instance, to when it arrives at the receiver. The choice to investigate the last mile of the supply chain was taken based on the limited research conducted thus far on integrating autonomous solutions, as well as the future research areas this choice implies. Further justifying the choice is the fact that the last mile of the supply chain represents its most expensive component [21]. Moreover, the last mile is considered the most challenging area in terms of externalities such as pollution, traffic, noise, congestion, and land use [11]. In view of logistics companies striving to reduce external costs and to increase customer service [11] the investigation of autonomous delivery solutions becomes particularly relevant. Thus far, to the best of the authors' knowledge, there are no literature reviews addressing this specific area and providing a comparison of the various autonomous solutions suitable for last-mile deliveries.

This paper is structured as follows. Section 2 describes the methodology applied to identify the latest research and technological trends. Section 3 presents existing autonomous delivery solutions and concepts. The findings are discussed and summarized in Section 4. Finally, the research agenda is presented in Section 5.

2. Materials and Methods

This work follows the approach of a systematic state-of-the-art review according to [22] (p. 95). While a state-of-the-art review "tend(s) to address more current matters in contrast to other combined retrospective and current approaches (. . .)", a systematic review refers to the 'systematic search (. . .) for research evidence" and aims to analyze both the already known and the unknown. Both include the identification of research gaps; thus, the work at hand follows the combined approach of a state-of-the-art review and systematic literature review. Ref. [23] suggests that the search strategy of a systematic literature review is crucial when it comes to the identification of relevant literature. Choosing appropriate search strings may be challenging, as terminology is not always applied in a standardized way, which can lead to less useful search results [23]. Thus, in addition to a systematic literature review and state-of-the-art review, the snowballing procedure can be applied [24]. For a successful snowballing search, first, a respective sample of literature needs to be identified by formulating and applying search strings; this is then followed by the snowballing procedure. In the context of this work, forward snowballing was applied, which refers to "identifying new papers based on those papers citing the paper being examined" [23] (p. 3). Furthermore, related papers and reports of previous or ongoing projects in the field were considered and reviewed.

The research design of this work follows that applied in [25]. The authors took into account three elements: theoretical approach, problem, and context(s). Afterwards, these elements were considered in the systematic review. As presented in Table 1, and in the light of this work, theoretical approach refers to autonomous delivery solutions (see Section 3) and last-mile urban logistics operations. The problem represents the aim of this work,

which is the identification and comparison of autonomous delivery solutions, and the contexts are, first, cities (last mile) and, second, integration of autonomous solutions in current processes.

Table 1. Research design (own illustration based on [25]).

Theoretical Approach	Autonomous delivery solutions	Systematic state-of-the-art literature review
	Last-mile urban logistics operations	
Problem	Identification of autonomous delivery solutions suitable to be integrated in last-mile urban logistics operations	
Context	Cities	
	Integration of autonomous solutions	

Following the research design, the literature search considered works published between 2005 and 2022 in English. Research conducted before 2005 did not consider autonomous delivery solutions. This is represented by for example the linear growth and limited existence of patents and unmanned aerial vehicle applications registered between 2000 and 2008. After this period, significant exponential growth can be observed [26]. The search library used was Web of Science. Figure 1 graphically represents the literature search performed. For each search term used (column 1), it shows the total search results (column 2) and those that were ultimately integrated in this work (column 3). Out of 280 initial search results, 17 were considered relevant and were integrated. Works that did not focus on last-mile operations or addressed purely on intra-logistics operations were excluded.

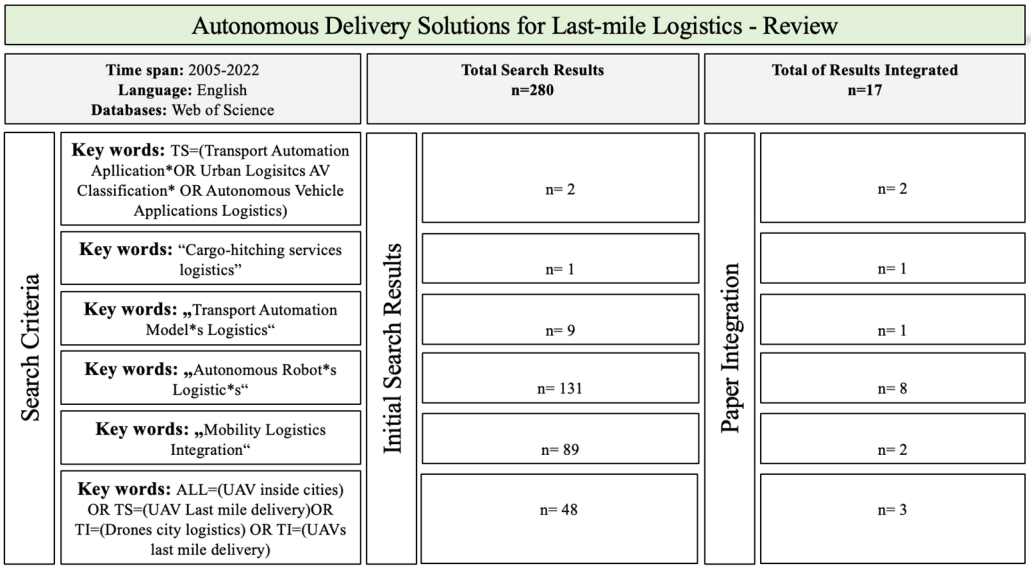


Figure 1. Graphical representation: literature search. AV—autonomous vehicles; UAV—unmanned aerial vehicles (own illustration).

During the last two decades, limited research has been conducted concerning autonomous solutions specifically for last-mile logistics operations inside cities. Ref. [2] calls for further exploration of the challenges faced by urban logistics and the potential impact of new technologies. The limited availability of literature is suggested by the total search results identified (see Figure 1) for this work. Most of the literature found addresses autonomous *passenger* vehicles [14,27,28]. Only a few studies have been conducted with regards to urban logistics, as identified by [29] (e.g., [27,30]). These address, for instance, operational efficiency or regulatory frameworks (see [8,16,27,31,32]]). However, in order to

ensure the smooth implementation of autonomous delivery solutions in logistics processes, research in this field is necessary [4,33].

3. Autonomous Delivery Solutions

This section presents existing but not necessarily deployed and recently developed autonomous delivery solutions suitable for last-mile logistics operations in cities. In fact, some of the solutions presented in as follows were designed for goods transport, but require further attention in terms of, for example, technological aspects, vehicle set-up, and vehicle applications, in order to ensure the awaited integration [14]. This section discusses autonomous delivery robots operating on both sidewalks and roads, unmanned aerial vehicles, the concept of a two-tiered system, and passenger and freight integration.

3.1. Autonomous Delivery Robots

Autonomous Delivery Robots (ADRs) are defined as "(. . .) pedestrian sized robots that deliver items to customers without the intervention of a delivery person" [30]. The literature distinguishes between two types of ADRs: sidewalk autonomous delivery robots (S-ADRs) and road autonomous delivery robots (R-ADRs). While S-ADRs use only sidewalks or bike lanes, R-ADRs share the road with other motorized vehicles. Besides these two types, other researchers further distinguish between vehicles that require human reference and that do not [14] A crucial aspect to be considered is that S-ADRs do not fulfil the requirements of motor vehicles under the law. Therefore, S-ADRs may require special attention with regards to governmental regulations [15].

S-ADRs may differ slightly when it comes to range and speed. Current developments mention a range capacity of around 20 km, speed of 8 km/h, and payload of up to 100 kg [34]. The limited speed and, thus, short braking distances of S-ADRs were highlighted positively by [14] in terms of safety. Concerning R-ADRs, they were found have impacts similar to e-vans concerning energy consumption per customer served, road impact, and overall efficiency, though this can vary depending on the number of customers served and the fleet size required. For example, adding R-ADRs to the road without replacing other vehicle types could increase congestion levels rather than decreasing them [29]. Figure 2 shows an example of a Hugo S-ADR and Figure 3 illustrates an R-ADR that is currently being tested in Belgium.



Figure 2. Sidewalk Autonomous Delivery Robot (S-ADR) (source: Hugo—private photo).



Figure 3. Road Autonomous Delivery Robot (R-ADR) currently tested in Belgium (source [35]).

Overall, using ADRs for last-mile logistics operations can solve courier shortages and gaps, and can thus lead to greater convenience and service for consumers. At the same time, ADRs represent a cost-efficient business solution [15]. While wheeled ADRs are most suitable for last-mile deliveries along sidewalks or roads, they are not ultimately capable of performing the last 50 feet, including climbing stairs and ringing doorbells. A solution may be legged sidewalk delivery robots. Their advantage is that they do not require a recipient when delivering a parcel [13]. However, legged sidewalk delivery robots are of greater technological complexity and can operate with far lower speed [36]. Thus far, legged sidewalk delivery robots have not been part of pilot studies, nor have they been deployed [13]. The FedEx stair-climbing delivery robot represents an example. Despite the expected potential and the recent appearance of ADR technologies [17], little research has been conducted so far.

Another type of vehicle that has been used for warehouse logistics operations is the automated guided vehicle (AGV). These are supposed to replace "(. . .) transport and part of the handling of the material (as well as) part of the internal logistics activities" [37]. Traditional AGV systems operate on pre-defined routes using, for instance, magnetic tape placed on the floor or laser sensors and virtual maps [38]. Considering more than 60 years of experience and the ongoing development of AGVs within intra-logistics, [38] foresees them playing an important role in the future developments of autonomous cars. Therefore, they may be related to autonomous delivery solutions such as ADRs. To mention an example, JD Logistics, one of the largest logistics companies in China, applies advanced AGV systems and aims to constantly improving their intra-logistics processes and performance (see [39]).

3.2. Unmanned Aerial Vehicles

Unmanned Aerial Vehicles (UAVs), also known as drones, have become an appealing technology in the logistics sector. UAVs can be operated both autonomously and by remote control [40]. The last mile of a delivery chain is seen as one of the most promising areas for using UAVs, according to [41]. In addition, the last mile potentially presents new market

opportunities [42]. UAVs can help in guaranteeing service and express deliveries. This can be advantageous when it comes to gaps between courier working hours and the availability of receivers at their homes [43]. Thus far, UAVs have been used for specific applications in the civilian (construction, logistics, disaster management, etc.), environmental (water, crop monitoring, etc.), and defense [42]. In the light of the growing e-commerce sector and increasing customer demand, UAVs may be a beneficial and sustainable solution in the transportation sector for the last mile [41]. To give examples, companies such as Amazon, Google, and DHL have already started testing and introducing UAVs in their delivery processes [44]. The global UAV portfolio represented 21,132 applications in 2017; it has grown exponentially since the year 2000, with globally 86,571 patents in May 2019. Compared to other countries, the Chinese market is the strongest when it comes to UAV development, followed by the United States [26].

Previously, [41] conducted an extensive literature review focusing on drone-aided routing. They found that most studies investigating UAVs in the transport field focus on the time optimization of a delivery, as well as minimization of transport cost. UAVs perform well with regards to speed and independence from traffic, as they use the air way, which can lead to improved service [41]. However, research is lacking on energy consumption and the CO_2 emissions from power generation for UAV usage. Despite the advantages regarding service and on-time deliveries (increased efficiency), Ref. [41] emphasizes the importance of real cost and externality evaluations (CO_2 emissions and energy consumption). Furthermore, despite operating at low cost, the payload capacity of UAVs is rather limited [42]. Moreover, legislations and regulations for UAVs need to be further investigated, as they differ from region to region, addressing, for instance, altitude, maximum load allowed, and time restrictions [41].

Ref. [45] compared deliveries using UAVs in both rural and urban areas in Korea. They found that the operational efficiency and positive environmental impact of UAVs were higher in rural areas, which are less accessible by ground transport compared to urban regions. This is due to lower population density in rural areas than in cities. Results show that improvements concerning the environmental impact in rural areas were 13 times higher compared to urban areas. However, results cannot be generalized and may vary depending on the power generation method applied by different countries [45]. In line with this, [29] refers to UAVs' capability to serve one customer at a time and thus found that UAVs are most suitable for short delivery durations of less than 2 hours and low customer density. A further important point to consider is the actual interaction between the goods and the receiver once the delivery is performed. In this light, Ref. [26] refers to three different scenarios when it comes to UAV interaction that need to be considered: first, door-to-door interaction between the end-receiver and the UAV; second, behavior of the UAV in case the receiver is absent (e.g., cooperation with a delivery station or hub); and, third, co-joining a courier during the delivery process [26].

However, when analyzing different concepts for urban logistics using UAVs focusing on their performance in Serbia, [46] identified a new concept in which UAVs show the best results. The concept is a three-step process; first, goods are delivered by a vehicle/truck to a logistics center outside the city. From there, consolidated delivery takes place to a micro-consolidation center inside the city, from which UAVs perform the final delivery to the receiver. To determine the performance of the UAVs, the factors of delivery cost, distance traveled by the ground vehicle, delivery completion time, CO_2 emissions, number of vehicle trips, and loading space utilization of the ground vehicle were taken into account [46] (p. 456). Concerning emissions, 37.37g CO_2/km was assumed for UAVs (electricity generation) while for a full commercial vehicle, the estimation was 305 g CO_2/km (see NTM, 2018 in [46]). However, despite the positive results, Ref. [46] calls for further investigations concerning practical applicability and legislative aspects. Moreover, [26,43] call for security and risks related to UAVs to be further investigated in future works. Collaboration presents opportunities for value creation for organizations involved in UAV development [26].

3.3. Two-Tiered System

3.3.1. ADRs and Delivery Vehicles

A two-tiered system in the context of urban logistics refers to a delivery process with two steps. One form of two-tiered system involves the use of micro-hubs located at several points in cities. From outside the city, parcels are first delivered by truck to the micro-hub. From there, the last mile can be covered by, for example, ADRs (e.g., [17,29]).

In their study, Ref. [17] found that the location of the micro-hubs in the city was most relevant in determining delivery performance. Their work and simulation did not consider dynamic ordering behaviors and seasonal fluctuations. However, such dynamics (e.g., on-demand delivery schemes or due windows) are seen as important for future logistics operations and thus require further research [17]. The suitability of applying two-tiered concepts became evident after developing an algorithm to identify the minimum and maximum make-span of a delivery process using unmanned ground vehicles [47]. Relatedly, Ref. [48] aimed to optimize the three criteria of location, routing, and inventory planning by proposing a multi-period two-tiered location inventory routing problem. They found inventory control to be the most crucial. Taking into account so called stock-out cost, both transportation cost and inventory holding cost can be reduced [48].

Instead of fixed micro-hubs, mobile depots present an alternative. A trailer equipped with relevant loading and warehousing facilities as well as offices can be used for both express deliveries and pick-ups. Loaded trailers can be moved to dedicated parking in a city, from where the final delivery step is performed with, for example, cargo bikes (see [49]. Similarly, ADRs could be applied to cover the last mile. Another form of mobile depot is the so-called "mothership van", which carries ADRs and releases and later collects them at certain locations inside a city. The mothership van does not need be autonomous and can require a driver for an electric or conventional van (i.e., [50]). Integrating a 'mothership' van into the two-tiered system shows benefits in reducing travel distances for the van and driver, energy consumption, and, possibly, emissions [29,49]. A well-tested example in the US, UK, Germany, and Switzerland is Starship ADR and their mothership van. The development was led by Daimler AG in 2017 after Starship Technologies was launched in 2014. Starship ADRs can perform deliveries within a radius of approximately 3–5 km and for 15–30 minutes after they have been sent out from the mothership van [50]. Similar to [17,29] emphasizes the importance of the location from which the mothership van sends out ADRs, due to the range limitations of ADRs. However, higher efficiency can be expected for fixed depots located at various locations inside the city than with a ground vehicle (mothership van), as this avoids adding an additional vehicle to the network, thus decreasing the energy required [29]. However, fixed hubs impose rental costs, which can add to the total operational costs of UAVs. Solutions may include vertical storage spaces or new opportunities such as Amazon's airborne fulfilment center (AFC) [26], in which a drone-friendly airship is used instead of a traditional warehouse, promising to increase customer service and on-demand delivery [51]. In China, pop-up stores have been popular. Digital innovations such as portable printers and smart apps allow couriers "to create pick-up locations on-demand" instead of physical warehouse or hub facilities [2] (p.3).

3.3.2. UAVs and Delivery Vehicles

[52] addresses both the technical and operational challenges of using UAVs for last-mile operations. From a technical point of view, challenges include the endurance and safety of UAVs, relating to battery performance, speed, and payload, as well as safety-related system requirements. This can impact the operational performance of drone deliveries. Limited range, for example, might require distribution centers located close to the customer. Restricted payload capacity may require conventional delivery modes by van for packages exceeding the payload [52]. A solution may be to integrate and coordinate both drones and vans. Ref. [52] (p. 87) considers such two-tiered systems by, first, considering deliveries done by UAVs to all customers within flight range while a van serves customers outside the flight range. Second, the system foresees that some customers, even if their location

is within the flight range, can be served if this leads to additional time savings. Third, if a customer is located outside the flight range of the UAVs, a solution is to "pair the UAV with a traditional delivery truck" and launch the UAV from the truck once it has reached a location closer to the customer. The study took the assumption that the UAV can serve only one customer once launched, while the truck can serve several customers in the meantime. Moreover, it was assumed that the UAV is flying constantly when sent out. This impacts the coordination and timing for returning to the truck and battery consumption. The described operation of a UAV in synchronization with a truck is referred to as the 'flying sidekick traveling salesmen' problem' [52] (p. 90). The case where the UAV is launched directly from a distribution center and both the UAV and truck operate parallelly and independently from each other is called the 'parallel drone scheduling traveling salesmen problem' [52] (p. 97). The literature proposes several optimization problems referring to UAVs and trucks in tandem (see [52]). Aiming to optimize deliveries using UAVs, [52] found that the flight speed of UAVs is crucial in terms of efficiency, even if higher speed may lead to decreased endurance. Ref. [53] considers UAV speed as a decision variable for the first time, while previous works (e.g., [52,53]) assume that the UAV would fly with constant speed. Defining speed as a decision variable means that speed of the UAV is not defined from the beginning and is assigned during the delivery process. Results of [53] show that highest savings can be achieved when flying at variable speeds and in regions with low customer density, and the study concludes that variable UAV speed "outperformed both the maximum speed UAVs and the maximum-range speed UAVs" [53] (p. 18). Moreover, variable speeds lead to less energy consumption per delivery and less waiting time for the truck [53]. Future research can focus on the use of multiple UAVs and delivery trucks for the flying sidekick traveling salesman problem, or the integration of the two approaches presented by [52]. Cost–benefit analyses including costs such as insurance, electricity and fuel, labor, maintenance, and operational cost [52].

3.4. Passenger and Freight Integration

Passenger and freight integration may allow the reduction of external costs without compromising mobility [54]. Passenger and freight integration concepts foresee passengers and goods sharing vehicle(s), road infrastructure, and urban space "at the same time" [54] (p. 33). Integrating passenger and freight transport can cause complexity, as it involves multiple stakeholders and actors both from the private and public sector to ensure 'efficient and reliable parcel deliveries' [54] (p. 33). Moreover, adjustments of scheduling schemes, fares, and related delivery processes might be required for successful implementation [55]. The concept is an existing approach applied in the rail and aviation sectors [18]. Passenger and freight integration provides a solution that could be adopted for autonomous vehicles. Environmental and operational benefits [56] and increased service [18] can be achieved using an integrated approach. Concerning service, an increase of the delivery frequency by a factor of four was found, given that the receivers are willing to pick up their parcels at certain points [18].

In 2007, the European Commission addressed the topic of passenger and freight integration [57]. Since then, little research has been conducted. Ref. [54] found only a few studies investigating passenger and freight integration (e.g., [18,58,59]). The review conducted for the work at hand identified two more publications on passenger and freight integration, which focused particularly on urban deliveries. [1] conducted an analysis of autonomous mixed-purpose fleets (an autonomous vehicle that is used for both passenger and goods transport) compared to autonomous single-purpose fleets (serves only one purpose, i.e., either passenger or goods transport). It is important to note when considering integrated passenger and freight approaches that passenger transport requires accuracy when it comes to pick up and arrival times, while goods allow a wider pick-up and delivery time window [1]. The results of [1] show that a highly utilized mixed-purpose fleet leads to higher profits for the fleet operator. On the contrary, if a large number of vehicles are available for requests (lower utilization), a single-purpose fleet can generate comparable

profits. However, it is important to note that this study was based on certain assumptions regarding various parameters, for example, parcel size, fares, type of goods transported, and static flows. Further research needs to be conducted for dynamic requests and delivery flows [1]. Ref. [54] discusses the potential for passenger freight integration in first- and last-mile logistics operations with regards to operational, socio-economic, and environmental factors. However, this study does not explicitly consider autonomous vehicles.

Concerning passenger and freight integration, [60] highlights the potential to increase the occupancy rate by using empty car seats during single-passenger rides. This can lead to increased transportation efficiency in cities. Autonomous vehicles and the ability to offer sustainable and affordable car-sharing in the future [61] could help in "re-shaping public transit" [1] (p. 392). Moreover, this may help to further improve same-day or time-window delivery [8]. In this light, autonomous mobility on demand (AMoD) is considered an efficient solution for passenger transport (e.g., [1,62,63]). However, such a solution is still highly dependent on passenger demand. To utilize their full potential, AMoD solutions could be used to satisfy good delivery demands during off-peak hours, for example. Furthermore, this can allow route optimization and low-cost structures [1].

Based on the studies above, passenger and freight integration has the potential to positively impact logistics operations and the environment and has socio-economic benefits. Since the concept is an existing approach applied in the rail and aviation sectors, passenger and freight integration provides a solution that could be adopted for autonomous vehicles. However, thus far, limited research has been conducted on this topic, leaving space for further examination.

4. Discussion

This review discusses various autonomous delivery solutions and reveals clear advantages and disadvantages of each. However, an existing solution does not automatically imply smooth operationalization. Different dimensions were used to compare solutions presented in this work. Referring to these dimensions, advantages and disadvantages of each solution are presented in Table 2. Moreover, Table 2 provides an overview regarding the suitability of each solution for different purposes. To provide an overview and compare solutions, dimensions included were safety, environment, transportation network, service, previous experience, method of operation, payload, energy demand, operation window, operational performance, and reaction to dynamic ordering behavior. The advantages and disadvantages of the solutions presented in this work are discussed as follows. Additionally, a research agenda is provided (see Table 3). Based on the research agenda, practical and theoretical implications are given.

ADRs have the potential to perform 24/7 operations. This can help in filling courier shortages and delivery gaps and can lead to increased service. Overall, ADRs are seen as a cost-efficient business solution once implemented. However, today, ADRs are not capable of performing the last 50 feet of a delivery including climbing stairs and ringing a doorbell, thus creating a limitation. Moreover, there is currently limited knowledge about energy consumption per customer served and whether the impacts would be similar to performing the delivery with an electric van. While S-ADRs are intended to operate on the sidewalk, R-ADRs require integration into the shared road network. This can lead to increased traffic if R-ADRs are added without replacing existing delivery vehicles.

Concerning UAVs, previous research mainly focuses on time optimization and cost minimization. Using UAVs in combination with several distribution or micro-consolidation centers inside and outside a city was found to have the best performance concerning cost, time, CO_2 emissions, and number of vehicle trips (see [46]). For last-mile logistics operations in cities with high population density, UAVs in combination with other delivery vehicles (i.e., a two-tiered system) present a sustainable delivery mode. As a standalone delivery solution, UAVs were found to be suitable to rural areas with low population density rather than high-density areas. A clear advantage of UAVs is their independence from road traffic, as well as their speed.

Table 2. Comparison of autonmous delivery solutions with regards to the identified dimensions. (+)—positive impact; (-)—negative impact (source: author).

Aspect / Autonomous Delivery Solution	Impact on Safety	Impact on Environment	Impact on Increased Service	Experience from Related Fields	Capability to Operate over Last 50 Feet	Mode of Operation	Payload	Energy Demand Per Customer Served	Impact on Road Transportation Network	Operation Window	Operational Performance Reg. Cost and Time Inside Cities	Reaction towards Dynamic Ordering Behavior
Autonomous Delivery Robots (ADR)	+	+	+	Pilots	No	Shared roads, sidewalks	Large	Left to future research	Left to future research	24/7	+	Flexible
Unmanned Aerial Vehicles (UAV)	Left to future research	+	+	Agriculture, military	No	Air	Limited	Left to future research	+	Limited (depending on country/regulations)	Limited as a standalone delivery solution	Flexible
Two-tiered system (ADR/UAV)	+	+	+	Pilots	No	Shared roads plus:shared roads/sidewalks/air	Depending on device: limited (UAV), large (ADR)	Left to future research	Left to future research	Potentially 24/7	Depending on the concept /number of tiers/vehicles used	Flexible
Passenger and freight integration	+	+	+	Air traffic, trains	No	Shared roads	Large	Low	+	Possibly during off-peak house	+	Limited

Table 3. Research agenda to support successful development and implementation of autonomous delivery solutions for last-mile logistics operations (source: author).

Research Area	Field	Topic
Autonomous Delivery Solutions—Overall	Energy consumption	Analysis of energy consumption, e.g., per customer served, and its impact on: - The grid system; - Operational efficiency; - Sustainability.
	Legislation	Investigation of legal aspects for operating autonomous delivery solutions: - Autonomous delivery robots: regulations and licenses for operation on public roads; - Unmanned aerial vehicles: regulations regarding height and time windows for operation; - Identification of different legislation in countries across Europe.
	Strategy	Development of strategic communication and implementation plans.
	Training	Development of educational programs to foster understanding and knowledge of autonomous delivery solutions inside organizations.
	Customer behavior	Research on the effect of dynamic ordering behaviors and seasonal fluctuations on logistics operations using autonomous delivery concepts.
	Acceptance	Research regarding the acceptance of autonomous delivery solutions as a pre-condition for successful implementation: - Concerning various stakeholders such as the public, freight companies, governments, working unions, and others; - Concerning different autonomous delivery solutions.
	Pop-up stores	Taking the example of China, mobile pop-up stores provide a solution for city logistics operations. Research can investigate to what extent pop-up stores can serve as a solution in European cities.
Autonomous Delivery Robots (ADR)	Road infrastructure	Research on the impact of implementing autonomous delivery robots on road infrastructure (e.g., traffic density, parking situation, safety).
Unmanned Aerial Vehicles (UAV)	Urban operations	Investigation of how UAVs perform in urban areas with high customer density, particularly for last-mile operations (potentially as a standalone solution).
	Safety and Risk	Safety and risk analysis of UAV usage for last-mile deliveries.
	Cost-benefit analysis	Cost–benefit analysis of UAVs including costs such as insurance, electricity/fuel, labor, maintenance, and operational cost.
	Collaboration	Given the strong market position China has in UAV development, national or even international collaboration is advised. Mutual learning can be achieved through research and development projects.
	UAV–receiver interaction	Investigation and evaluation of different interactions between the receiver and UAV during the delivery process (e.g., door-to-door interaction, UAV and parcel locker, UAV and courier).
Passenger and Freight Integration	Scheduling	Development of scheduling schemes for effective and optimized integrated transport.
	Last-mile operations	Investigation of passenger and freight integration for last-mile operations using autonomous vehicles, for instance: - Autonomous shuttle busses; - Autonomous passenger cars; - Autonomous trams or trains.
Two- tiered System	Location of tiers (UAVs and ADRs)	Simulation and investigation of optimal locations for distribution and consolidation centers/tiers with special regards to dynamic ordering behaviors.
	Storage space	Identification of solutions for storage space/micro-hubs for goods in cities. Solutions can focus on alternatives to traditional physical and fixed storage spaces.
	Usage of multiple UAVs and trucks	Effect of using multiple UAVs and delivery trucks to perform deliveries (flying sidekick traveling salesmen problem).

At present, there is limited knowledge as to whether UAVs lead to external cost reduction. In particular, the topic of power generation and energy demand per customer served are under-researched. Moreover, the limited payload of UAVs and different legislation depending on the country in which a UAV operates require further consideration and may create limitations for operation. Referring to the limited load capacity of UAVs, a solution may be to integrate UAVs in a two-tiered system. Once goods have been delivered to a consolidation center or city hub during the first tier, UAVs can perform the last-mile delivery

from there. Similarly, the concept can be applied to ADRs with limitations in range and speed. A variation of the two-tiered concept is to use a van instead of a fixed consolidation center. The so called 'mothership' van then serves as a mobile depot, releasing UAVs or ADRs at certain points along the route. The disadvantages of integrating a van are that an additional vehicle is added to the transport system, requiring a driver. This might cause inefficiencies concerning traffic and energy demand. In either case, whether using a fixed depot or a mobile van, [17] found that the location of the first-tier stop inside a city was crucial to performance.

Passenger and freight integration is a beneficial concept due to its integrated approach. The solution promises to positively impact the environment by sharing space and vehicles for transportation purposes, for example, for passenger and goods transport. The aim of integration is the reduction of external costs such as pollution, traffic, congestion, and noise, especially in cities. Passenger and freight integration has been applied in rail and air traffic. Experience from existing approaches can be beneficial when applying the concept to autonomous vehicles. Integration can lead to increased delivery frequency and, thus, increased service and, potentially, decreased cost. Despite these advantages, there is uncertainty when it comes to dynamic ordering behaviors, various parcel sizes, and different types of goods. Moreover, scheduling of trips must be aligned, since timing applies differently to passenger transport and goods transport. Time accuracy is more important for passengers than in the delivery of goods.

Addressing the safety aspects and potential impact on environment of the devices presented can positively influence their acceptance. Cost-saving factors in terms of fuel consumption and labor can be driving forces for logistics service providers to implement autonomous delivery solutions. Moreover, increased service and higher customer satisfaction levels are further incentives. Integrating autonomous delivery solutions in last-mile logistics operations can help logistics service providers achieve more sustainable logistics and may lead to new business models. Training and education for the workforces operating with the devices are crucial, important to consider, and relevant to all the solutions presented, especially since work tasks will change or shift towards other roles such as driving operation, maintenance, and manufacturing [26] once autonomous solutions are implemented. As an example, JD Logistics, a Chinese company, offers dedicated UAV training and is especially interested in cooperating with universities [26].

As presented in this section, different solutions have advantages and disadvantages, as well as different research needs. Research needs are addressed in Table 3, which presents a research agenda. Based on the research agenda, practical-managerial implications for policy makers, businesses, and manufacturers are given. Theoretical implications mainly relevant to researchers are also outlined.

Concerning practical-managerial implications, the lack of a legal framework for operating autonomous delivery robots on public spaces such as roads or sidewalks requires that governments act. Similarly, addressing the usage of UAVs, there are gaps in legislation concerning, for example, flight height and operation window. It may be beneficial to take a national or even international approach when defining regulations. For businesses, especially logistics service providers, developing strategic communication and implementation plans is recommended. It is necessary to prepare for the arrival of new autonomous delivery solutions by creating awareness and transparency. Furthermore, developing educational programs, particularly concerning the operation of ADRs, is essential for creating a knowledgeable and confident workforce. Risk and safety aspects are crucial, and potential risks must be eliminated prior to deployment. It may be useful to conduct risk and safety analyses and tests during various development stages alongside researchers. Therefore, collaboration between various groups is strongly recommended. Collaboration can take place between academia, the private sector, and governmental institutions to avoid groups working in silos. Specifically, it would be beneficial to work internationally and foster mutual learning with countries and markets that already have experience in certain areas.

Theoretical implications can be derived from the research agenda. Our findings can serve as input for researchers targeting relevant areas. For all solutions presented, the actual energy demand per customer served is still unclear and depends on, for example, population size, urban density, and technology used. Moreover, and applicable to all solutions presented, customer behavior may influence operational efficiency and performance. Therefore, the effect and organization of dynamic ordering behavior or seasonal fluctuations can be analyzed. In addition to the various economic, environmental and social advantages mentioned, ADRs specifically will have an impact on infrastructure and road networks. Traffic density, parking space, and safety are topics that can be further investigated. This work discussed UAVs extensively and found that, in combination with delivery vans or integrated within a two-tiered concept, they perform well. However, there is insufficient knowledge about drones as a standalone delivery solution, especially in high-density areas. The effect of using multiple UAVs in combination with a delivery van can be further explored. Furthermore, a cost-benefit analysis based on existing findings concerning cost and benefits is advised. Optimal hub locations in cities can be simulated and further explored depending on the type of delivery solution applied. Regarding hubs and storage spaces, alternatives to traditional fixed depots may be explored. Passenger and freight integration, an existing and a functioning approach in aircraft transport, requires scheduling schemes that can be applied for autonomous shuttle busses, passenger cars, trams, and trains.

5. Conclusions

This work aimed at identifying autonomous solutions suitable for performing last-mile logistics services. It provides a comprehensive overview of possible autonomous delivery solutions for logistics services. The literature review includes most recent studies and discusses the advantages and disadvantages of the solutions considered. The review allows different technologies to be compared in terms of the relevant aspects identified, which was not done in previous reviews. Finally, a research agenda is provided, as discussed in the previous section (see Table 3). The research agenda may serve as orientation for researchers, industrial actors, and governmental institutions to further develop autonomous delivery technologies and to prepare for and ensure successful market implementation.

The research agenda presented in this work indicates future research directions. The aspects of energy consumption per customer served and the impact of the presented solutions on the grid system are crucial before market implementation. Country-specific legislative regulations for both UAVs and ADRs form another area for investigation. Acceptance of autonomous delivery solutions by various stakeholders is a pre-condition for successful implementation. The concept of a two-tiered system including both ADRs and UAVs deserves further consideration in terms of the location of the different tiers. Finally, topics such as training, customer behavior, insurance and liability, impact on road infrastructure, and specific solutions for passenger and freight integration should be further explored to allow smooth deployment.

This work considers different autonomous delivery solutions suitable or adaptable to last-mile logistics operations. The approach chosen was a rather generic one, as the work does not distinguish between product specifications of different manufacturers of the solutions. This constitutes a limitation. Future research can take into account the product characteristics of solutions and analyze and compare them. The presented research agenda identifies future research areas based on the current maturity levels of the technologies. The fast pace of technology development in the field deserves attention, as research needs can shift rapidly. Previous works were considered under a systematic literature review complemented by the snowballing procedure and considering gray literature. The choice of search strings and database can influence the outcome of a literature search, constituting a further limitation. Future research can adapt and expand the literature search to other databases and search strings. Moreover, this work used literature in English mainly produced in Europe and the USA. The Asian market is developing rapidly and already

applying autonomous solutions. Future studies can include the Asian market and add outcomes of the investigation to the research agenda presented herein.

Author Contributions: Conceptualization, V.E.; methodology, V.E.; writing—original draft preparation, V.E.; writing—review and editing, E.R. and LV. and P.L.; supervision, E.R. and P.L.; funding acquisition, L.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Vrije Universiteit Brussel, grant number SRP56: SRP-Onderzoekszwaartepunt: Autonomous Mobility & Logistics.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This was a literature review; information was collected by reviewing peer-reviewed scientific journals and gray literature.

Conflicts of Interest: The authors declare no conflict of interest.

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