Drone Delivery Using Public Transport: An Agent-Based Modelling and Simulation Approach

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Abstract. Drone delivery is considered as one possible solution to the last-mile delivery problems arising from the growth of e-commerce and customer expectations. Besides, urban public transport allows accessibility and connectivity among various locations within a city. Merging these two transportation modes, we propose a new futuristic delivery concept called Drone Delivery using Public Transport (DDPT). DDPT allows drones to deliver packages by riding existing public transport vehicles and aims to resolve the problems of last mile delivery. The purpose of this paper is to introduce the new DDPT concept and investigate its potential by comparing it with the traditional mode of truck delivery. Accordingly, we develop four agent-based simulation models and conduct an initial simulation study with 36 cases by varying the number of packages and their inter-arrival times. The comparison analysis is based on four key performance indicators: (1) Delivery Service Level, (2) Average Delivery Time, (3) CO_2 Emissions and (4) Utilization. The results indicate that the DDPT concept is more efficient and environmentally friendly than traditional delivery.

Keywords: Drone delivery · Public transport · Last-mile delivery · Agent-based simulation

1 Introduction

The rapid adaption of internet over the past years has played a crucial role in altering methods of consumer consumption by establishing trust towards the online stores [1]. This has led to an exponential rise of the e-commerce market which in turn gave birth to last mile delivery challenges [2]. Last mile delivery is considered the most expensive, wasteful and environmental degrading part of the supply chain [3, 4]. Bringing competitive edge for retailers, many companies are placing efforts in finding solutions to the hurdles faced by last-mile delivery. Drone delivery is one such solution, especially for small and light packages [5].

Drones are unmanned aerial vehicles (UAVs) – electric or hybrid means of transportation that fly above the ground [6, 7]. For last mile delivery, the three main reasons for the adoption of drones are cost, speed and convenience [8]. This has driven Logistic companies, such as Alibaba [9], DHL [10], Google [11] and Amazon [12], to start investing in and testing drone delivery. Amazon predicts that delivery using drones will help to reduce the last mile costs by 80% and reduce delivery time

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significantly [13]. Similar to Amazon, DHL has shown that drones can reduce average delivery time from 40 min to just 8 min along with 80% reduction in cost per delivery when compared with normal truck delivery [10].

However, drones alone face challenges in performing last-mile deliveries due to their battery life constraints [14] and social concerns with regards to numerous drones in the sky [8]. Previous work has focused on combining drones with trucks [15] (TSP-D) and autonomous mobility [16] (DDAM) for delivery. With TSP-D solution to many problems, such as carbon emissions, traffic congestion in last mile delivery, are still unclear. Whereas, DDAM still needs clarity for its feasibility and viability. An alternative delivery method combining drone delivery with public transport is suggested for future research by [16]. This method relies on future assumptions that a drone can carry substantial weight and can charge itself on a charging pad installed on the roof of public transport, but appears to be a possible solution to the last-mile delivery challenges.

Thus, the purpose of this paper is to further develop the Drone Delivery using Public Transport (DDPT) concept and investigate its potential by comparing it with the traditional mode of truck delivery. Accordingly, we develop agent-based models to represent both DDPT and traditional truck last-mile deliveries in the city of Bremen, Germany. Subsequently, we conduct an initial simulation study and compare the two delivery modes on four key performance indicators (1) Delivery Service Level, (2) Average Delivery Time, (3) CO_2 Emissions and (4) Utilization. The paper proceeds as follows. Section two presents the DDPT concept, while section three explains the methodology used in this study. We present and discuss our results in section four. Lastly, section five provides a brief summary of the investigation, its limitations and outlook for further research.

2 Drone Delivery Using Public Transport (DDPT) Concept

Similar to the DDAM concept, the DDPT concepts limits the flying time of the drones by utilizing existing resources. While DDAM suggests that drones could ride on top of autonomous vehicles, DDPT proposes that the drones could use public transport vehicles, such as trams, buses and trains, as an intermediary transportation method for delivery. In essence, the drone picks a parcel from a packet shop, flies to the nearest public transport stop, hops on the public transport, rides it to the public transport stop nearest to the parcel's destination and flies the remaining distance to the destination.

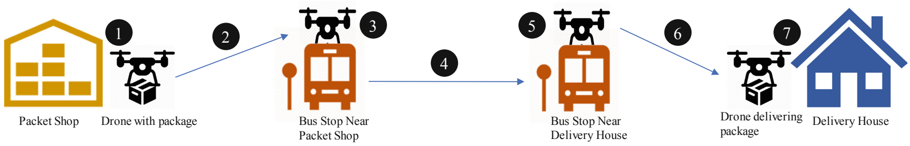


Fig. 1. Concept illustration of DDPT with one Bus connection.

Figure 1 shows a single transfer process in DDPT with bus consisting of seven steps:

Step 1: Drone is loaded with packages at the Packet Shop.
Step 2: Drone searches for the nearest Bus stop.
Step 3: When the bus with the direction towards the Delivery House arrives, the drone flies onto the roof of the Bus.
Step 4: The bus drives in its original route while the drone stays idle.
Step 5: When the Bus has reached the stop nearest to the Delivery House, the Drone disconnects from the Bus.
Step 6: The drone flies towards the Delivery House.
Step 7: Delivery of Package is done by drone at the Delivery House.

The process remains the same for train and tram. In addition, the drones can also interchange in the various combinations of public transport depending on the end location of delivery house and the connectivity of the public transport. In that case, the drone gets off at a changeover stop and then hops onto another public transport that goes in the direction of the delivery house. Figure 2 shows an example for a transfer from a bus to a tram.

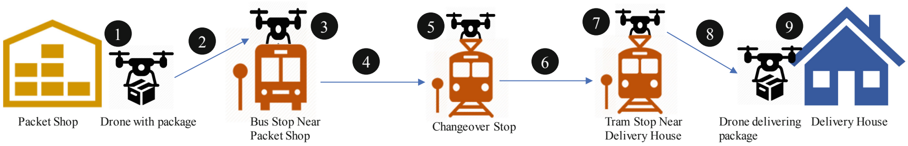


Fig. 2. Concept illustration of DDPT with a Bus-Tram changeover.

3 Methodology

3.1 Simulation Setup

Agent-based simulation is a common approach for modeling package delivery [17]. In order to compare the DDPT concept to traditional truck delivery, two separate agent-based models are created to represent the two delivery methods respectively. Moreover, two different delivery types are modelled: (1) intra-city delivery and (2) delivery from an online retailer. In the intra-city scenario, it is assumed that a package is dropped in a packet shop in the city and needs to be delivered to a customer in the same city, while in the delivery from an online retailed, the package needs to be delivered from the distribution center of the online retailer (located out of the city center) to a customer inside the city.

The models are developed using AnyLogic Software to model package deliveries in the western part of the city of Bremen, Germany. The locations of five DHL offices are used as Packet Shops (PS) and Amazon's regional distribution center in Winsen is considered to represent the online retailer. For the DDPT model, the routes and schedule of the local public transport are adopted. The average speeds of the public transports are set the same as stated by transport service providers: for bus 40 km/h, for tram 40 km/h and for train 120 km/h. The average speed of drone is set to 80 km/h [18]. For the truck delivery model, trucks perform milk runs to deliver packages running at an average speed of 40 km/h (aligned with the urban speed limit in Germany).

3.2 DDPT Models

The intra-city DDPT delivery model includes the following agents: Delivery House, Tram, Bus, Public Transport Stop and Packet Shop. Figure 3 shows the general model process flow. The packages are divided in the five Packet Shops according to the population density of their corresponding regions. Some packages need to be delivered to delivery houses from the same region as the Packet Shop where they were generated (intra-region), while other times they need to be delivered to the region of another Packet Shop (inter-region). On start-up two drones leave each Packet Shop, one carrying inter-region packages and the other – intra-region. 84% of packages weigh less than 4–5 kg [19], whereas a drone can carry up to 300 kg [20, 21] and thus it is assumed that a drone can carry 10 packages at once. Customized functions are created within the model to navigate the drone agent by calculating shortest distances between public transport stops, its current location and packages' destination locations. Customized functions are also created for the drone to hop onto the correct public transport in the right direction and find out the changeover stop; this is achieved by comparing collections of stops and the stop nearest to the delivery house.

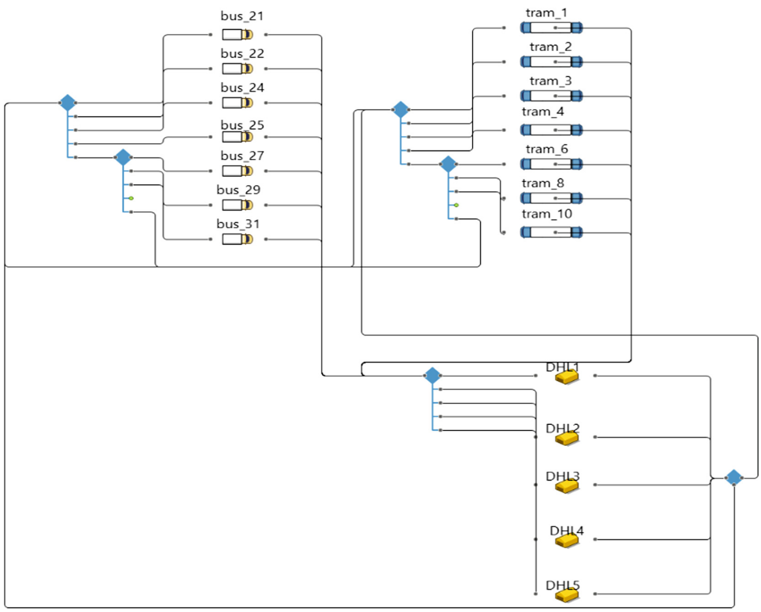


Fig. 3. Model process flow – DDPT: intra-city delivery.

The model for DDPT delivery from an online retailer is similar to the DDPT intra-city model with small modifications. The Packet Shop agents are replaced by one distribution center agent in Winsen. The packages are created at the distribution center and are assigned to one of the five Bremen regions depending on their delivery destination. There is one drone agent doing deliveries to each region. There are additional train agents, which are used by the drones to travel from Winsen central station to Bremen central station. Once, in Bremen central station, the drones continue using the bus and tram network.

3.3 Truck Delivery Models

The traditional truck delivery model includes Delivery House, Packet Shop and Truck agents for both intra-city and online-retailer deliveries. Similar to the DDPT intra-city model, the packages are divided into inter-region and intra-region packages based on population density. Inter-region deliveries can be performed on the same day, while inter-region deliveries can only be conducted on the next day, as we assume that it takes one day to deliver the packages to their corresponding packet shop. Each packet shop is assigned one truck performing a milk run inside the packet shop's region.

In the online-retailer truck delivery model, we assume that the delivery from the distribution center to the packet shop nearest to the package destination takes one day. The remaining delivery is the same as in the intra-city delivery model.

3.4 Key Performance Indicators (KPIs)

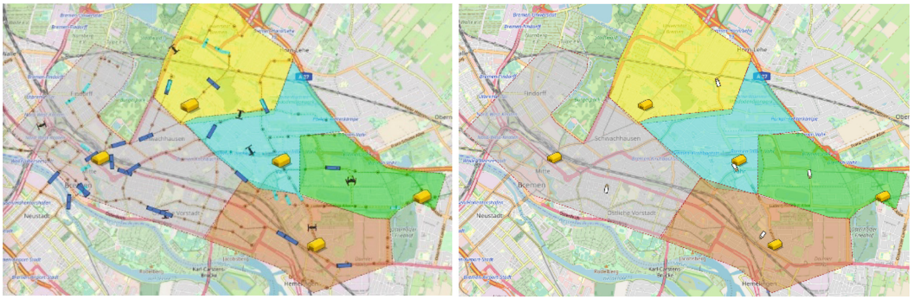
For comparison between DDPT and traditional truck delivery, four KPIs, focusing on operational and environmental aspects, are monitored in the simulation models: (1) Delivery Service Level, (2) Average Delivery Time, (3) CO_2 Emissions and (4) Utilization. Delivery service level is an important factor for delivery and is calculated by obtaining the percentage of total packages delivered from the total packages available. Delivery time is the time between customer's order generation and package delivery. The CO_2 emissions are used as a measure for the carbon footprint of the two delivery methods. They are calculated based on the distance travelled and the rate of CO_2 emissions for each vehicle: 162 g/km for trucks [22], 0.004 g/km for drones [23], 46 g/km for trams [24], 92 g/km for bus [24] and 9.7 g/km for trains [25]. The utilization of the drone or truck is calculated as the ratio of the time the drone or truck spends delivering packages to the total time of the drone or truck in the system.

4 Results and Discussion

4.1 Experiment Generation

The aim of the simulation is to compare DDPT and traditional truck delivery, which is done by changing two parameters. A total of nine simulation scenarios are created for each of the four simulation models by varying the number of packages and their inter-arrival times. The total number of packages is varied with the parameter values of: 70, 140 and 210. In addition, three different package inter-arrival times are used: no interval, random intervals and fixed intervals. No Interval represents the case when all packages are available for delivery at the start of the simulation run. Random and fixed intervals represent the cases when a new package is generated after a random or fixed interval respectively. Each experiment is iterated for 10 times.

Based on the public transport schedule in Bremen and the fact that drones can operate longer times independently, the DDPT simulation time is set to 8:00–20:00, whereas for truck delivery the standard working hours of 8:00–17:00 are used [26]. A screenshot presenting an overview of the simulation animation can be found in Fig. 4.



(a) DDPT Intra-city Delivery (b) Truck Intra-city Delivery

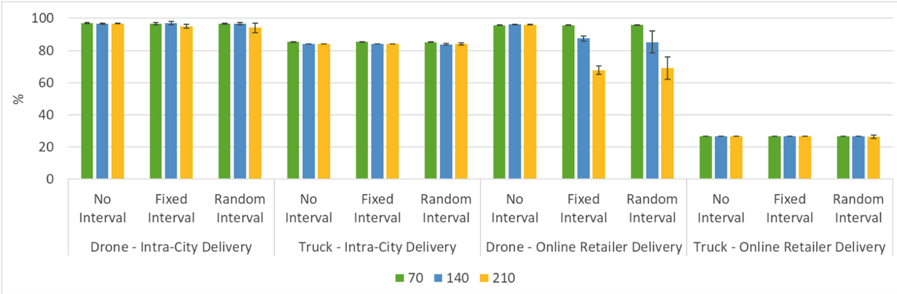
Fig. 4. Simulation experiment overview.

4.2 Experiment Results

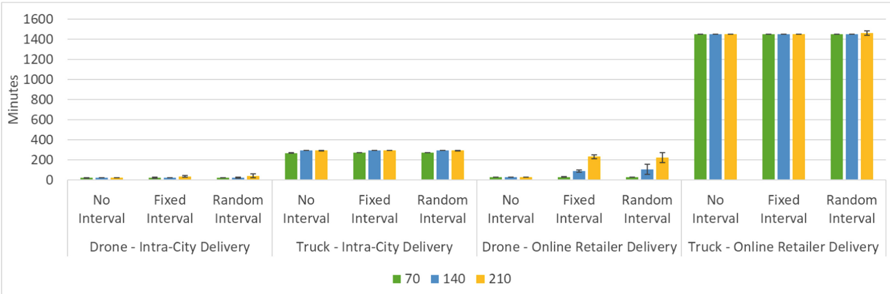
Figure 5 shows the results for the four KPIs obtained from the experiments by varying the two parameters: number of packages and inter-arrival times.

The service level for drones is higher than for trucks across both the intra-city and online retailer delivery (Fig. 5(a)). In the intra-city delivery, DDPT has the advantage of being able to deliver inter-region packages directly on the same day, while the truck delivery needs to wait for the inter-region packages first to be delivered to their corresponding Packet Shop, thus leading to lower service level for the truck delivery. For online-retailer delivery, all the packages that need to be delivered by truck take one day to reach from the distribution center to the Packet Shops in the city, which lowers the service level for truck delivery excessively. On the other hand, the DDPT drones, already located at the premises of the retailer, can leave the distribution center immediately, take the train to Bremen and deliver packages directly. By combining drone delivery with public transport, DDPT can fulfil more deliveries faster.

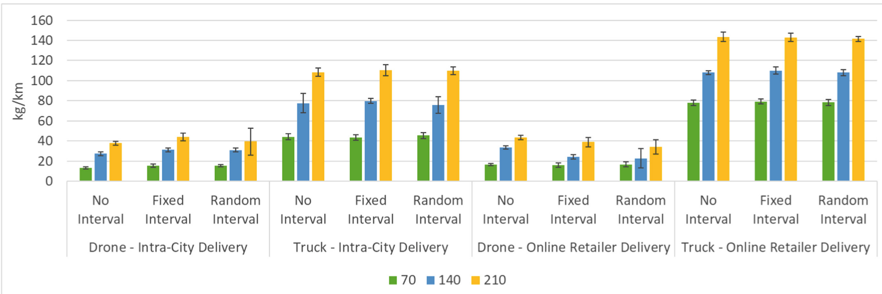
The delivery time for trucks is a lot higher than for drones across both the intra-city and online retailer delivery (Fig. 5(b)). This stems from the one-day delay in package delivery of inter-region packages and package delivery from retailer to Packet Shops. Drones are not impeded by the delay barriers which is the primary reason for the delivery time being much less.



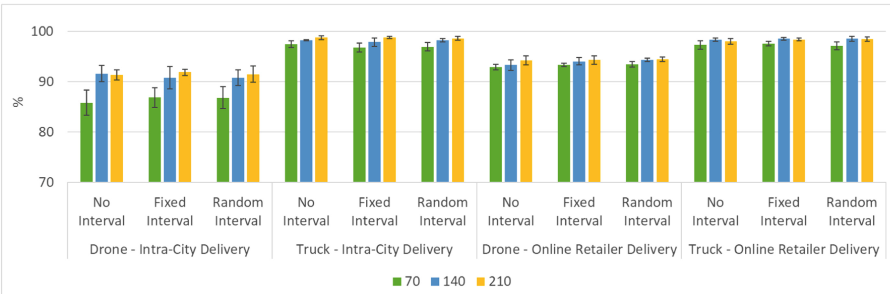
(a) Delivery Service Level



(b) Average Delivery Time



(c) CO2 Emissions



(d) Utilization

Fig. 5. KPIs simulation results.

CO_2 emissions in the truck delivery scenarios are greatly higher than emissions in the DDPT scenarios across both delivery types (Fig. 5(c)).

The results for utilization are different than the results for the other KPIs as the Truck Utilization is slightly higher than the drone utilization for both delivery types (Fig. 5(d)).

For all the experiments we see that as the number of packages increases, the Utilization, delivery time and CO_2 emissions increases, while the delivery service decreases.

When comparing the time parameters of each models, we see that the No Interval scenario has the highest delivery service level with the least delivery time. The better efficiency of no intervals is because all the packages arrive at the start of the day and the drones and trucks all leave together which reduces the overall utilization as less time is spent delivering.

After observing the experiment results, it can be implied that DDPT is better than truck delivery for package delivery. DDPT is much faster, has higher service levels, and emits 2–4 times less CO_2 emissions than truck delivery. One slight drawback of the DDPT concept is the fact that the utilization of drone is less than trucks. However, when looking at the values of average delivery time and service levels, it can be ignored.

5 Conclusion

An agent-based simulation study was conducted to investigate the viability of the DDPT concept when compared to traditional truck delivery. Our findings suggest that DDPT is viable and more efficient than truck delivery for intra-city deliveries as well as deliveries from online retailers. Delivery companies can achieve greater customer satisfaction through DDPT due to lower average delivery time and greater service levels. Delivery companies can also significantly reduce CO_2 emissions by adopting the concept of DDPT, reducing the deliveries' environmental impact. Thus, the main contribution of this paper is the development and evaluation of an innovative and novel concept that can help companies handle the last mile delivery challenges.

Even though, the simulation analysis and design are created based on realistic values and considerations, there are still certain limitations during the analysis and the design phase of the simulation. The DDPT models are generated based on futuristic assumptions (1) a drone can carry substantial weight and can charge itself on a charging pad installed on the roof of public transport, (2) legal regulations would allow drones to fly from a public transport stop to the final package destination and (3) advances in drone technology would make its operating costs comparable to the costs of traditional truck delivery. Delays, traffic problems in public transportation or actual customer order density have not been considered. Lastly, only 10 iterations are run per simulation scenario due to the limited time and computing capacity. Future research can further study the DDPT concept by comparing it with other existing delivery concepts including real-world traffic flows and package destination distributions.

To bring the DDPT concept to life, a pilot run can be conducted utilizing the public transportation network of a particular city such as Bremen where approximately 500–600

Drones can easily replace the conventional truck type of delivery. This prototype can be used to evaluate the installation of drone charging pads on public transportation, the connection of drone with the public transport, the way the customers receive packages from the drones, the pay load and weight capacity of the drones and the placement of drone at the public transportation stops. This would contribute to a better understanding of the challenges and issues that the DDPT concept can face in real life.

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