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ORIGINAL PAPER

Simulation of B2C e-commerce distribution in Antwerp using cargo bikes and delivery points

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Abstract

Purpose The growth of e-commerce is accompanied by an increasing distribution of parcels in cities resulting in externalities like traffic congestion or emissions. As a consequence, different delivery concepts like bike deliveries or delivery points have been suggested. Naturally, companies will only accept these changes, if they do not result in higher costs. However, it is difficult to predict the impact of a certain delivery concept in a certain city. This leads to the research question, how different delivery scenarios for a certain area can be assessed and compared, especially if some of them have not been implemented.

Methods Using a case study, we demonstrate how the effects of different delivery concepts can be quantified with the help of a simulation study. We take care to accurately model the delivery processes and utilise a real-world dataset and realistic cost values. On the basis of these inputs, we simulate and analyse the current state-of-the-practice in the distribution of e-commerce goods in Antwerp and compare it to possible `what-if' scenarios.

Results The results highlight that the investigated delivery concepts can benefit either the companies or the quality of life in the city. Operational costs of companies can be reduced by stimulating customer self-pick-up, while externalities decrease with the implementation of a cargo bike distribution system.

Conclusions We demonstrate that both operational and external costs can be minimised, if involved stakeholders from industry and the public look for sustainable delivery solution jointly.

Keywords B2C e-commerce · city logistics · simulation · vehicle routing

1 Introduction

The distribution of goods plays a major role in enabling economic and social activities in cities. Especially with the rise of e-commerce shopping, an increasing number of people order products online and have them delivered at home. Nowadays, this B2C distribution of parcels accounts for 56% of all shipments in e-commerce [1] and, thus, B2C e-commerce has been identified as a major challenge in the urban logistics literature [2–6]. The growth in parcel transportation is accompanied by an increase in externalities like emissions, which affect the quality of urban life in a negative way. This trade-off between the need to distribute goods and the liveability of cities can be analysed from the perspective of different stakeholders.

From the perspective of a logistic service provider (LSP), there is a growing pressure from the e-commerce sector to keep prices for shipping and handling as low as possible. This competition for lower prices in the last-mile delivery has pushed LSPs to cut their operational costs to the minimum. In other words, the last mile delivery of parcels is a purely cost-driven business which discourages the development of more sustainable distribution solutions [7]. Therefore, standard deliveries are still vastly based on traditional distribution networks, using vehicles such as diesel vans instead of eco-friendly alternatives.

In contrast, local authorities and inhabitants strive for cities with a high quality of life, including efficient transportation and traffic systems without too much congestion, noise and emissions. These negative effects of distribution in urban

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areas are expressed by external cost metrics. In increasingly complex cities, external costs can only be minimised by promoting distribution systems that are sustainable and efficient.

Thus, there is a clash of interests between different stakeholders when it comes to today's parcel distribution systems. In order to compromise and put sustainable and efficient delivery solutions into practice, stakeholders need to be able to compare possible options. However, there are usually no numbers available to compare the state-of-the-art with other `what-if' scenarios, and if so, they are rough estimations at best. This situation makes it difficult to argue in favour of one delivery solution over another.

In this paper, we demonstrate how this problem can be addressed with the help of a simulation approach. This approach allows us a realistic assessment of the current situation and possible alternatives. Using the city of Antwerp as a case study, we analyse the cost structure of `what-if' scenarios for B2C parcel distribution and compare them with the current situation. In the first alternative scenario, customers can choose to pick-up their parcels from delivery points (DP) instead of being delivered at home. In the second alternative scenario, an LSP implement a delivery system via cargo-carrying capable bikes. Parcels are delivered by vans to DPs in the city centre, from where they are distributed to the customers on bike routes. With this study, we aim to answer the following research question: *How do different designs in urban parcel distribution affect the operational and external costs, and is there a way to minimise both and, thus, satisfy all stakeholders?*

This work is structured as follows. In Section 2 we introduce the basic concepts and state-of-the-art research in urban parcel distribution. In Section 3 and Section 4 we motivate and explain the design of our simulation study. The results are described in Section 5, followed by a discussion in Section 6.

2 Urban logistics and e-commerce deliveries

Most products that are bought remotely are shipped as parcels in trucks or vans and brought to people's doorstep, a concept which we call in the following '*traditional home deliveries*'. The advancing development of e-commerce has changed the landscape of home deliveries profoundly. Instead of going to physical stores, more and more people purchase products online. These changes in shopping behaviour have an effect on the mobility in cities, with some shopping trips being substituted by parcel transportation. However, the precise impact of this substitution on the overall traffic volume is not clear [6, 8]. For instance, in a survey-based study, the author found that the e-commerce-related increase in freight transport was higher than the corresponding decrease in customer trips [9]. In general, the effects of e-commerce on transport are still uncertain and have been the focus of research during the last years [3, 4, 10]. Browne [11] argues that the traffic volume due to home deliveries is affected by several factors, such as the customer behaviour, the consolidation of deliveries and the number of returned goods. Mokhtarian [12] agrees that the impact of e-commerce on transport depends on both, changes in shopping behaviour as well as changes in the distribution system.

These findings lead to the question `What kind of distribution system is an adequate response to changes in shopping behaviour?'. Possible alternatives to traditional home deliveries have been widely studied recently, specifically for the e-groceries market [13] and in the context of so-called urban distribution centres [14].

The concept of *self-pick-up* involves the customer in the delivery process. Instead of delivering parcels to the customer, the parcels are delivered to *delivery points (DP)*, from where the customer collects their order. DPs are spreading rapidly across Europe and have been the focus of recent research. Early contributions focused on the accessibility of delivery point networks [15–17]. Durand and Gonzalez-Feliu [18] compared self-pick-up to traditional home deliveries and found that an `all delivery point' scenario would be the most beneficial in terms of total kilometres driven with vans and trucks. Accordingly, several studies agree that delivery points have the potential to reduce the travel time of freight vehicles as well as that of customers [4, 10, 19].

The success of DPs can also be attributed to the possibility of *failed deliveries*. A home delivery can fail, if the customer or neighbours are not at home at the time of delivery. In this case, the parcel needs to be shipped to a nearby service point or DP, which leads to a substantial extra delivery effort. For instance, in the UK the additional costs due to failed deliveries amount to more than one billion dollars per year [20].

Cargo bikes present a more recently-developed distribution solution, which is especially focused on the reduction of environmental impacts. The idea of cargo bikes is to avoid the dense car traffic in urban areas, and instead deliver parcels on bike routes, which are more flexible and cause less externalities. In [31] the authors found that home delivery via cargo bikes causes significantly fewer external effects than conventional shopping, traditional home delivery via vans and deliveries via delivery points. Results of a pilot study in London confirmed that last-mile delivery operations can be cheaper without adding relevant costs to the distribution by combining urban distribution centres and bike deliveries [32]. Similarly, Maes & Vanelslander [33] concluded that delivery costs of vans and bikes are almost comparable. The authors identified the higher speed on highways and the relatively low load capacity of cargo bikes as major barriers to the implementation of a B2C bike distribution system. In contrast to that, a cost calculation based on data from Belgian companies showed a decrease in overall costs by up to 45% [34].

In conclusion, solutions for e-commerce transport have received wide attention. However, their precise effects on operational and external costs are not always clear and results are usually based on analytical estimations or pilot results. Moreover, most studies are limited to one or two of the concepts described above, as presented in Table 1. The goal of this paper is to conduct a comprehensive quantitative simulation study which analyses the benefits and shortcomings of all those different concepts in the context of B2C distribution in the city of Antwerp.

3 Simulation

In this paper, we explore the potential benefits and shortcomings of different urban distribution strategies in the B2C delivery sector. Our methodology is hereby based on the concept of simulation. The main reason for this choice is that conducting a real-life case study is intractable in this case due to its prohibitive costs (e.g., in order to study the impact of bike-deliveries, we would need to use and acquire delivery bikes). Moreover, the use of a simulation allows us to (1) generate a multitude of virtual case-and (2) collect sufficient data for an analysis. The most important benefits of this approach are its feasibility, scalability and flexibility. Experiments can be set up rather quickly and in a short amount of time, even though they require a careful planning of the design. Once the implementation of the experimental design is completed, any amount of data can be generated for any size and layout of the simulated entity, e.g., for a neighbourhood, for a city, or for a whole country. Finally, input parameters e.g., cost values or locations, can be changed, and the sensitivity of these changes can be incorporated in the analysis. Simulation has successfully been used before in urban logistics [35–39].

There are some limitations to simulation studies, which have to be considered carefully. Most importantly, the constructed simulation model is an abstraction of reality, and care must be taken that no important features or attributes are lost in this abstraction process. In other words, the practical implications of the results are only as meaningful as the simulation model correctly reflects reality. Secondly, a simulation requires accurate input data to model the considered processes precisely, e.g., travel times of distribution routes or distances between two locations. We will take care to explain and motivate our model assumptions in Section 4.

Finally, the evaluation of a simulation study is based on a statistical analysis. A simulation usually captures the dynamics of complex systems. In the context of logistics, the delivery locations will change day-by-day, and so will the delivery routes. To account for these dynamics and still derive a general idea of how the system behaves, different simulation runs have to be executed. In this context, it is important to choose a sufficient number of simulation runs and a sufficient length of each run. The target metrics will then be computed as the average over all simulation runs.

4 A simulation study for B2C e-commerce distribution in Antwerp

The goal of this study is to analyse the cost structure of state-of-the-art B2C distribution in Antwerp and compare it to alternative scenarios. On the basis of the presented findings in the literature, our hypothesis is that the implementation of delivery systems based on DPs and cargo bikes can present

Table 1 Overview about studies in urban logistics and last-mile distribution on e-commerce

	Context	Methodology		Considered characteristics				Considered costs	
		Simulation	Analytical	Failed Deliveries	Self- Pick Up	Cargo Bikes	DPs	Internal costs	External costs
[21]	Italy	•			•				
[22]	Korea		•			•	•	•	•
[23]	Italy	•					•	•	
[24]	Netherlands	•						•	
[25]	China	•							
[10]	USA	•			•		•		
[26]	China	•				•	•	•	
[27]	Belgium		•	•		•		•	
[28]	N.A.		•				•	•	•
[29]	France	•			•		•		
[4]	UK		•	•	•				
[30]	Finland	•					•	•	

a reasonable alternative in urban logistics. Moreover, we will analyse the effect of three parameters on the cost structure of B2C distribution: (1) the demand density, (2) the percentage of self-pick-up customers and the (3) congestion within the city. In the following, we first describe the current delivery process in Antwerp, and then we present how we transform this real-world activities into a simulation framework.

4.1 The distribution process in Antwerp

The simulation study is based upon the daily distribution activities of a B2C logistic service provider (LSP) in Belgium. The current situation was studied by interviews with drivers and managers as well as by a field study where one of the authors accompanied a driver on a typical delivery day. We further obtained two datasets from the LSP, one including the delivery destinations over a period of three months, and a second one comprising the aggregated travel times and distances per driver per day.

The LSP's delivery operation is executed via medium-sized diesel vans with an assumed maximum capacity of about 300 parcels. A typical delivery day of a driver starts around 6:00 am at the distribution centre at the fringe of the city of Antwerp. He loads the parcels and plans the route, before driving into the city and starting the distribution. Each driver performs a distribution tour alone and visits 99 customers on average. For each customer on the tour, the driver gets at close proximity, parks, fetches the parcel from the van and delivers it at the customer's door. If the customer or any neighbours are not at home, the respective parcel is delivered to a nearby DP, from where the customer can pick it up. We computed from the dataset that the average duration per stop, including parking, fetching and delivering the parcel, amounts to 2.5 min. The delivery routes are planned by the driver, without any computer assistance. After all parcels have been delivered, the driver returns to the distribution centre for a debriefing. We estimated from the dataset that a driver typically spends 6 h for delivering activities in the city, and two hours for the remaining activities before and after each tour (loading, preparation, driving into the city and returning to the distribution centre, debriefing). Note that we cannot derive the actual delivery routes nor the specific durations of tours from the data, and we will derive those values by simulating the distribution process on the basis of the above observations.

4.2 Simulation of the distribution process

The simulation of delivery routes is done in two steps. Firstly, we generate demand, by defining the location of customers. Secondly, we compute routes to deliver the parcels to customers.

4.2.1 Generation of demand

We generate customer demand on the basis of the real-world dataset. The dataset contains the locations of all deliveries in Antwerp over a period of three months. We use this dataset to compute the spatial distribution of parcel demand.

First, we divide the urban area of Antwerp (about 4 km^2) into a grid of 100 smaller districts (400 m^2 each) and compute for each district the average number of demands per day. This resolution is a compromise between the accuracy of a demand location (size of a district) and the accuracy of the estimated demand quantity (data points per district). Fig. 1 visualises the resulting distribution where the demand is especially high in the residential areas in the centre and in the southwest of the city. In each simulation run we define the total demand in the city, e.g., 100 parcels per day, and distribute this total demand among the districts (e.g., if 2% of the demand in the dataset falls in district *A*, the probability of assigning one particular demand to *A* is also 2%). The precise demand location within each district is chosen randomly. An example of this process from a spatial demand distribution to specific customer

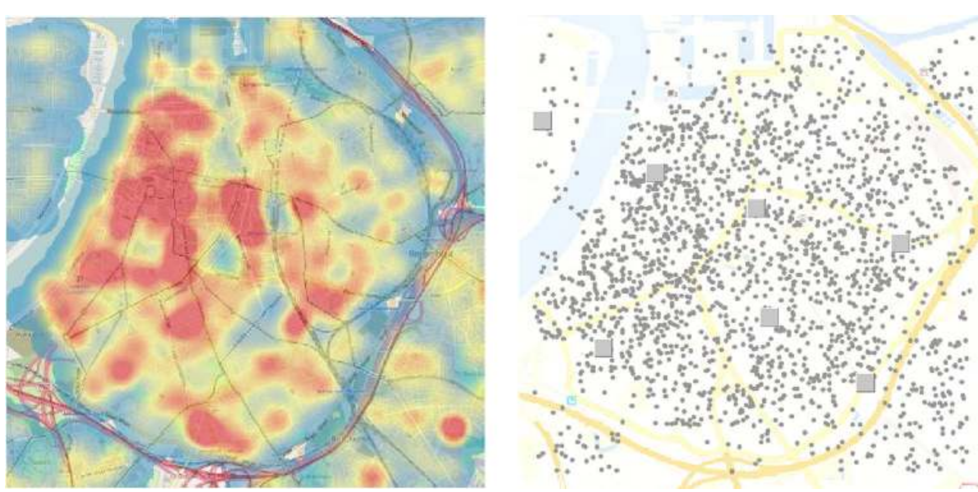

Fig. 1 Generation of customer locations and DPs (right) on the basis of actual demand (left, Source: [40])

locations is presented in Fig. 1. Since the final location is determined randomly, it might not represent a valid address, e.g., the location might be a point in the river. These invalid customer locations are reassigned to the nearest valid address when generating the routes in the next step. Finally, we locate seven DPs in our simulation model at the actual locations of service points of a large LSP in Antwerp.

4.2.2 Computation of delivery routes

After the generation of the customer locations, we compute the travel time between each pair of customers and DPs with Open Street Maps. Open Streets Maps is a freely available web service to obtain trip durations between two locations based on the real street network. Also, it assigns our randomly chosen locations to the nearest available address. The distances between each pair of destinations is computed with the Manhattan distance, which is one of the most accurate estimators of road distances in inner cities (see for instance [41]). On the basis of these values, we compute delivery routes. The length of one delivery route is hereby constrained by the working hours of the driver and the capacity of the vehicle. We computed from the dataset that a driver spends on average 6 h delivering parcels in the city. We use this time horizon as a constraint. Before every simulation run we conduct a pre-test and determine how many parcels can be delivered within 6 h with the current parameters. The length and number of required delivery routes then follow from the results. For instance, if the customer density is higher, it takes less time to drive from customer to customer, and therefore, more customers can be visited on one route. Each route also visits a near DP from time to time, to return failed deliveries.

The planning of delivery routes resembles the popular Vehicle Routing Problem (VRP) in the field of combinatorial optimisation. Thus, we can compute cost-efficient delivery routes by utilising one of the many heuristics developed to solve the VRP [42, 43]. Because of its low implementation complexity and fast processing time, we use the Clark-Wright Savings algorithm [44]. Even though it does not compute optimal routes, i.e., routes that have minimal travel time, the gap to the optimal solution is usually relatively small. Given that routes, in reality, are usually not optimal either, e.g., because drivers rely on intuition or companies do not use a planning instrument, this should represent a good estimation of actual delivery routes. In the case studies below we need to compute routes for several thousand customers in a feasible time and we, thus, speed up the route computation with the following idea. Since customers in the same neighbourhood are usually delivered on the same delivery route, we assign customers to spatial clusters. These clusters are computed for each delivery day in such a way that they do not exceed the maximum number of customers per route (i.e., the number of customers that can be visited within 6 h). Each cluster of customers as well as the nearest DP is then delivered by a separate tour which is computed with the Clark-Wright Savings algorithm. An example of this clustering approach is visualised in Fig. 3.

We make the following assumptions when computing the routes:

(1) Open Street Maps computes the duration of a trip under the assumption of free flow. Thereby, it ignores traffic-related delays (e.g., traffic jams during rush hours). To account for traffic-related delays, we need to apply a factor for congestion. Since the choice of this factor might change the results, we conduct a sensitivity analysis to investigate the impact of congestion on delivery costs. More concretely, we consider free-flow (about 26 km/h on average), minor congestion (about 17 km/h), and heavy congestion (about 13 km/h). Since, for instance, in French cities the average car speed was estimated to be around 16 m/h [45], we assume that this value represents a good estimate of the actual traffic situation in Antwerp (even though in big cities such as London the average speed can drop as low as 8 km/h [46]). In reality, congestion is also dependent on the specific time and the specific road, but since such accurate data is not available, we assume the same congestion factor for the whole day.

(2) The simulation focuses on the distribution of parcels within the city, and models the activities before and after as fixed events. Therefore, the computed delivery routes start and end at motorway exits at the city border. We assume that the routing from the distribution centre to the city and back is the same for every delivery route, and model this stem mileage as a fixed cost per route, as explained in Section 4.3.

(3) All parcels have the same priority, i.e., it is not necessary to fulfil certain demands before others.

(4) Finally, we derived from the dataset that about 11% of the deliveries fail, i.e., both the customer and their neighbours are not at home at the time of delivery. These customers are chosen randomly, and their parcels are delivered to the nearest DPs from where they need to pick it up. Likewise, a pre-defined percentage of customers are self-pick-up customers. Those customers chose not to be delivered at home, and are therefore not included in the delivery routes. Instead, they have to go to the nearest DP. These model assumptions are visualised in Fig. 2.

4.3 Analysis of delivery costs

The computed delivery routes reflect the B2C delivery activities of one day, and we are interested in the resulting

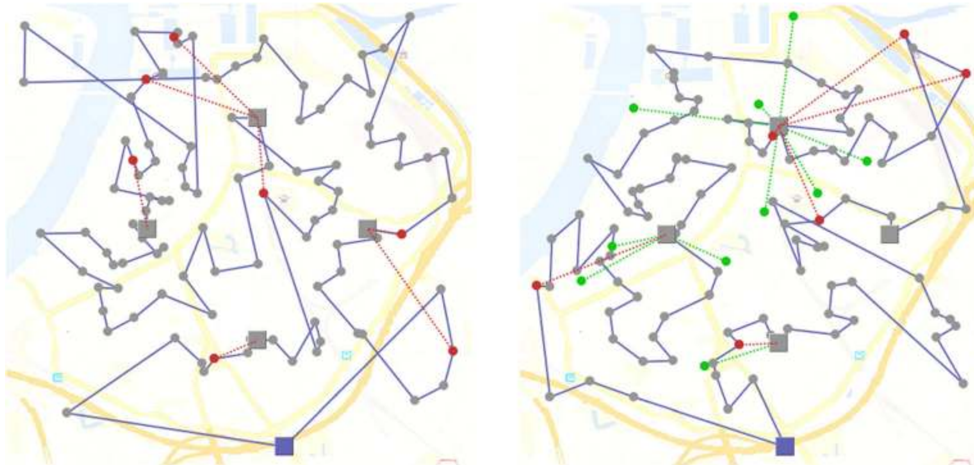

Fig. 2 Simulated delivery route. Starting from the highway exit, all customers (dots) and DPs (squares) are visited once. Red dots denote failed deliveries. (right) Green dots indicate self-pick-up customers

operational and external costs. Since the location of demand is stochastic, the distribution routes of every simulated day are slightly different. To account for this variability, we simulate 100 individual days and average the costs over all days. The results between different simulated days are relatively stable with a low variance. With 100 datapoints, the 95% confidence interval for estimated external costs and operational costs is in all experiments less than 1% around the average (i.e., if the average is 100, then the 95% confidence interval is at most [99,101]).

As operational costs, we consider all variable costs related to the distribution activities in the city. All in all, we can distinguish between the labour costs for the carriers, the costs for using the vehicles, and the costs for using DPs.

The labour costs are computed on the basis of the required working hours, assuming one driver per vehicle. Loading the vehicle in the morning, preparing the tour, driving from the distribution centre to the city, returning to the distribution centre and debriefing in the evening requires 2 h per route, as estimated from the dataset. Within the city, the travel time in the city is obtained from the results of the simulation and the average time for a stop at a customer amounts to 2.5 min, including parking and handing over the parcel.

For the vehicles we consider variable costs of €0.18 / km, and neglect fixed costs since we assume that sufficient vehicles are available. The total number of kilometres driven is determined by the delivery routes in the city, as well as 10 km for trips from and back to the distribution centre. More precisely, let D denote the length of all delivery routes within the city in km, T the respective travel time in minutes, R the number of routes, and S the number of deliveries. Then the operational costs O are computed as $O = 0.30(T + 2.5S + 120R) + 0.18(D + 10R)$. Hereby, T, D and R are obtained as results from the simulation. A complete overview of all parameters used in simulation is given in Table 2.

As external costs, we consider the externalities caused either by delivery vans or by customer trips to a DP. Since the exact quantification of corresponding costs is still under discussion in the literature, we chose the externalities that have received the most attention, namely emission, noise and congestion. We chose corresponding cost values on the basis of calculations in [48]. Hereby, we need to consider the modal choice of customers when picking up their parcel. If a customer uses their car, their trip contributes to the delivery-related external costs. On the other hand, walking or biking does not result in externalities. Intuitively, the greater the distance between a customer and the nearest DP, the more likely it is that he will use a car. Findings of modal choices in Belgium confirm this intuition and we extract the following estimates for

Table 2 Overview of parameters to determine operational and external costs. Source: [47]

General parameters	
Labour costs for drivers	€0.30 / minute
Average time per delivery	2.5 min
Probability that a delivery fails	11%
Parameters for delivery tours by van	
Driving speed in the city	17 km / h
Capacity limit of a van	300 parcels
Operational costs of delivery van	€0.18 / km
Stem mileage per delivery tour	10 km
Time limit for a delivery tour within the city	6 h
Time required for activities before and after a delivery tour	2 h
Parameter for delivery tours by cargo bikes	
Driving speed in the city	12 km / h
Capacity limit	10 parcels
Parameters to compute external costs (only applies to distance driven by cars and vans)	
Emissions	€0.11 / km
Noise	€0.05 / km
Congestion	€0.49 / km

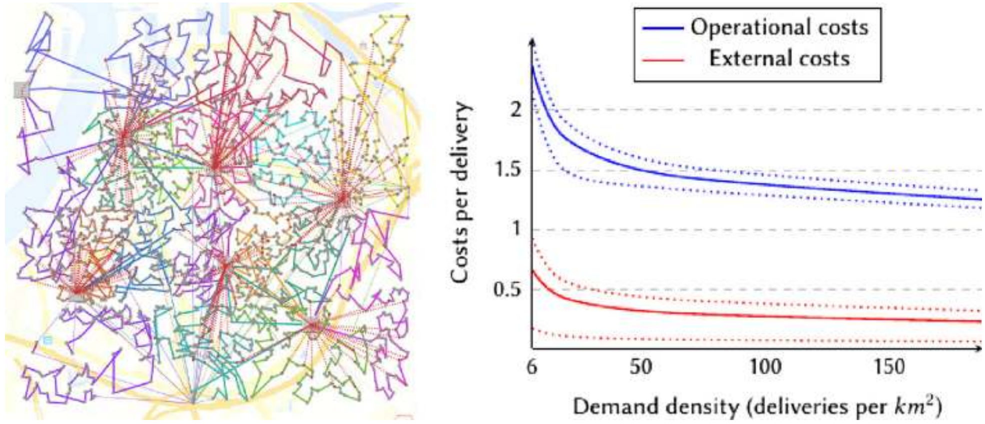

Fig. 3 (left) Routes for high demand are computed by clustering the customers, and serving each cluster by a separate tour, as indicated by the different colours. (right) Costs per delivery as a function of demand, the dotted lines below and above present free-flow (26 km/h) and heavy congestion (13 km/h), respectively

our study: If the distance between customer and DP is smaller than 200 m, the customer will use their car in 10% of the cases.

If it is between 200 and 500 m, the likelihood of car usage increases to 30%, for 500 to 1000 m to 50%, and for distances of more than 1000 m, the customer will take the car in 70% of the cases. Let P denote the distance that customers travel to DPs with their car to pick-up parcels. Then the external costs E are computed as $E = (0, 11 + 0, 05 + 0, 49)(P + D + 10R)$ [47].

5 Results

We analyse the cost structure of four B2C distribution scenarios in Antwerp. In the first experiment, we analyse the state-of-the-practice of the distribution system of e-commerce in Antwerp (home deliveries by vans) as a function of the demand density. The results of this analysis constitute the baseline, which we will compare to the other hypothetical alternatives. In the first alternative, we investigate the effect of customer self-pick-up from DPs. In the second alternative, we study the possible implementation of a bike delivery system. Finally, we combine the ideas of bike delivery and self-pick up in a hybrid system. For each of these experiments, we compute the operational and external costs per delivery, and conduct a sensitivity analysis for the most impactful parameters.

5.1 Simulation of home deliveries by vans

The B2C parcel distribution market in Belgium is composed of one large carrier and several smaller ones. The large LSP is estimated to deliver about 2000 parcels per day in the centre of Antwerp, whereas the smaller ones deliver about 100 parcels. Depending on this demand level, LSP have different cost structures. If the routes are planned well, we should observe an economy-of-scales effect. We compute the costs per delivery for varying demand and also conduct a sensitivity analysis to determine the impact of congestion on costs. The setup and the results are visualized in Fig. 3.

All in all, the congestion factor seems to have only a minor impact on the operational costs, the results for free-flow and heavy congestion are within a 10% margin around the results for slight congestion. This relatively low sensitivity can be explained by the observation that carriers spend the majority of their time with non-driving activities (parking, fetching and delivering the parcel), since distances in the city centre are rather short. In contrast to that, congestion has a much stronger effect on external costs. Even though the distances remain similar, according to [48] the external costs related to congestion drop to about €0.01/km for free flow while reaching about €0.76/km for heavy congestion.

In line with our expectations, we observe a decrease in operational and external costs with a growing number of deliveries. While the operational costs per delivery drop from €2.37 for 6 deliveries per km^2 to €1.25 for 190 del/km^2, the external costs decrease from €0.66 to €0.23 per delivery, assuming slight congestion. This cost decrease can be attributed to a more efficient routing. With a higher demand, the distance and travel time between two successive customers on a route becomes lower, as shown in Table 3, and thus, more customers can be visited on a route. With a density of 125 del/km^2, the routes are so efficient that driving from customer to customer accounts for only 20% of the time in the city. External costs account for about 28% (6 del/km^2) to 18% (190 del/km^2) of the operational costs.

In these experiments, we assume that each LSP has its own DPs in the city, independent of the demand. However, in reality, only larger LSPs have this infrastructure, whereas smaller LSPs cannot afford to maintain their own service points. They usually collaborate with shops from which customers can pick up nondelivered parcels in exchange for a service fee paid by the LSP. Thus, the B2C delivery market is biased towards size. Not only do large LSPs have the advantage of smaller variable costs per delivery, and can, therefore, offer more competitive prices, they also own the infrastructure to offer better services.

Table 3 Results from the simulation of van deliveries for different demand densities

	100 deliveries (6.25 del/km^2)	500 deliveries (31.25 del/km^2)	2000 deliveries (125 del/km^2)
Routing of vans			
Number of routes	2	5	17.1
Deliveries per route	50	100	117
Distance driven between two deliveries (m)	683	325	173
Time driven between two deliveries (min)	2.2	1.1	0.6
Time (as % of time spend in the city)			
Time driving in the city	47	31	20
Time delivering in the city	53	69	80
External Costs			
Distance driven by delivery vans (km)	68	162	346
Distance driven by customers to DPs by car (km)	12	64	262

5.2 Simulation of self-pick-up

As discussed in Section 2, there is an increasing interest of LSPs to explore the opportunity of customer self-pick-up, i.e., customers can choose to pick up parcels themselves from a nearby DP instead of being delivered at home. This concept has two advantages for LSPs. Most importantly, it reduces the number of deliveries since fewer customers need to be visited. Also, it can reduce the number of failed deliveries, e.g., when households with working people choose the self-pick-up option since they will not be at home anyway. On the downside, self-pick-up results in additional traffic and external costs when customers travel to the DPs by car to pick up their parcel. In the following, we investigate these opposing effects from the perspective of a large LSP with 2000 deliveries per day.

As expected, the variable operational costs per delivery decrease linearly with the number of self-pick-up customers. More precisely, it drops by about €0.01 for each additional 1 % of self-pick-up customers, as shown in Fig. 4. The magnitude of these savings changes if we consider a variable cost for each parcel that is picked-up at a DP, e.g. for service and storage. For larger LSPs that have their own service points this variable costs is likely to be small, whereas smaller LSPs have to collaborate with external shops and pay about €1 per picked-up parcel. We investigated the effect of these costs in a sensitivity analysis, and found that even with high pick-up costs, self-pick up is still favourable for LSPs. However, the decrease in operational costs comes at the expense of higher external costs, which grow by half a Cent for each additional 1 % self-pick-up since more customers need to travel to the DPs.

These results highlight that customer self-pick-up is highly cost-efficient for LSPs. However, the promotion of self-pick-up might be difficult, since most customers are used to the high comfort of home deliveries. One idea to promote self-pick-up is the offering of price reductions. In our case, the delivery price could be reduced by up to about €1 (the operational variable cost per delivery) for those customers that choose to pick-up the parcel themselves, without touching the LSP's profit. On the other hand, there is no reason for public authorities to promote a self-pick-up based delivery concept, since externalities increase.

5.3 Simulation of bike deliveries

With self-pick-up we have identified a distribution concept that benefits LSPs, but does not enhance the quality of life in cities. Reversely, with cargo bikes, we now analyse a distribution concept that is expected to decrease the externalities

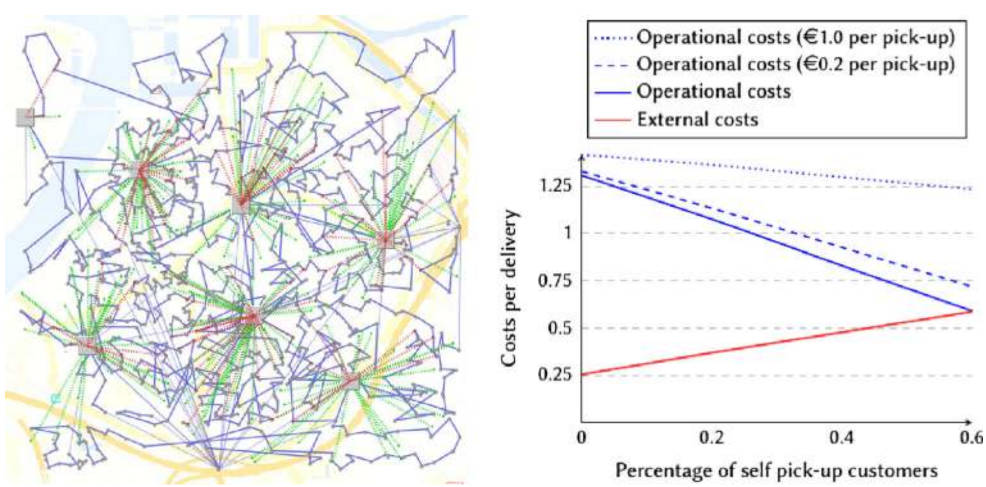

Fig. 4 (left) Delivery routes for a large LSP with self-pick-up. (right) Costs per delivery as a function of the percentage of self-pick-up customers

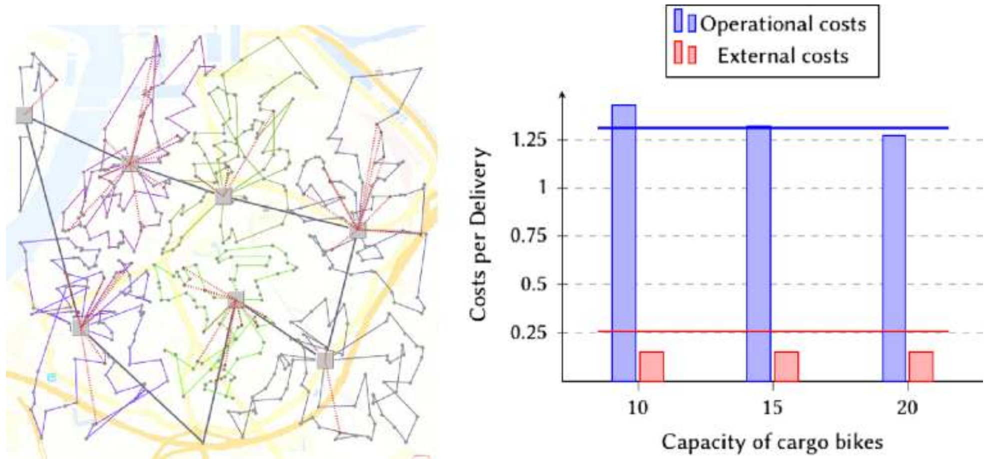

Fig. 5 (left) Parcels are brought to the DPs (grey lines) and delivered from there to the customers on bike routes. (right) Costs per delivery for different capacities of the cargo bikes, compared to traditional delivery (lines)

of parcel distribution. We model this scenario as follows. The parcels are brought from the distribution centre to the DPs in the city by vans. At the DPs the parcels are unloaded and buffered, and then distributed by cargo bikes to the customers. In other words, the DPs act as transhipment points between vans and cargo bikes. This process is visualized in Fig. 5. A similar system has already been implemented and tested in London [46].

We compute two sets of routes, the routing for the vans, and the routing for the cargo bikes. The routing for the vans from the city border to the DPs is computed in the same fashion as above, assuming a fixed stem mileage and preparation time per tour and an average speed of about 17 km/h in the city. Since the vans only visit a few points, the maximum duration of 6 h per tour is never reached, and we set the number of parcels per van to an assumed maximum van capacity of 300. The unloading of parcels at a DP is defined to take 20 min.

Secondly, we compute the bike routes from the DPs to the customers. Each customer is assigned to its closest DP, and then for each DP we solve the resulting VRP. We assume that the cargo bikes can carry at most 10 parcels at a time, so that drivers have to return to the DP for a refill several times. Each refill is assumed to take 5 min. Further, we assume that the bikes drive at an average speed of about 12 km/h. The service time per delivery remains 2.5 min as above. Unlike the van routes, the bike routes are not associated with external costs.

Consistent with previous studies, e.g. [46] or [31], we observe that bike deliveries can yield a drastic decrease in external costs by 40% from €0.25 to €0.15 per delivery, compared to traditional home delivery via vans. These results are presented in Fig. 5. The reason for this cost reduction is a decrease in the distance that is travelled with vans in the city, as shown in Table 4. Despite these findings, one of the main argument against bike deliveries in practise is an expected increase in travel time and, thus, working hours. Our results confirm that the driving time in the city would increase by almost 134%. However, the stem mileage drops significantly, and the travel time accounts for a relatively low percentage of the total time spend on delivering activities and, thus, the operational costs for the LSP increase by only about 9% from €1.31 to €1.43 per delivery. There are two main reasons for these longer travel times: (1) The limited capacity of the cargo bikes renders the routing more inefficient. In fact, if we assume that the bikes can carry up to 20 parcels, we observe a decrease in operational costs, as demonstrated by the sensitivity analysis in Fig. 5 (Electrically-assisted cargo tricycles can even carry more than 30 parcels at a time [46]). (2) We assume that the trips between two customers by bike takes longer than by van. Especially in dense city areas this assumption might no longer be valid, since some areas are easier accessible by bike and shortcuts can be used. Also, the average service time might be lower, since parking and fetching the parcel should be simpler compared to using a van.

Consequently, our parameter choice is rather on the low side (low bike capacity, slow biking times, long service times) so that the operational cost increase of 9% can be interpreted as estimate, and the real increase in variable costs is likely to be smaller. Additionally, the two scenarios have other structural differences that might influence the decision-making process in reality. In the case of joint bike deliveries the LSP need to acquire cargo-carrying capable bikes, and can reduce

Table 4 Comparison of simulation results for van and bike delivery for an LSP with 2000 deliveries (125 del/km^2)

	Delivery by vans	Delivery by bikes
Number of routes by van	17.1	7
Distance driven by van (km)	527	211
Distance driven by van in the city (km)	356	141
Distance driven by cargo bike (km)	0	502
Time spend driving in the city, with bikes and vans (hours)	20.8	48.6
Time spend driving in the city (as % of time spend in the city)	20	35

the number of vans. Moreover, this scenario might enable other potential benefits, such as night deliveries of the DPs.

5.4 A compromise between low externalities and low operational costs

With the previous experiments, we have demonstrated that the concepts self-pick-up and bike deliveries can only decrease either operational or external costs at the expense of the other. Thus, both concepts cannot satisfy all stakeholders and will, therefore, be difficult to implement in practice. These findings lead to the question, whether a feasible compromise can be found that benefits LSP as well as enhances the quality of life in cities.

The starting point for a compromise is the observation that the external costs of failed deliveries and self-pick-ups depend crucially on the distance between customers and DPs. If the distance is rather low and the next DP is only a few streets away, fewer people will use a car to pick up their parcel. At the same time, customers will feel more inclined to accept the self-pick-up option. The distance between customers and DPs can be decreased by opening more DPs in the city, which requires a significant investment that might discourage LSPs. However, public authorities could provide those additional DPs, under the condition that LSPs lower external costs by changing the distribution system to bike deliveries. In this way, public authorities directly incentivize bike deliveries and greener cities. In the following, we analyse whether these ideas would be beneficial for all stakeholders.

We choose the same setup as in Section 5.3 and consider a large LSP with 2000 deliveries per day that implement a bike delivery systems originating from DPs. This time, public authorities provide another 6 DPs. We choose the location of these additional virtual DPs in such a way that the city is roughly covered uniformly with DPs, and the average distance between customers and DPs decreases from 290 to 220 m. As a possible consequence, more customers choose to use the DPs for self-pick-up, and we investigate the resulting effects on costs (Fig. 6).

With an increasing number of self-pick-ups we again observe growing external and shrinking operational costs. The break-even point for the LSP is reached at about 10% of self-pick-ups. If at least 200 customers choose to not be delivered at home, this bike delivery scenario becomes profitable for the LSP, compared to the state-of-the-practise. On the other hand, external costs are lower than those of traditional home delivery, if less than about 25% of customers choose self-pick-up. Thus, there is a margin of between 10% and 25% of self-pick-ups, in which bike deliveries with additional DPs are beneficial for both, public authorities and LSP.

These findings suggest that a delivery system based on cargo bikes can be beneficial for all the stakeholders, if it is correctly implemented and incentivized. It requires a sufficient density of DPs in the city, and a possibility for customers to pick up parcels themselves. At the same time, the percentage of self-pick-ups should either be not too high, or customers should be encouraged to not use their car for pick-up trips. The latter could be achieved by further increasing the number of DPs and thereby improving customer access.

5.5 Discussion of limitations

In the simulation studies above we tried to annotate the delivery activities with as realistic cost and time values as possible, mostly on the basis of observations from a real-world dataset. For those parameters that we needed to estimate and that showed to have a significant effect on the overall result, such as the average congestion in the city or the capacity of a cargo bike, we conducted a sensitivity analysis to investigate how changes in these parameters would affect the outcome. A cost that we only considered in a sensitivity analysis is the cost for those parcels that are stored and picked-up from a DP. The extent of this cost depends on the infrastructure of the considered LSP. Smaller LSPs usually collaborate with shops from where customers can pick up their parcel, while larger LSP

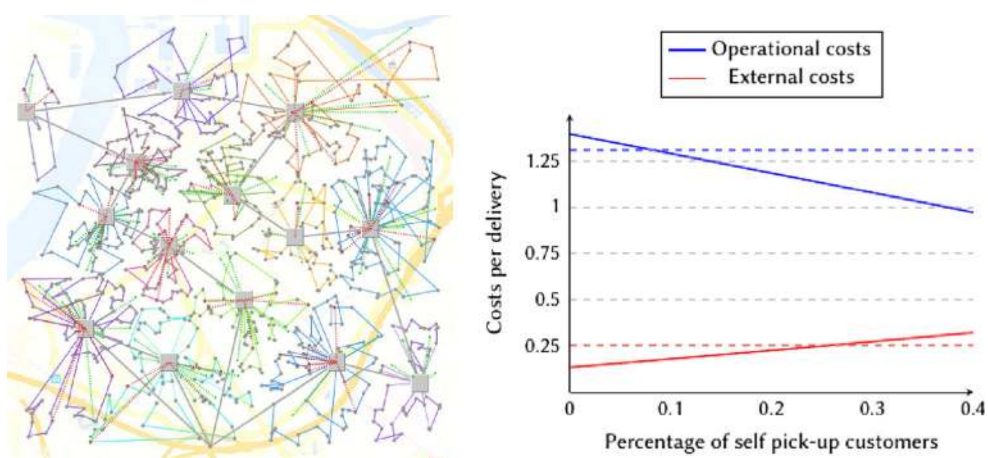

Fig. 6 (left) Parcel distribution via cargo bikes with additional DPs and self-pick-up. (right) Costs per delivery for a varying number of self-pick-up customers, compared to traditional home delivery (dashed lines)

have their own service points which also offer other services. While in the first case the cost per picked-up parcel amounts to about €1, in the latter case the costs are almost negligible, since the infrastructure is there anyway (and which we assumed in the analysis).

The collaboration with shops presents an interesting option to readily extend the coverage of DPs without large capital investments, even though shops might not be suitable transhipment points for bike deliveries. A thorough analysis of different infrastructure options, however, is beyond the scope of this paper. Such an analysis would require investigating such topics as the implementation of DPs, the upgrading to transhipment points of DPs, the payments to shops, and the purchasing and selling of cargo bikes and delivery vans, all of which present a considerable research challenge. In this paper, we have focused on the cost of various transportation options, *given* a certain infrastructure set-up.

Finally, we implicitly assumed that all parcels are sufficiently small and light to be transported by a cargo bike. Even though this assumption probably holds for a vast majority of parcels, some parcels might have to be distributed by van. The investigation of such a hybrid system of bike and van deliveries is also beyond the scope of this paper.

6 Conclusion

In this paper, we have investigated the cost structure of different scenarios for urban B2C distribution in Antwerp. We generated demand on the basis of a real-world dataset and computed delivery routes with realistic cost values. By the comparison of different scenarios, we found that external costs, related to the transportation with delivery vans, account for 18%–28% of the operational costs. Also, we showed that the parcel delivery market is unbalanced in the sense that small LSPs have higher operational costs per delivery than a large LSP. Those operational costs can be reduced by stimulating self-pick-up, at the expense of rising external costs. Reversely, a bike delivery system can significantly reduce external costs but slightly increases the costs of LSPs. Consequently, neither self-pick-up nor bike deliveries alone seem to be beneficial for all stakeholders. However, a combination of both concepts, fueled by the implementation of additional DPs, represents a B2C delivery system that improves the quality of life in Antwerp and is also appealing to LSPs. The efficiency of such a delivery system could be further enhanced if, for instance, multiple LSPs collaborate and execute and plan the last-mile delivery jointly to make use of the economy-of-scales effect that we observed.

These results highlight the importance of looking at urban B2C distribution from a global perspective. Several stakeholders are involved that follow different goals and strategies. Public authorities have no incentive to support the introduction of self-pick-up and, likewise, an LSP will be rather unwilling to consider a bike delivery system when facing higher variable costs. However, these arguments arise from an isolated perspective, and they change if stakeholders look for alternatives jointly.

Furthermore, a fruitful dialogue between stakeholders requires a realistic assessment of possible `what-if' scenarios. We demonstrated how such an assessment is possible with simulation studies. By means of simulation, we could model and evaluate different delivery strategies, which allowed us to extract reasonable cost values. Overall, our simulation model is relatively simple and easy to use. However, an accurate simulation requires accurate input data, and the availability of good data might present the biggest hindrance for simulation studies in practice. In our case, we used a real-world dataset of deliveries, the number of demands, information about the B2C delivery market in Belgium, cost values, and information about travel times and distances. Additionally, we observed that a slight change in parameter settings already impacts the results and following conclusions.

Finally, our study focused on the urban B2C parcel distribution in the city of Antwerp. Therefore, care should be taken in generalising our findings to other cities. Every city has a different size, infrastructure, demand density and market distribution among LSPs, and we have shown that all of these parameters affect the cost structure of B2C delivery services, and therefore also the practical relevance of the considered scenarios. Furthermore, we did not consider the time-dependency of travel behaviour and congestion. Especially during rush hour travel times and therefore routing choices might be different than during other times. However, the consideration of time-dependency requires detailed data that is available for only few cities. Another interesting extension could be an analysis of the precise effect of the location and number of DPs on costs. We showed that a higher density of DPs in a city can be beneficial for all stakeholders, and this effect could be further explored.

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