Design and Operation of an Urban Electric Courier Cargo Bike System

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Design and Operation of an Urban Electric Courier Cargo Bike System

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Abstract— **In recent years, the number of packages sent by Courier, Express and Parcel (CEP) services has increased significantly. Many people order products online expecting fast delivery and, additionally, more than every tenth product is sent back to the merchant. Delivery tours, which are mainly conducted by diesel trucks, account for increased traffic congestion and air pollution, especially in cities. Therefore, CEPs are required to create innovative solutions. In this paper, we present a project in Munich, Germany, where the last mile package delivery is carried out by a CEP company by cargo bikes and eBikes. To this end, two containers and one truck-trailer are placed in the city center which function as depot stations for the parcels to be delivered nearby. We analyze the delivery data, present an optimization scheme for finding suitable container locations, and simulate the routes conducted by cargo bikes for an average day. It can be concluded that the presented approach is a feasible solution for the package delivery in densely populated cities. The vehicle mileage covered by diesel trucks per day is significantly reduced from 180 km to 45 km, approximately.**

I. Introduction

Logistics is the management of the flow of goods between the point of origin and the point of consumption in order to meet requirements of customers and companies. In recent years, the logistics market has been growing, mostly due to a higher number of online purchases. Online commerce in Germany has raised its business volume in 2015 by 12% as compared to 2014, selling products with a total revenue of more than 40 billion Euros (46 billion Dollars) [1]. At the same time, more than every tenth product delivered to customers is sent back to the merchant [2]. These developments directly affect the Courier, Express and Parcel (CEP) industry: the German association of CEP services states that the number of parcels delivered raised from 1.7 billion in the year 2000 to more than 2.6 billion in 2013 [3].

This strong increase in the number of parcels delivered coincides with a rising awareness regarding traffic congestion and air pollution in big cities. Since 2008, the Clean Air for Europe Act prescribes limits on the concentration of air pollutants [4]. Several large cities, including the municipality of Munich, are fined due to constantly violating these air quality standards. At one monitoring station in Munich, the average measured NO_2 (nitrogen dioxide) pollution in 2015 was more than twice as high as the allowed judicial limit of $40\mu g/m^3$ [5]. At the same time, Munich has to cope with a high level of congestion, being the third most congested German city with an average of 30% extra travel time in 2016 according to the TomTom Traffic Index [6]. Delivery tours, especially in densely populated inner-city areas, account for increased traffic congestion and air pollution. According to [7], CEP companies use diesel-powered trucks for 98% of their tours. In Frankfurt, CEP companies cover more than 250 tours per day with an average length of 50 km and approximately 90 stops each. The emmissions on these tours add up to more than 1,500 kg NO_x (nitrogen oxide), 240 kg PM_{10} (particulate matter) and 1,100 t Tank-to-Wheel CO_2 per year [7]. This means that emmissions by CEP services in urban areas cannot be neglected and environmentally friendly yet cost-efficient solutions need to be found. In some areas, CEP services provide post stations, where customers living nearby can pick up their packages themselves. However, more than 90% of the German customers stated in an online survey that home delivery is important or very important to them [8]. This means that delivery tours covering the so-called last mile cannot be omitted completely.

The main goal of this paper is to present the recent developments of a project in Munich where package delivery is carried out by a CEP company by cargo bikes and eBikes. For the project, two containers and one truck-trailer are placed in a designated project area in the city center. These containers function as depots for the parcels to be delivered nearby. There are three main issues that this paper addresses:
1) Where can the containers be optimally placed?
2) Which routes are optimal for the cargo bikes and how many hours are needed to deliver the parcels?
3) What is the effect of the new solution considering the total vehicle mileage covered by diesel trucks?

The remainder of the paper is organized as follows: First of all, we are going to introduce studies related to our work in Section 2. In Section 3, we are going to present the considered project in more detail and show the project area as well as the results of the delivery data analysis. The methodology used henceforward can be seen in Figure 1. In Section 4, we depict plausible locations of the containers and routes in order to optimize delivery. Based on the spatial distribution of historic deliveries we are going to optimize the locations of the containers to be placed in a mathematical way. Unfortunately, the mathematically optimal solution is not always feasible with real world constraints. Narrow

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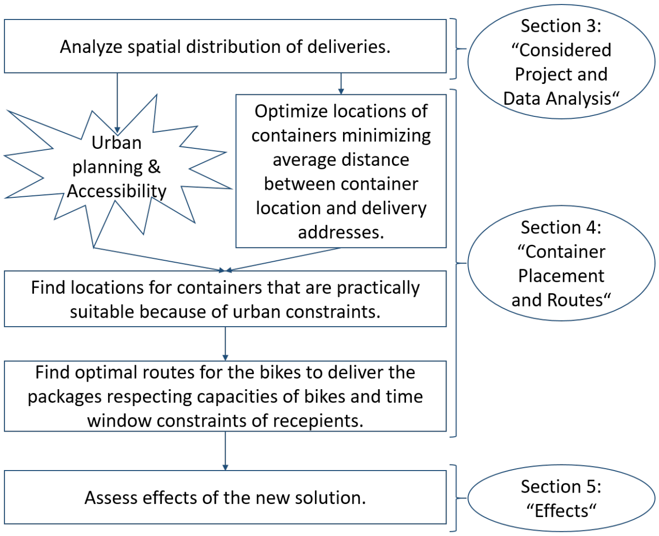


Fig. 1: Flowchart explaining the methodology.

streets and urban planning ideas impose restrictions on where the containers can be placed. Therefore, a new practically suitable solution needs to be found afterwards. We compare both the depot placement of the mathematical model and the practical locations regarding the distances that need to be covered by cargo bikes and calculate optimal delivery routes. Afterwards, the effects on total vehicle mileage covered by diesel trucks will be discussed. Finally, we give a short conclusion and outlook.

II. Related Work

Many researchers and practicioners have already analyzed logistics processes in cities – a good overview is given in [9]. While urban logistics consists of different segments, e.g. retail, consumer shopping trips and catering, CEP is one of the fastest-growing urban logistics businesses [9]. Due to increasing urbanization and the urge to reduce the ecological footprint in big cities, most studies focus on measuring and improving the environmental effects. An overview of initiatives for improving sustainability in urban freight is given by Quak [10]. Macroscopic studies describe the process of improving city logistics as a difficult task due to inflexible structures and the fact that many stakeholders take part in decision processes: companies, municipalities, residents and customers need to be satisfied [11], [12]. However, especially in Western European cities, many messengers use cycles, as they are faster and more reliable in congested urban environments [13]. According to a survey, even 80% of car messengers agree to the statement that using cargo bikes makes sense in their city [14]. Cities can play a major role in setting the right preconditions. For example, providing space for depots is essential, and pricing of city streets and parking lots also motivates CEP companies to use cycles [15]. It can be shown that using bikes instead of cars to deliver goods has a significant impact on the CO_2 footprint of logistics [13]. Conway et al. [16] compared cycle freight systems in London and Paris and drew conclusions for a possible implementation in Manhattan. According to the authors, last mile delivery can most likely be shifted to cleaner vehicles without increasing overall costs. Lenz et al. assume that cycle freight could have a share of one fourth among commercial inner city traffic [15]. The idea of placing containers in order to switch from a bigger truck to a lighter and more eco-friendly vehicle has been analyzed in the CityLog project [17]. Even though the transshipment area was not placed in the city center and vans instead of cargo bikes were used for the last mile delivery, both financial and ecological benefits were obtained.

TABLE I: Components of the project.

Component	Size	Availability in project
Container	36.0m^3	2 (in Northern project area)
Truck-trailer	14.0m^3	1 (in Southern project area)
eBike	2.2m^3	3 (1 at each depot location)
Cargo bike	1.5m^3	3 (1 at each depot location)

Our paper contributes to the current research by presenting an existing project in detail, where inner-city logistics is carried out using cargo bikes. The optimization approaches given for finding depot locations and routes can be transferred for planning similar concepts in other cities.

III. Considered Project and Data Analysis

The considered project runs for four years and aims to assess the possibilities of an ecological delivery system for CEP services. In the project area, two containers and one truck-trailer functioning as package depots are placed. At each depot location, one cargo bike with a capacity of 25-30 packages and one eBike with a capacity of 40-50 packages are used to deliver the parcels. Table I shows the components of the project. In this section, we are going to describe the characteristics of the project area and the results of the data analysis. The project area is located in the city center comprising parts of the districts Ludwigsvorstadt-Isarvorstadt and Sendling (see Figure 2). Both districts have a high population density of more than 100 inhabitants per hectare and are characterized by a high building density and narrow streets. Both districts together have around 55,000 households [18], but not all of them lie in the project area. As can be seen in Figure 2, the Northern part of the project area is served by a different package distribution center than the Southern part of the project area. Therefore, these two parts have to be treated separately. A closer look at the distribution of delivery addresses weighted by the number of packages delivered in the analyzed period of time is given in the zoomed detail of Figure 2. In the analyzed period of time (one year in total), more than 60,000 packages were delivered in the Northern project area (depicted as orange points in Figure 2) and more than 10,000 packages were delivered in the Southern project area (drawn as blue points in Figure 2). Throughout the project, two containers are located in the Northern (orange) area and one truck-trailer is located in the Southern (blue) area.

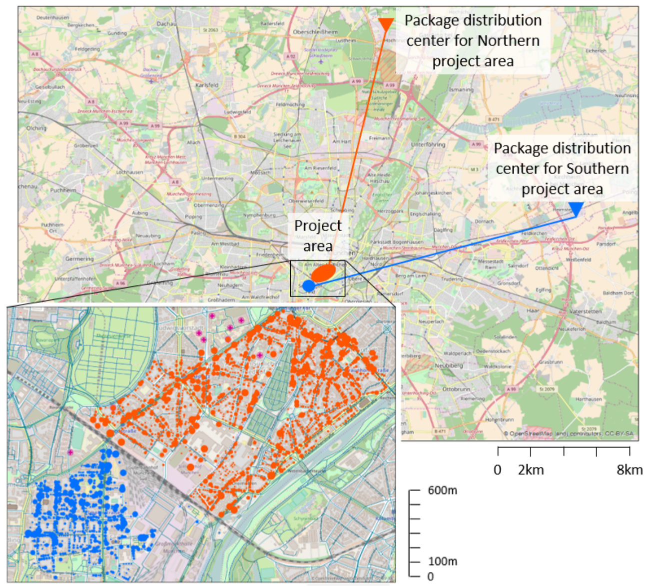
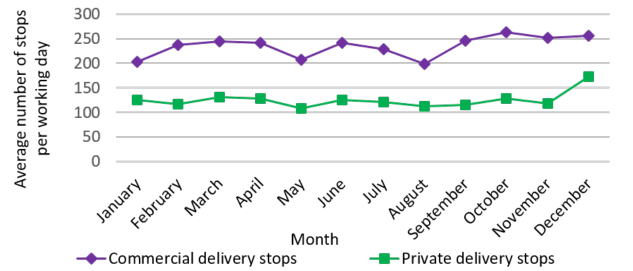
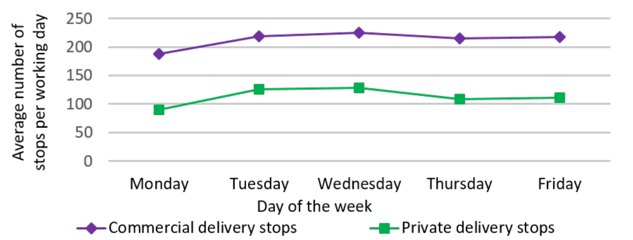


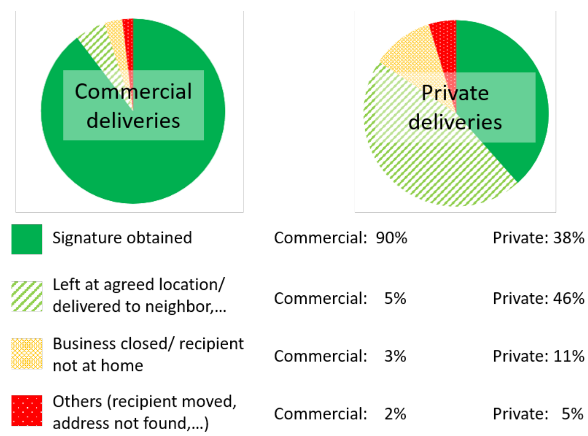
Fig. 2: Project area divided into two subareas where one is supplied by the distribution center in the North and one is supplied by the distribution center in the East of the city.



(a) Average number of stops in project area per day depending on the month.



(b) Average number of stops in project area per day depending on the day of the week.



(c) Success rates of commercial vs. private deliveries.

Fig. 3: Results of delivery data analysis.

The data considered for this study were provided by a CEP company and consist of delivery data (DD) of one year starting from August, 2015. The DD incorporates delivery or pick-up addresses, dates delivered, and additional constraints such as time windows. The set also consists of reasons for which a package might not have been accepted, for example, if no one was present at time of delivery. All addresses of the DD obtained belong to the project area, where the system is implemented. Within the analyzed period of time, more than 80,000 stops were made at customer addresses in the project area where packages needed to be delivered (delivery stops) or picked up (pick-up stops). Approximately 65% of the stops were commercial and 35% were with private customers. This means that 212 commercial stops and 113 private stops were made on an average day. More than 80% of the stops did not have to consider a special time window and only 1% of the stops were pick-up stops.

In Figure 3a, the distribution of delivery stops over the year is shown. The number of commercial delivery stops is always higher than the number of stops serving private customers. It can be seen that the average number of commercial delivery stops declines in May and August where there are many public and school holidays. During these months, many small businesses are closed and even bigger companies do less work than usually because many of their employees are on vacation. In contrast, delivery stops serving private customers are relatively constant throughout the year, with a significant rise in December when people order and send presents for Christmas and/or other holidays. In Figure 3b, we show the distribution of delivery stops over the week. In this figure, the lines representing commercial and private stops are almost parallel. Private delivery stops decline a bit more in the end of the week. One reason could be that most people order products online on the weekend, and these products are generally sent by the merchants on Mondays or Tuesdays and hence delivered to the recipients on Tuesdays or Wednesdays. Figure 3c shows the success rate of delivery attempts classified into delivery stops with commercial customers and stops with private customers. It can be seen, that the success rate of delivery attempts is much higher with commercial customers. This is easy to understand, as the packages are delivered during the day when shops and businesses are open but private recipients are not at home. However, many private delivery attempts can still be considered successful, as the parcels can be left at a location that was agreed upon or with a neighbor. All in all, around 5% of commercial delivery attempts and around 16% of private delivery attempts fail in the sense that the package could not be delivered.

IV. Container Placement and Routes

In this section a description about container placement and delivery routes will be given. As explained in the introductory section, in a first step, the location allocation problem is optimized mathematically. Afterwards, the solution is adapted to urban constraints such as accessibility and urban planning. Finally, the routing problem is optimized and compared for the different container locations.

Both the mathematical location allocation problem as well as the vehicle routing problem are approximated using the commercial geographic information system software ArcGIS Desktop by Esri [19]. The program contains an add-on called "network analyst" which can approximately solve most of the common combinatorial graph-theoretical problems including general location allocation and routing problems. The road network data were obtained from OpenStreetMap as explained in [20]. This means, that the considered distances were not approximated using the Euclidean distance but calculated using the well-known Dijkstra algorithm on the street network of Munich.

A. Container Placement

As explained in the previous section, the project area consists of two regions that have to be treated separately due to the fact that they are served by different package distribution centers (see Figure 2). Throughout the project, two containers are placed in the Northern project area and one truck-trailer is placed in the Southern area. To find the mathematically optimal locations for containers and trail truck, the problem is modeled as a p-Median Problem. The p-Median Problem is a classical combinatorial problem that has been studied by many researchers in the past decades. A good overview of different variants of the problem and heuristics can be found in [21]. It aims at choosing p locations out of a set of potential facility locations such that the sum of weighted distances between each demand point and its closest facility is minimized. The distances between each demand point and its closest facility location are weighted by the demand that is sent to this demand point. Speaking in terms of our project, the distance between a container location and a delivery address is weighted by the number of delivery stops at this very address in the DD. The delivery addresses given in the DD are quite well distributed and cover the whole project area. We thus consider the set of delivery addresses as the set of potential facility locations. As stated above, we use commercial software to approximately solve the problem. The problem belongs to the mathematical class of $\mathbb{NP}$-hard problems, which means that, most probably, it cannot be solved exactly in polynomial time. However, the solver in [19] finds good results that are nearly optimal in short time. It first calculates a distance matrix with the lengths of the shortest paths between each potential container location and each delivery address. The solver randomly creates initial solutions and subsequently uses an exchange heuristic by Teitz and Bart [22] to improve the initial solutions. Afterwards, several improved solutions are combined by using metaheuristics and, finally, a good approximate solution is returned. Results of the optimization are shown in Figure 4. The average distance between a delivery stop and its closest container is approximately 490 m in the Northern project area and 410 m in the Southern project area.

However, due to urban restrictions, size of container and accessibility, those particular areas could not be utilized. Therefore, further analysis was necessary in order to be able to obtain a practical solution while still trying to minimize average distance from theoretically obtained container placement to the historical delivery destination. Figure 4 depicts both the mathematically optimal and the practical solution found in collaboration with the municipality. Obviously, the average distance between any delivery stop and its closest container increases in the practical solution. It can be seen that the practical solution in the Northern project area is not too different from the optimal one, the average distance in this case increases from 490 meters to 570 meters. In the Southern project area, finding a practically suitable location was much more difficult. It is easy to see that the location considered as the practical solution is not close to being optimal in this case – consequently, the average distance increased from 410 meters to 840 meters. Please note that this distance information is approximate, as back premises and rear entrances are not always located correctly on the map. Even though the comparison of optimal and practical solution, especially in the Southern project area, is rather discouraging, urban restrictions have to be respected in order to obtain a solution that works in real world conditions.

In the following chapter, we are going to calculate routes for the delivery of parcels for both container placements and are going to compare the results regarding the length of routes and the time needed to deliver the parcels.

B. Routes

In order to find optimal routes for delivering the packages from the depot locations to the recipients, we partition the delivery addresses depending on their nearest depot location. For each set of delivery addresses, the problem of finding routes is mathematically modeled as a Pickup and Delivery Problem with Time Windows (PDPTW), one of the many variants of the Vehicle Routing Problem (VRP). For an overview of variants and heuristics for the VRP, see for example [23]. The PDPTW aims at finding optimal routes from depot locations to customers where packages are delivered or picked up while respecting the capacity limits of the vehicles and the time windows set by recipients and providers. The VRP solver in [19] first generates a start-to-destination cost matrix of the costs for the shortest path between all order and depot locations in the network. Based on this cost matrix, a first solution is created by placing the orders individually in the most appropriate route. The first solution is then optimized by rearranging

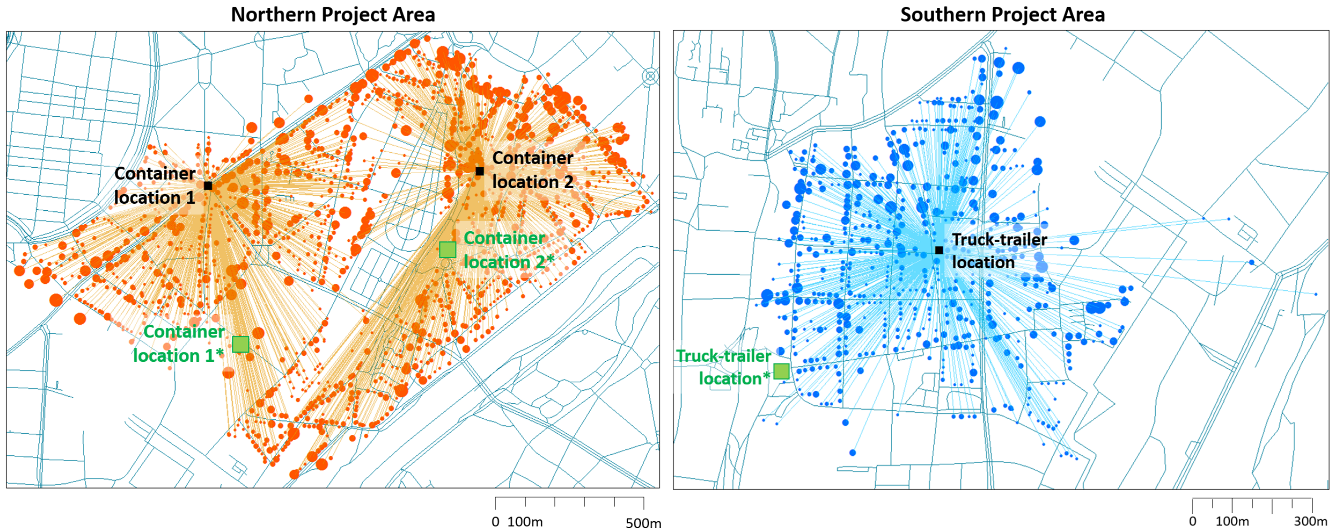


Fig. 4: Mathematically optimal (black) and practically suitable (green) solution for container locations in the two parts of the project area.

the orders of the individual routes. In addition, jobs are shifted and exchanged between routes. The heuristic used in this method is based on a taboo-search metaheuristic and is proprietary. However, it has been continuously developed over many years at Esri, and results in efficient routes.

The results of the route calculation are summarized in Table II. We assume an average speed of 15 km/h and a service time of two minutes at each delivery address plus one minute for each additional parcel delivered or picked up at the same address. On average, 1.3 parcels were delivered at each address. Additionally, we assume that a cargo bike can carry 30 and an eBike can carry 40 packages, on average. The actual capacity depends on the weight and size of the parcels, which are not available in the DD. The comparison of routes considering the optimal and the practical container placement shows that the differences regarding the time needed to deliver the parcels are small. Even in the Southern project area, where the optimal and the practical depot placement differ the most, the difference in average duration of the delivery routes is only 5 minutes. This means that even when dealing with less than optimal container locations, the resulting bike routes are still feasible.

The delivery routes given the actual container placement are shown on a map in Figure 5. In the Northern project area, two containers are placed. The delivery addresses served by Container 1^* are displayed as blue triangles. Container 1^* handles approximately 127 packages per day that are delivered by cargo bike and eBike on 4 different tours. The tours have an average length of 4.55 km and an average duration of 74 minutes. Container 2^* handles 168 parcels per day, the delivery addresses are depicted by green circles in Figure 5. Starting from Container 2^*, the eBike makes 2 tours delivering 80 packages and the cargo bike makes 3 tours, while managing to deliver the rest of the packages. The average distance traveled is 4.10 km and each tour takes about 75 minutes. In the Southern project area, we have simulated a day with 69 deliveries, where 7 of which were priority deliveries and 1 pickup. Therefore, the routes also consider the time window thresholds, while still systematically optimizing the tours. Figure 5 depicts two resulting routes, one carried out by cargo bike and one by eBike. The average distance traveled is approximately 5.25 km per tour while taking 1 hour and 25 minutes to accomplish. In reality, this would also be possible if one eBike alone handles the area but makes more than one tour.

This simulation demonstrates that the presented solution is feasible in a dense urban area as the total length of the tours to be driven every day is short enough for the cargo bikes to be charged only at night. It especially makes clear that even though the mathematically optimal container placement could not be realized, the project still offers a viable solution. Deliveries and pick-ups with a strict time-window can be integrated into the tours with priority to ensure that the level of service is not compromised. After finishing the delivery tours, the cargo bikes and eBikes are parked at a bike shop nearby, where the eBikes are charged. Because of the short distances, which are traveled between each delivery or pick-up, one cargo bike and one eBike at each container represent a realistic solution and replacement for the current system being implemented today.

V. EFFECTS

The approximate number and lengths of the delivery tours carried out by cargo bikes and eBikes are given in Table II and it can be seen that they are short enough to be covered every day. The solution can hence be implemented in urban areas without loss of delivery reliability. However, the solution is an improvement to the existing situation only if the environmental effects are positive. The presented

TABLE II: Overview of routing results for an average day.

Parcel depot (see Fig. 4)	Number of deliveries & pick-ups	Number of routes taken	Average length of routes	Average duration of routes
Optimal locations	*363 deliveries and 1 pick-up at 279 addresses*	*11*	*3.78 km*	*74 minutes*
Container location 1	133 deliveries at 99 addresses	4	4.01 km	74 minutes
Container location 2	162 deliveries at 122 addresses	5	3.50 km	71 minutes
Truck-trailer location	68 deliveries and 1 pick-up at 58 addresses	2	4.00 km	80 minutes
Practical locations	*363 deliveries and 1 pick-up at 279 addresses*	*11*	*4.47 km*	*76 minutes*
Container location 1*	127 deliveries at 95 addresses	4	4.55 km	74 minutes
Container location 2*	168 deliveries at 126 addresses	5	4.10 km	75 minutes
Truck-trailer location*	68 deliveries and 1 pick-up at 58 addresses	2	5.25 km	85 minutes

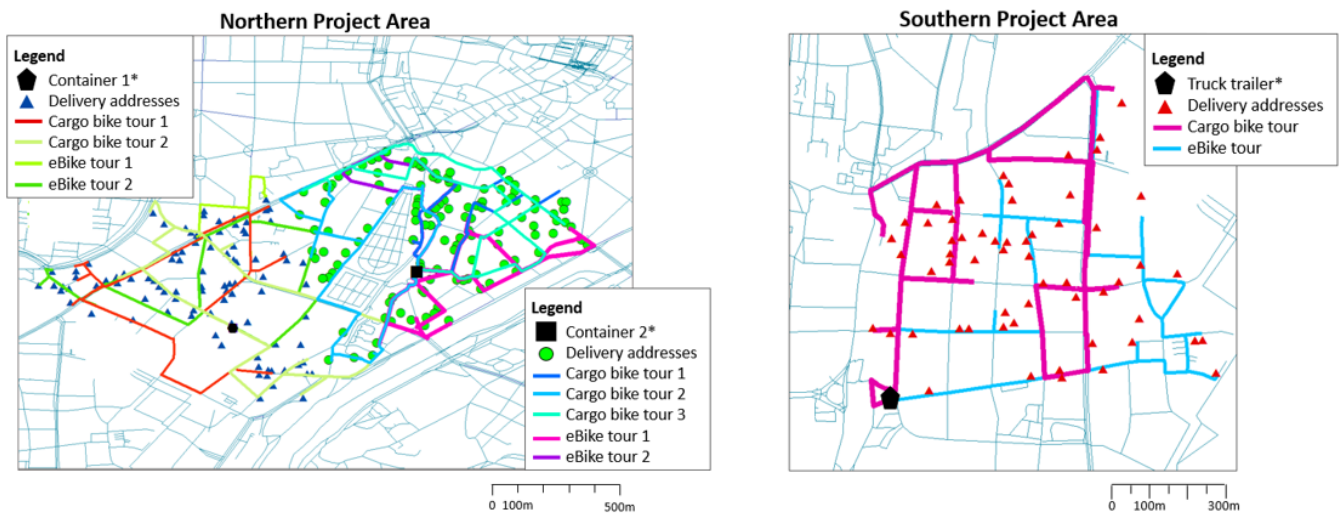


Fig. 5: Routes of the cargo bikes and eBikes.

solution with two containers and one truck-trailer replaces three delivery tours formerly performed by diesel trucks with a total distance of about 60 km each. Obviously, some distances still need to be covered by trucks. The two containers placed in the Northern project area are carried from the package distribution center in the North to the city center with just one truck. The truck leaves from the package distribution center in the morning, brings the first container to Container Loation 2* and then continues to Container Location 1* (see Figure 4). Here it stays with the second container until doing the same trip backwards in the evening. The total distance covered is 44 km every day. The truck-trailer placed in the Southern project area is carried from the package distribution center in the East of the city to its designated location by any package delivery truck heading that direction anyways. This means, that almost no extra distances need to be covered to place the truck-trailer there. In total, the number of km traveled by diesel trucks to deliver parcels in the project area reduces from around 180 km to around 45 km each day which is a significant decrease. Using the approximate formula for calculating local CO_2 emissions published by the U.S. Environmental Protection Agency [24], one liter of diesel burnt accounts for approximately 2.66 kg CO_2. Assuming that the usual delivery vehicles have a consumption of 10 l diesel per 100 km on these tours while the bigger truck transporting the two containers consumes 15 l diesel per 100 km, approximately 30 kg CO_2 are saved each day. This leads to a saving of 7.5 t CO_2 per year.

As the capacity of the containers is much higher than the average number of packages delivered in the considered areas, and the residents in the affected districts are excited about the project, the delivery regions are being further extended. 330 parcels are going to be delivered from Container Location 2* and around 180 packages from Container Location 1*. This means that instead of replacing three diesel-truck delivery tours of 60 km each, the CEP service is going to replace 5 delivery tours. Therefore, the reduction in km traveled by diesel trucks is going to increase from 135 km to 255 km daily. In order to achieve this goal, the fleet of cargo bikes and eBikes is increased. Furthermore, an electric truck shall be tested for carrying the containers to the center to further reduce emissions. All in all, this could lead to saving around 20 t in local CO_2 emissions every year.

Additionally, the presented solution has a smaller impact on traffic flow. Usually, the delivery trucks disturb the traffic flow by double parking in order to deliver the parcels, and doing u-turns in order to reach a delivery address faster [25]. The trucks used to carry the containers and truck-trailers mainly use the freeway and main roads to reach the center where they only need to stop once at each depot location. They indeed block about 2 parking spots each for the whole day, however, the depot locations were chosen such that the impact on residents is minimized. Bicycles are more convenient in urban traffic and they especially need less space to park in front of the customer's addresses. Therefore, they have an additional advantage compared to the current delivery and other solutions using delivery vans such as the CityLog project [17].

VI. Conclusion and Outlook

In this paper we presented an approach for the design and operation of an urban logistics system for CEP services. We explained how optimal container locations and routes for such a system can be found. It was shown that the delivery from depot containers to customers with cargo bikes is a reasonable alternative considering the average distances covered by bike, even though the practical container locations have to fulfill many constraints and are hence not mathematically optimal. Furthermore, the analyzed system leads to a significant reduction in kilometers driven by diesel trucks while still assuring on-time delivery. Due to the positive experiences with residents and customers, the project area will be further extended. It is conceivable that the considered system is implemented in other cities as well, and the presented optimization approaches are transferable. The system is especially suitable for cities with a high population density but wider streets.

It is arguable if the presented solution using container depots is feasible for the large-scale problem considering more CEP services because suitable locations for the depots are hard to find in densely populated city centers. Nevertheless, in a next step, we are going to consider the number of packages delivered by all CEP services together and want to analyze the possibility of shared container hubs, for example. Renting storage rooms and using them as depots could also be an option, but implies more effort for handling the packages. Therefore, another focus lies on the financial effects of the presented concept and the satisfaction of the deliverers with the new system.

Acknowledgements

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