Towards a sustainable and autonomous last mile delivery

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Abstract: Last mile delivery is one of the main loss-making processes within the supply chain management. Several aspects affect this process, and an appropriate management becomes complex due to the urban environment in which it takes place. This context in many cases is congested and presents several constraints: high presence of vehicles and people, reduced speed, busy parking lots and others. In addition, urban areas are under stress due to the increased demand for home delivery products, determined mainly by rise of e-commerce. Many cities are also adopting more restrictive policies in the mobility sector, with streets being converted to pedestrian or low-vehicle zones. The recent challenges are focused on increased efficiency of last mile delivery activities by considering different factors. In this paper, an innovative solution based on the use of unmanned autonomous vehicles and district hub approach is adopted for the last mile delivery. The study focuses on optimizing last-mile delivery operations satisfying customer requirements with a sustainable approach. A sustainable evaluation model is proposed based on the analysis of environmental impacts, the study of economic effectiveness, and the analysis of social impacts, quantifying external costs. A simulation case study is proposed to evaluate the impacts of the proposed approach. The findings highlight how the use of unmanned autonomous vehicles and district hub approach can improve sustainability performance in last-mile delivery activities.

Keywords: Environmental and social impact; Last-mile delivery; Autonomous vehicles; Hub-and-spoke model, Sustainable logistics

1. Introduction

Managing the last mile delivery process is a critical challenge, especially in the current environment of strong e-commerce demand. It is one of the main loss-making processes within the supply chain management. Several aspects affect this process, and an appropriate management becomes complex due to the urban environment in which it takes place. This context in many cases is congested and presents several constraints: high presence of vehicles and people, reduced speed, busy parking lots and others. Many cities are also adopting more restrictive policies in the mobility sector, with streets being converted to pedestrian or low-vehicle zones. The recent challenges are focused on increased efficiency and timely deliveries activities by considering different factors.

This paper explores the last mile delivery opportunities provided by recent technologies: an approach based on unmanned autonomous vehicles and district hubs. An evaluation is made of the sustainability of the proposed approach based on routing optimization in last-mile urban delivery.

In sustainable logistics models, improving process efficiency is a key aspect; therefore, focusing on last-mile logistics, the least efficient link in the supply chain, becomes significant (Wang et al., 2016). In urban areas, logistics activities are less efficient, and demand is high due to the huge number of people and high rate of delivery. However, this generates more externalities or external costs (Silvestri et al., 2020), which in the urban area can be summarized mainly as: air pollution, climate change, noise pollution, congestion, accidents, infrastructure wear and tear, oil dependencies.

The last-mile delivery optimization topic is receiving considerable attention in literature. In fact, as mentioned, it is an aspect that can significantly influence and can lead toward more sustainable cities. Several studies have been carried out to identify methods and models for delivering goods in the last-mile with sustainable approaches (Silva et al., 2023). In this view, it emerges how environmental, economic, and social aspects must be considered equally important (Bosona, 2020). Among the many factors analysed, the latest technological innovations that are attracting much interest because they could bring important improvements are related to the use of autonomous delivery solution (Engesser et al., 2023). Different unmanned autonomous vehicles are analysed and the most promising for last-mile delivery are unmanned aerial vehicles such as drones, integrated vehicles for passenger and freight transport, and especially autonomous delivery robots since they are better suited to the urban environment (Alverhed et al., 2024). In fact, the optimization of the last-mile logistics with these unmanned autonomous vehicles, such as robots, becomes very interesting as real-world pilot case applications begin to spread with positive results. The use of robots allows for more safety deliveries and in a reduction of delivery time. A literature review proposes several routing approaches related to deliveries with robots, identifying five delivery models: truck-and-robot delivery, delivery with cover options, hub-and-robot delivery, truck-and-robot without robot depots, and truck-and-robot with robot depots (Heimfarth et al., 2022). The hubs and depots used in the last-mile delivery are similar concepts of urban consolidation centres and are based on the hub-and-spoke logistics model, in which the confluence points of a large number of goods become the logistics facilities for proximity delivery.

The study of hub optimization and minimization of robot travel distance is applied to a two-tier last-mile delivery system using robots (Bakach et al., 2021). The model proposed by the authors is based on a system in which goods are transported by a truck to local hubs, and at these hubs they are stored and loaded onto robots. Studies based on similar concepts have looked at the efficiency of truck tours and robot scheduling for hub-based deliveries (Poeting et al, 2019a, and Poeting et al, 2019b).

Among the aspects analysed in the literature, customer satisfaction is also of considerable importance, since in recent years the development of logistics models and software mobility management platform has been based on aa user-centric approach (Fanti et al., 2018). Studies show that the use of autonomous robots with planned routes even on sidewalks saves time and results in earlier delivery of goods to customers (Jennings and Figliozzi, 2019). Service quality can also be improved through the integration of last-mile routing and last-mile delivery decision through optimizing on-time delivery by employing unmanned autonomous robots (Alfandari et al., 2022). The use of autonomous robots for small deliveries and in the case of short distances can reduce the number of late deliveries (Schaudt et al., 2020) and customers could get their parcels faster, also fewer vehicles could be used, resulting in improved delivery performance (Chen et al., 2021).

This paper focuses on evaluating the sustainability of the last-mile delivery approach with unmanned autonomous vehicles and district hub, based on the use of existing parking infrastructure considered as hubs. The idea improves integrated routes and avoid the need for specific hubs and storage facilities. The proposed approach is based on the strategically combining of centralized hubs, with a focus on the use of large municipal parking lots such as park-and-ride areas facilities, and unmanned autonomous vehicles to improve the speed, accuracy, and sustainability of last-mile deliveries. The choice of hubs is a key factor in optimizing last-mile delivery systems, especially when involving unmanned autonomous vehicles into the logistic framework. The choose of existing infrastructure as the basis for these hubs is critical for different reasons.

First, using an existing infrastructure allows to implement a logistics system in a more economically, environmentally, and socially sustainable way. The second aspect is related to the strategic choice of hubs for last-mile delivery in a city; this decision requires consideration of several aspects such as proximity to high-demand areas, traffic patterns and accessibility. Therefore, the optimal placement of hubs can affect the important reduction in the overall distance travelled by unmanned autonomous vehicles, and consequently improves the efficiency and speed of the entire last-mile delivery process. Large municipal parking lots, such as park-and-ride areas facilities, are existing infrastructure and provide many parking spaces, central location, and accessibility to different urban areas. The proposed approach of using these infrastructures for last-mile delivery operations with unmanned autonomous vehicles can generate a twofold benefit: minimizing new logistics infrastructure in highly densified urban areas with concomitant negative impacts on the population and locating district-hubs in strategic sites. The greatest benefits are related to their proximity to areas of high demand, in addition to convenient access points. In this way, the overall efficiency of last-mile deliveries can be significantly optimize.

In this paper, an assessment of the economic, environmental, and social sustainability of a study proposed in literature (del Cacho Estil-les et al., 2024) on last-mile delivery optimization approach with a model based on the use of unmanned autonomous vehicles and district hubs is proposed. This analysis allows for an instrumental evaluation of the implementation of new logistics models. To this end, simulation results of minimizing the total length of routes travelled by unmanned autonomous vehicles while satisfying customer needs are used to assess sustainability impacts.

The unmanned autonomous vehicles and district hubs approach for last-mile delivery is a highly innovative logistics system, not yet used in real-life situations. Therefore, no sustainability analyses have yet been carried out for this urban freight delivery strategy. However, some studies have been carried out on the sustainability of urban freight delivery with the use of unmanned autonomous vehicles, but purely based on the environmental aspect and impacts calculated according to LCA and footprint methods, as reported below. Assessing the economic, environmental, and social sustainability of a new logistics model becomes crucial for today's strategic choices in reducing the impacts of urban delivery activities.

The proposed approach is applied to a case study describing the last-mile delivery problem in two districts of the city of Bari (Italy). The results show the reduction of externalities caused by last-mile delivery in dense urban areas.

The innovation of this paper is notable by a sustainability assessment based on external costs and the use of strategically located of district-hubs within municipal parking lots such as park-and-ride. The optimization of the last-mile delivery system is further improved as route reduction with unmanned autonomous vehicles is most effective in proximity to high-demand areas, central accessibility, and with the use of existing infrastructure.

This study differs from others that have addressed the problem of evaluating sustainability in the use of unmanned autonomous vehicles for last-mile delivery (Garus et al., 2022), both in terms of the model proposed and the methodological approach. In most cases, indicators, based on LCA and footprint analysis, are used to assess the sustainability of the model. In this paper, a different approach is proposed, based on the evaluation of factors, not only environmental, but also economic and social, by calculating the costs of externalities between a traditional urban logistics model and the selected innovative one.

The paper is organized into four other Section: definition of the problem in Section 2; the methodology is explained in Section 3. A simulation case study is proposed in Section 4. Finally, Section 5 concludes the article, summarizing the main findings and implications.

2. Problem definition

This section outlines the last-mile delivery system considered in the study mentioned in Section 1, which is based on considering both unmanned autonomous vehicles and a district hubs approach. In the problem, depicted in Figure 1, a truck operates as the primary transporter for goods and unmanned autonomous vehicles such as robots, which transport them to the hub. In the hub, robots are loaded with necessary packages and then leave to deliver them to designated customers. This study is based on evaluating the economic, environmental, and social sustainability of the innovative model analysed, in which the goal is to identify the best routes for a group of robots in delivering packages to specific customers, including load capacity and time constraints.

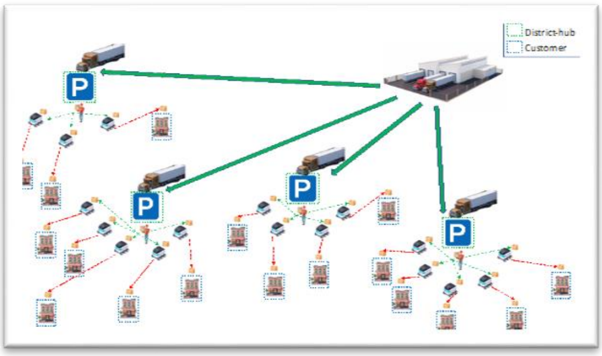

Figure 1: Last mile delivery model with District-Hub and unmanned autonomous vehicles

Unmanned autonomous vehicles with batteries capable of providing energy up to 40 km range were considered in this problem. Therefore, minimization of the total length of the robots' travelled routes main was defined as the main objective. Last mile delivery operations are carried out by starting with the departure of robots from the district hub in order to deliver parcels to customers. Also considering the predefined time constraints of the problem, the robots return to the district hub, repeating the operation with subsequent deliveries by loading additional packages, minimizing resources. Processes thus become cyclical, ensuring an efficient and continuous delivery system as robots connect the district hub and customers. The study mentioned in Section 1 is based on optimizing this workflow to improve strategies that can be used in last-mile delivery. The mathematical model created to solve the routing problem, considers several factors, such as the amount of goods each robot can carry, time constraints, and total distance traveled. This optimization model aims to make last-mile delivery faster and improve the operation of city logistics.

2.1 Optimization model

The objective function of the optimization model proposed by del Cacho Estil-les et al., is based on minimizing the total length of the routes travelled by robots while satisfying customer needs. This also means minimizing the path time and resources for last-mile delivery of parcels with robots, from the district hub, located in large municipal parking such as park-and-ride area, to customers (considered to be nodes). The entire network representing the delivery flow of goods thus described was modelled through a fully connected directed graph. This methodology allows both district hubs and customer nodes to be represented and considered for the entire delivery network.

The optimization model was developed considering the following assumptions: each customer request is quantified as a unit parcel, not considering the weight of the parcels; the delivery service time is a function of the time it taken to complete each delivery successfully; the distance between each pair of nodes is related to the weight of the arcs connecting the nodes; and the calculation of travel time between nodes is based on the average speed set for the robots. Deliveries are made by the system with several possible routes, where for each path the model considers that each robot starts its journey from the district hub and ends it at the hub. The aforementioned parameters and decision variables, each of which contributes to the efficiency and effectiveness of the last-mile delivery system, form the basis of optimization model. The mathematical model is formulated as a MILP.

3. Methodology for sustainability assessment

In the last-mile logistics, literature proposes five categories of innovations to reduce the negative externalities generated: innovative vehicles; proximity stations; collaborative and cooperative logistics; optimization of transport management and routing; innovations in public policies and infrastructures. The use of these innovations can be improved impacts sustainability in the last mile delivery. An example is the collaborative and cooperative logistics approach, in which urban consolidation centres (or hubs) are implemented in many cases with shared transportation means. The use of unmanned autonomous vehicles such as robots is an economic and environmental opportunity due to the increase in both the vehicle utilization ratio and the load space saturation ratio. This makes it possible to invest in more sustainable vehicles (e.g., electric robots) as they payback time becomes short and to have a shorter fleet turnover rate. Last mile delivery is an activity with goods that are not bulky and small. Therefore, especially in the delivery of e-commerce products, unmanned autonomous vehicles and district hub approach could be an opportunity. In fact, dense urban areas require more efficient and less impactful management of last-mile delivery activities, while also considering the mobility of people and the constraints of the surrounding environment: congestion, few available parking spaces, reduced speeds, pedestrian areas, and other.

On this basis, an alternative logistic system for last-mile delivery is proposed to provide a more economic, environmental, and social sustainable approach. The idea is based on the use of unmanned autonomous vehicles and district hub, localized in large municipal parking such as park-and-ride areas. These areas are very close to the city centre and to strategic infrastructure such as links to high-speed roads. This makes it easy to get trucks from logistics platforms or nearby transportation infrastructure (port, airport, highway) into the hubs, the district-hub, avoiding investment in new facilities. The district-hub can thus easily provide adequate space to load goods into vehicles suitable for last-mile delivery and limited impact on the city and its citizens. Robots' route optimization allows to increase the logistic system efficiency and reduce transport externalities: the use of unmanned autonomous vehicles, small in size, electric without internal combustion engine, and using defined routes (e.g. sidewalks, bus lanes, bike lanes, pedestrian areas) has generated several benefits for city logistics and traffic systems. Robots do not need parking lots during delivery activities. Congestion is reduced, especially in dense urban areas. Energy consumption is lower than traditional light commercial vehicles, and air emissions and pollution are absent in the city. The robots can be used throughout the day and not in defined time windows, as is done in several cities to reduce congestion. The district-hub located close to dense areas and thus the use of robots with lower speeds, combined with vehicle safety technologies, should reduce accidents. In addition, many of these features are also social benefits for citizens.

Economic sustainability is affected by the time of use of unmanned autonomous vehicles: the high investment or rental cost of robots can be amortized in a shorter time with a high number of deliveries. Vehicle costs also include software and route scheduling costs, as well as safety costs related to a service remotely management performed with a tele-operator involved in driving the robots when necessary (unsafety condition). In addition, operative costs such as electrical energy, maintenance, personnel and others are considered.

The sustainable evaluation of the framework of the conceptual model proposed is based on the follow steps:

- analysis of the environmental impact: reduction of emissions factors between the existing last-mile delivery and the proposed approach;
- study of the economic effectiveness: analysis of the actual costs for delivery and use of unmanned autonomous vehicles and district-hub approach, through defining the break-even point;
- analysis of the social impact with the reduction of externalities factors affecting citizens.

The sustainable assessment of environmental, economic, and social aspects is carried out with the analysis of data and relevant peculiarities of the analysed context.

4. Simulation case study

The simulation case study was developed comparing the last-mile delivery performance of two scenarios: the first scenario is based on traditional approach with the use of single light commercial vehicle (LCV). The second scenario is developed with the use of unmanned autonomous vehicles, such as robots, and district-hub approach. The two scenarios will be developed considering two districts, Murat and Madonella, in the city of Bari (placed in southern Italy). The choice of these two districts and of the context in which the simulation case study was carried out is based on the urban morphological typology: the streets are within a regular network and the districts, being very central in the city, have a high density, which represent ideal conditions for the use of unmanned autonomous vehicles, such as robots, and district-hub approach. In each district 12 customers are considered. The sustainability assessment in simulation case study is performed by considering the differential costs of the two scenarios. The assumptions considered for the development of the simulation case study are as follows: the demand level in the defined period and the number of users where the goods are delivery is the same in the two scenarios.

In the first scenario, the assumptions made are as follows: last-mile delivery is performed by a single LCV, with a euro 5 engine, which will have to serve 24 customers considering an urban route of 15 km, with an estimate of 10 minutes per delivery (considering moving, parking and delivering the package to the final customer) generating a total time of about 240 minutes. Based on data collected in the Italian market, and specifically referring to the case study area, an LCV rental cost of about 900 €/month including insurance and maintenance costs, is assumed for subsequent analysis, and the operating cost is equal to 1848 €/month, considering 22 working days in a mount, 2 operators for 4 hours a day with an hourly cost of 10 €, and a fuel cost of 4 € daily.

In the second scenario, two district-hubs are considered, one for each district, strategically located within the park-and-ride areas, taking advantage of location benefits: proximity to high-demand areas, central accessibility, and access to transport infrastructure (high-way). District-hubs are considered management centres for coordinating the urban delivery activities of a fleet of an unmanned autonomous vehicles consisting of a total of 8 robots. Table 1 described the number of robots with which each hub is equipped (4 robots) and the fundamental parameters such as starting hub, average speed, maximum working time, and load capacity for each robot, considered in the optimization model proposed by del Cacho Estil-les et al.

Table 1: Robots data

Robot	Departure district-hub	Average speed [km/h]	Wotking Time [min]	Load capacity [parcel unit]
R1 – R4	HUB 1	6,5	540	2
R5 – R8	HUB 2	6,5	540	2

The objective of route optimization is to minimize the distance travelled and consequently reduce the overall delivery time. The simulation case study of the last-mile delivery network in the two districts of the city of Bari, considering customers and district-hub location are shown in Figure 2.

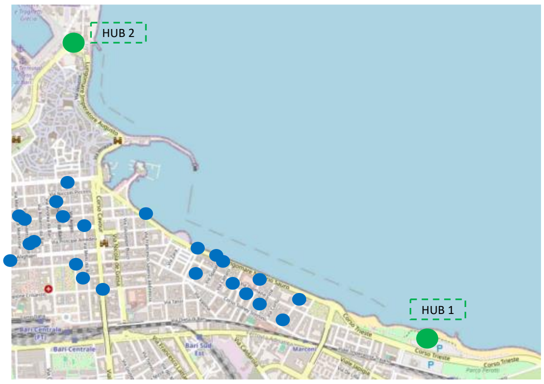

Figure 2: Simulation case study of last-mile delivery in the Bari city centre

Service time for each customer is estimated at 10 minutes. The nodes linked to district-hub 1, Murat district, are n_0 to n_{11}, while the nodes linked to district-hub 2, Madonnella district, are n_{12} to n_{23}. The two district-hub are respectively identified with nodes n_{24} and n_{25}.

4.1 Optimization results

Results of route optimization for the last-mile delivery problem with unmanned autonomous vehicles and the district-hub approach, as described, were implemented by Cplex and the solution is found in few minutes. Table 2 summarizes them.

Table 2: Optimization results of routes, time and distance

Robot	Departure district-hub	Customer served [n_i]	Travel Time [min]	Travel distance [km]
R1	HUB 1	3 - 2	203.07	13.55
		23 – 22		
		19 - 18		
		21 - 20		
R2	HUB 1	8 – 6	214.35	15.83
		17 – 14		
		15 – 13		
		16		
R5	HUB 2	11 – 10	198.71	13.07
		1 – 4		
		5 – 9		
		12 - 0		
R6	HUB 2	7	37.63	3.02

In this scenario, all 24 customers have been successfully served and not all robots have been utilized, demonstrating an efficient allocation of resources. In fact, only 2 robots from district-hub 1 and 2 robots from district-hub 2 were used.

The maximum delivery capacity for each robot is 2 customers in each route. The results show that each robot performs a maximum of 4 routes except for the last route of robot r2 and that of robot r6, where a different configuration is performed.

Table 2 shows the total distance travelled by the robots, which is 45 km. This result proves that the routing plan is efficient and minimizes the overall travel distance, contributing to resource and energy saving. Furthermore, considering that the solution proposed by the model did not used all robots even though it successfully delivering parcels to all customers, it shows a very good result. This achievement shows that the robot fleet considered has the capacity to operate with additional customers, demonstrating the scalability and efficiency of the unmanned autonomous vehicles and district-hub approach. The potential of this outcome translates into the ability to expand and optimize last-mile delivery operations to add more customers without significant increases in resources or operational time.

In the two scenarios analysed, the external cost related to the use of unmanned autonomous vehicles considers only the additional values, excluding the common external costs. Considering recent review of the scientific literature on the transport external costs in urban areas (Van Essen et al., 2019), an estimation of the differences external costs is reported in Table 3.

Table 3: External costs

External cost	LCV [€/km]
Air pollution (table 16 in Van Essen et al. (2019)	0,0324
Climate Change (table 25 in Van Essen et al. (2019)	0,0275
Noise pollution (table 35 in Van Essen et al. (2019)	0,011
Congestion (table 48 in Van Essen et al. (2019)	0,873
Accidents (table 8 in Van Essen et al. (2019)	0,041

The additional costs for air pollution, climate change, noise pollution, congestion and accidents are related to the kilometres travelled and to vehicle types. The proposed simulation case study is solved by a standard solver: entering the formulations into excel with an automatic calculation of the results, on an Intel-Core i7 quad-core, 2.4 Ghz CPU with 8 GB RAM.

4.2 Environmental sustainability

The environmental aspects are linked to air pollution and climate change caused using LCV for the last-mile delivery. In the proposed method the average daily distance travelled is equal to 15 km. Considering the external costs related to the average daily distance travelled, the saving is about € 237.20 per year. It is a good result for the environmental sustainability of the last-mile delivery in urban areas and to reduce the footprint of transport activities.

4.3 Economic sustainability

The analysis of economic aspects aims to define the value of the rental service of the unmanned autonomous vehicles in which the proposed method is cost-effective or not. Considering the insurance and maintenance costs, the energy cost and the amortization of the investment cost to purchase the vehicle (based on the useful life and a zero final value), the annual cost of an LCV is € 32.976. The district-hub approach has no cost by not requiring new infrastructure, however the rental cost of unmanned autonomous vehicles for the same service must be lower than the cost of the LCV approach to be economically sustainable. Therefore, in the case study simulation, the use of 4 robots needed for the same delivery service requires an annual rental cost for each vehicle of less than about € 8.244. Currently these vehicles are used in experimental condition and the monthly rental cost is about € 3.000 per each robot. The deployment of these technologies will lead to lower costs and make this new approach economically sustainable as well.

4.4 Social sustainability

The social external costs identified in comparing the two scenarios are related to decrease in factors classified as noise pollution, congestion and accidents. Considering the kilometers travelled in the two scenarios and the differences in externalities, the proposed approach saves external social costs of € 3663 per year.

4.5 Discussion

The conducted analyses show interesting results in assessing the sustainability of the two scenarios considered of the last mile delivery. However, the results need to be interpreted: each of the two scenarios has advantages and disadvantages. The traditional approach to last-mile delivery by LCV is better in rural areas or extended suburban areas of cities, where congestion is very low and parking areas are available. In fact., the impacts of this activity to environmental and social aspects are minimal, and the delivery time is faster than in the other scenario. Therefore, in this case the higher investment of using unmanned autonomous vehicles is not justified.

On the contrary, in city centre areas with high levels of population density, congested and few available parking spaces, the impacts of traditional approach of last mile delivery are much higher. In these contexts, it becomes interesting to evaluate the proposed innovative approach of last mile delivery as it enables significant benefits.

5. Conclusion

In this paper, a sustainable evaluation of a unmanned autonomous vehicles and district hub approach used as an alternative logistic system for last-mile delivery is proposed. This approach is based on the use of district-hub, i.e. large municipal parking such as park-and-ride areas in order to have hub very close to the city centre and to strategic infrastructure such as links to high-speed roads, without new logistic investment. The routing optimization, considering city constraints, of the unmanned autonomous vehicles such as robots, used in the last-mile delivery from and to the hub, enables the reduction of logistics impacts to the city. A comparative analysis model on the environmental, economic, and social sustainability is adopted to evaluate if the proposed approach achieves best values than the use of traditional vehicles in the last-mile delivery activities. The assessment uses external costs to evaluate the differences in social and environmental impacts through analysis of air pollution, climate change, congestion, and accidents. In addition, a cost analysis approach is adopted to identify the economic value where the proposed approach become cost-effective.

A simulation case study is carried out to assess the possible increase in sustainability with the adoption of the proposed model compared to the traditional approach in the last mile delivery activities. The findings highlight how the use of unamend autonomous vehicles and districts-hub can improve performance from environmental, economic, and social perspectives. The context of the simulation case study is based on the urban morphological typology that allows the optimization model analysed to be replicated and generalized to multiple urban districts. Certainly, the use of unmanned autonomous vehicles and district-hub approach is most effective in the more central areas of the city, as the reduction in the parking spaces, the congestion increases and the reduction in speed, greatly affect the efficiency of traditional last-mile delivery. Further analysis on the simulations can be done by evaluating the implementation of the sustainable model based on the optimization model, in pedestrian-friendly districts such as old towns, traffic-calmed areas, and others.

It should be noted that a simplified simulation case study is proposed in this paper, as the number of customers considered is limited, compared to real last mile delivery cases where a large number of customers are managed.

The proposed approach is a preliminary discussion for future applications of innovative unmanned autonomous vehicles in the city areas in the coming years. Some examples of using these autonomous vehicles for mail delivery are already being applied in pilot tests (YAPE robots, 2024) and have shown remarkable results in service utility and reduced transport impacts of externalities. On the other hand, however, there are issues related to workforce reduction, safety of robots under unforeseen operating conditions, and user acceptance, which still need further study and research.

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