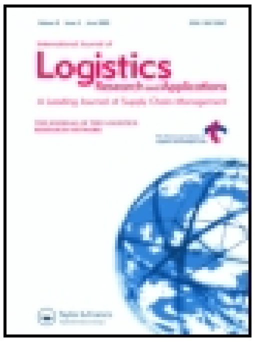

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A decision support system to investigate dynamic last-mile distribution facilitating cargo-bikes

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ABSTRACT

This work presents a decision support system to facilitate efficient urban last-mile distribution. Orders are collected and delivered by a fleet of both conventional vehicles owned by a logistics provider and cargo-bikes operated by freelancers. Additionally, micro-hubs are operated to perform transshipments between multiple vehicles. To investigate the corresponding problem setting, an agent-based simulation is developed, which uses dynamic optimisation procedures to generate and select vehicle routes and transshipment points. Experiments motivated by dynamic real-world urban restaurant delivery services investigate the impact of cargo-bikes, urban consolidation and guaranteed delivery times. Potentials are discussed and implications for successful implementations are provided. Results highlight the importance of having a sufficient number of active cargo-bikes available and benefits of incorporating consolidation strategies to guarantee timely deliveries.

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Dynamic routing; simulation optimisation; urban consolidation; cargo-bikes; decision support system; food logistics

1. Background

Food delivery services are gaining popularity. For restaurant operators, providing the option to order food online tends to lead to an increase in order frequencies (Kimes 2011). To deliver products, horizontal cooperation, e.g. multiple competing restaurants share delivery resources, enables one to reduce costs and increase performance in logistics (Cruijssen, Cools, and Dullaert 2007). Furthermore, it can lead to a considerable increase in service quality (Serrano-Hernandez et al. 2016). Consequently, numerous logistics providers are entering the market to enable restaurant operators last-mile deliveries to customers' premises (e.g. Deliveroo 2016; foodora 2016; UberEATS 2016). Such services, however, require considerable logistical efforts to guarantee a fresh and timely delivery at low costs. In urban areas, planning is further complicated as lead times are dependent on current traffic situations (Hopkins and McCarthy 2016) and as restrictions for motorised vehicles exist.

A potential strategy to improve operations is the combination of cargo-bikes and micro-hubs. Cargo-bikes are used to deliver goods to clients, enabling shorter delivery routes by driving in areas restricted for motorised traffic and being less impacted by traffic conditions. Additionally, micro-hubs, i.e. transshipment points where goods are transferred from one vehicle to another, are operated to consolidate multiple shipments. Consequently, motorised vehicles bring goods close to the city centre while the last-mile distribution in congested or restricted areas is performed by cargo-bikes, potentially reducing delivery times and costs. Potential locations for transshipment points are manifold and include large parking areas, loading zones as well as existing infrastructure of the provider.

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To evaluate the performance and to support implementation, this work presents a decision-support system (DSS) incorporating an agent-based simulation and dynamic solution procedures to route and schedule requests with a fleet of conventional vehicles operated by the logistics provider and cargo-bikes operated by freelancers. It enables the investigation of highly dynamic settings in which both demand and transport resources are subject to uncertainty. Results of a computational study based on real-world settings in Vienna, Austria, are presented, investigating, among others, the impact of consolidation, guaranteed delivery times and availability of cargo-bikes. Consequently, the contribution of this work is twofold: (i) a DSS to model and optimise dynamic urban last-mile deliveries facilitating cargo-bikes and micro-hubs is presented and (ii) implications on benefits and drawbacks of urban consolidation strategies are derived to support future implementations.

The remainder of this paper is structured as follows: Section 2 reviews related literature, while the problem is defined in Section 3. The developed DSS is described in Section 4 and computational experiments are introduced in Section 5. In Section 6, results are presented and discussed. Concluding remarks are given in Section 7.

2. Related work

The impact of cargo-bikes in urban settings is studied from various perspectives, mostly investigating cost, environmental and traffic-related factors. Terminology, major implementation barriers and policy recommendations to facilitate urban freight deliveries with cargo-bikes are provided in Schliwa et al. (2015). The authors provide an overview of recent literature and research projects in this field and list key findings of the studied works. Furthermore, the work highlights that different terms are often used to indicate various human-powered or electrical assisted vehicles types. Common terms include cargo-bikes, cargo-cycles, cargo-bicycles or cargo-tricycles, and are mostly dependent on the number of wheels and if the vehicle contains cargo boxes and electric power support. For readability, the term cargo-bike is used throughout this paper to indicate any such type of vehicle independent of the number of wheels or power source. Additionally, Schliwa et al. (2015) provide results of interviews with 10 United Kingdom-based urban logistics providers facilitating cargo-bikes for urban last-mile distribution. Results indicate that the market is mostly dominated by small- and medium-sized enterprises which are highly dependent on a large number of flexible part-time staff. Geographic factors such as highly dense areas and narrow streets in historic city centres as well as the presence of restrictions for motorised traffic were further identified as major drivers for the implementation of cargo-bikes. Likewise, Rudolph and Gruber (2017) conduct an extensive review of literature and real-world best practices as well as 45 expert interviews to derive potentials, recommendations and constraints of cargo-bike operations. The authors focus on German-speaking countries and six market segments, namely postal services, courier services, parcel services, service trips, internal/on-site transports and home delivery services. Relevant company, product and environment-specific factors influencing cargo-bike operations are identified including, among others, the regulative framework, preferences of decision-makers and sustainability issues. For home delivery services, which are the focus of our work, the authors note that company sizes and characteristics vary tremendously among such providers and cargo-bikes with two wheels are mostly used for operations.

2.1. Impact of cargo-Bike systems in urban settings

Multiple works study both real-world and theoretical implementation of cargo-bike systems and their impacts on urban traffic planning and business processes. In 2013, Lenz and Riehle (2013) provided an overview of real-world tests conducted by businesses and publicly funded projects within Europe, which investigated the use of cargo-bikes for freight deliveries. Western and Central Europe was identified as the core area of application with the UK, Austria, Belgium and Germany having the most identified freight logistics providers facilitating cargo-bikes. Additionally, the authors noted that operations exclusively take place in cities with a population of more than 100,000. The majority of providers were small enterprises with half of all companies employing a maximum of 15 employees. The maximum travel distance for a single trip ranged from 4 to 50 km, while the maximum cumulative travel distances per day varied between 80 and 120 km. The authors estimate that 25% of all commercial freight deliveries within city centres will be performed by cargo-bikes in a medium time frame. Perception of cargo-bikes as a suitable mode of transport for freight deliveries was identified as the major obstacle hindering broader implementations. Gruber, Kihm, and Lenz (2014) investigate the market potential of cargo-bikes for courier services in Germany. Current business areas, various costs factors and company characteristics are analysed from an operations management perspective. The authors indicate limited driving ranges, purchase prices and publicly available information as major obstacles for successful implementation of cargo-bike operations. Additionally, results of a binary logit regression model are provided analysing the willingness of drivers to switch from their current delivery vehicle to electric cargo-bikes. Furthermore, similar to the setting analysed in our work, the authors note, that most cargo-bikes are currently operated by freelancers as many providers do not own vehicle fleets or directly employ driving staff. The impact of owning cargo-bikes on mode choices from a household perspective is studied in Riggs (2016). The author conduced an online survey of recent buyers of cargo-bikes from a California-based vendor and performed a regression analysis on the responses. Results show that particularly trips involving children show a strong connection to the usage of cargo-bikes. A real-world case study of the impact of commercial cargo-bikes in Paris is further presented in Koning and Conway (2016). Based on data originating from an online survey of cargo-bike operators in 2014, freight volume and vehicle-type distribution were estimated. A substantial growth in the usage of cargo-bikes as well as a reduction in local pollutants and road congestion is reported, while savings in noise and CO_2 pollution are minor. Cargo-bike deliveries by restaurants and grocery stores were not included in the sample. Urban mail delivery is investigated in Choubassi et al. (2016). The authors study the economic impact of replacing US Postal Service vehicles with electric cargo-bikes in three urban areas and provide net present values of various delivery modes. Different vehicle depot configurations are compared and the recommendation to place vehicle depots for cargo-bikes within the operational area are given. Various scenarios analysing the impact of replacing conventional vans with cargo-bikes in Porto, Portugal, are investigated in Melo and Baptista (2017). A microscopic traffic simulation model is developed to estimate traffic conditions and derive corresponding environmental and operational impacts of operating cargo-bikes. The model simulates individual vehicle behaviour and adjust travel speeds based on traffic density over time, however, in contrast to our work, it does not include any vehicle routing optimisation procedure or consolidation of urban freight shipments. Based on computational experiments performed on a modelled transport network totalling 26 km, the authors state that up to 10% of vans can be replaced by cargo-bikes in areas with maximum linear distances of 2 km.

2.2. Impact of operating urban consolidation points

The impact of operating urban consolidation centres is studied in Browne, Allen, and Leonardi (2011). For Central London, the authors report results of a trial in 2010 where urban micro-consolidation centres were operated to distribute office supplies. Electric power-assisted cargo-bikes and vans were facilitated. While CO_2 emission per parcel delivered dropped significantly, total travel distances increased due to lower vehicle capacities. Additionally, results showed a reduction in various vehicle-related costs such as fuel, insurances and maintenance expenses, while costs for hiring drivers and operating distribution centres increased. In contrast to stationary urban consolidation points, Arvidsson and Pazirandeh (2017) investigate the impact of operating mobile depots in urban areas from a sustainability perspective. Therefore, the authors consider a vehicle, e.g. a bus, truck, barge or tram, which circles the city to perform transshipments with low emission vehicles such as light electric vehicles and cargo-bikes. Results of a ex ante evaluation show that implementations of such a concept can lead to environmental and social benefits while still remaining economically competitive. The impact of fleet composition and depot location in city logistics operations is studied in Koç et al. (2016). The authors develop an adaptive large neighbourhood search (ALNS) metaheuristic considering three different speed zones. To test the solution procedure and derive implications, benchmark instances are generated where the area is divided into three nested squares, with the lowest travel speed occurring in the centred one. Computational experiments run on these instances indicate benefits of operating a heterogeneous vehicle fleet and locating vehicle depots outside the city centre. The policy of combining vans with cargo-bikes in a city distribution context is studied in Anderluh, Hemmelmayr, and Nolz (2017). A circular area in the city centre of Vienna, Austria, is assumed, which cannot be crossed by any motorised vehicles due to driving restrictions. Various customers have to be visited, which are located both outside and within this restricted area. A solution procedure based on a greedy randomised adaptive search procedure (GRASP) metaheuristic and path relinking is introduced to solve the corresponding optimisation problem. Computational studies discuss the impact of facilitating cargo-bikes and temporal synchronisation at urban consolidation points. Cost savings through the combined usage of van and cargo-bikes are achieved in some settings, however, all instances enable providers to reduce emissions by substituting vans with cargo-bikes. In contrast to our work, customers are pre-classified to cargo-bike or van customers and can only be served by the respective vehicle type. Additionally, the problem is studied from a static perspective and, consequently, any dynamic changes in demand or fleet size are not considered. However, in cargo-bike operations for food delivery services, such considerations are of importance as changes or increases in demand can occur suddenly, which need to be processed and fulfilled in a short-time frame. Furthermore, the available fleet size may vary substantially as vehicles are often operated by freelancers or flexible part-time workers (e.g. Gruber, Kihm, and Lenz 2014; Schliwa et al. 2015; Rudolph and Gruber 2017).

The combination of simulation and optimisation procedures enables the consideration of such complex interactions and uncertainties in the problem setting (Glover, Kelly, and Laguna 1996). The simulation enables one to generate a diverse range of scenarios, which are used to guide of optimisation procedures to find promising solutions in uncertain and dynamic settings. For an extensive overview on various methods and ways to combine simulation and optimisation methods, refer to Fu (2015). Within our work, an agent-based simulation is developed to model uncertainty in daily operations such as sudden demand and varying fleet sizes. For an overview of recent developments in agent-based simulations and its various application areas, refer to Macal (2016), who lists hybrid modelling, i.e. combining simulation techniques with other operations research methods, as a major topic requiring future work. In our work, this combination is achieved by calling a dynamic vehicle procedure at various times during a single simulation run to plan delivery routes and schedule transshipments. The corresponding vehicle routing problem of optimising the transport of food deliveries from pickup to delivery points can be classified as a Pickup and Delivery Problem (Parragh, Doerner, and Hartl 2008). In our work, pickup points refer to locations where goods are available for collection by a vehicle, e.g. restaurants, and delivery points indicate the locations of customers where the food items have to be delivered. The majority of work reviewed in Parragh, Doerner, and Hartl (2008) focuses on static problem settings and, consequently, does not consider dynamic events. An overview of such dynamic vehicle routing problems, i.e. problems where not all information is known at the start of the planning horizon and is revealed over time, is given in Pillac et al. (2013) and Ritzinger, Puchinger, and Hartl (2016). Of the reviewed articles in those works, none explicitly investigates the impact of cargo-bikes and urban consolidation. Consequently, further work incorporating dynamic settings to assist the operation of urban consolidation points and cargo-bikes is required.

3. Problem description

The problem investigated in this work is motivated from the operations of an urban logistics provider delivering food items from multiple competing restaurants to end consumers in an area where restrictions for motorised vehicles are present. Customers can order from a restaurant at any time and expect that the order is delivered within a maximum delivery time frame. As some restaurant operators own multiple locations, e.g. various branches, the logistics provider has to select from which location the order should be collected. For final delivery to the customers, multiple freelancers are available, who collect and deliver items with cargo-bikes. Availability of such freelancers, however, varies over the day as cargo-bike drivers can dynamically lock into and out of the systems at any time depending on personal availability and preferences. Consequently, the logistics provider further operates motorised vehicles to decrease delivery times for long distances and utilisation of cargo-bikes. To exchange goods between motorised vehicles and cargo-bikes, urban consolidation points are operated. Consequently, the logistics provider has to select pickup locations, schedule orders to vehicles and perform routing and consolidation decisions between multiple vehicles with the objective to both decrease delays and driving durations.

The problem is defined on a weighted directed complete graph. The vertex set consists of various locations of interest, classified into supply points, denoted as sources, demand points, denoted as sinks, as well as depots and hubs. Arcs are associated with asymmetric driving durations between the locations for multiple vehicle classes. Each vehicle class, grouped into heavy and light vehicles, is further specified with a maximum allowed distance and capacity, where, typically, heavy vehicles have longer range and higher capacities. Heavy vehicles, i.e. vans, are used to deliver goods to hubs. In contrast, light vehicles, i.e. cargo-bikes, are used for final deliveries to sinks. Heavy vehicles are owned by the logistics provider and, consequently, assumed to be available at all times. In contrast, the availability of cargo-bikes is subject to uncertainty as these are operated by freelancers.

Demand is generated dynamically throughout the day by customers associated with various sinks spread over the study area. Each requested demand has to be delivered within a maximum delivery time guaranteed by the provider, e.g. within 30 min from the placement of an order. To fulfil the request, the shipment has to be picked up from a feasible source, i.e. a source where the specific goods are available, and transported to the customer's sink. A minimum delay between generation of the demand and earliest allowed pickup time from a source is specified to consider order processing and preparation time. Shipments can be transshipped at one of the given hubs in the study area. Each loading and unloading operation results in a time delay. Additionally, temporal synchronisation has to be considered to guarantee feasible operations, i.e. vans have to deliver goods to hubs before they can be picked up by cargo-bikes. If goods cannot be stored at hubs, this synchronisation has to be exact, indicating that the light and heavy vehicles have to be present at the same time. Due to parking restrictions, it is further assumed that vans cannot wait at the hub in case of an early arrival, however, waiting of cargo-bikes is enabled. Table 1 summarises the specific components of the studied problem setting.

The main objective is to improve service quality, i.e. minimise the total delay of shipments, while the secondary objective, in lexicographic order, is to minimise total travel distance. The corresponding solution procedure to solve this problem setting has to perform the following decisions subject to dynamic demand and variable fleet size: (i) from which source, at which time and by which vehicle a shipment is picked up, (ii) if a shipment should be consolidated and, if so, (iii) at which micro-hub and at which time the transshipment is performed.

Table 1. Main components of the defined problem.

Component	Description
Source	Location where products originate and are available forpickup
Sink	Location where products have to be delivered
Hub	Location at which transshipments from heavy to lightvehicles can be performed
Depot	Location where vehicles start and end trips
Heavy vehicle	Vehicle (e.g. van) owned by the logistics provider todeliver goods to hubs
Light vehicle	Vehicle (e.g. cargo-bike) owned by freelancers to delivergoods to sinks
Shipment request	Request for a shipment from a source to a sink. Eachrequest is indicated with an earliest pickup time, a latestdelivery time and loading delays

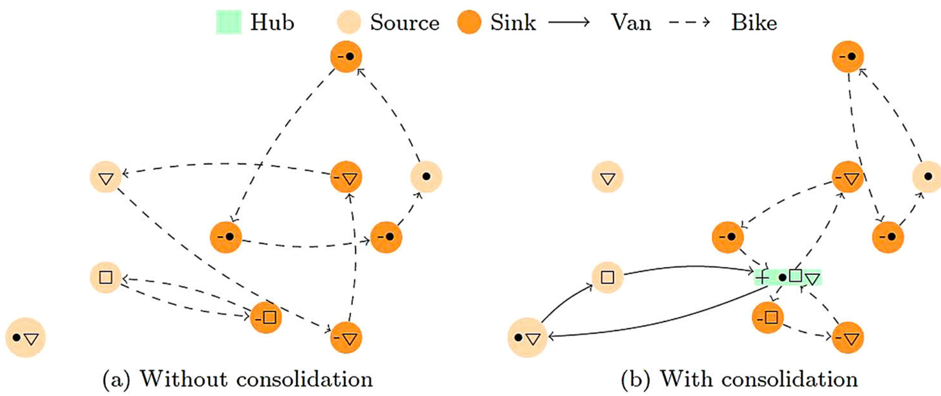

Figure 1. Delivery of various products (•; ▽; □) with vans and cargo-bikes.

Figure 1 shows a simplified example of the investigated problem setting with and without the option of consolidation at hubs. One van and three cargo-bikes are available and three different products have to be delivered to various customers. Each product is available at one or more sources and customers are indifferent regarding from which source an order is fulfilled. Depots are assumed to be located at any of the source or hub locations and sink can only be reached by cargo-bikes. Without consolidation, cargo-bikes are required to travel long distances to deliver products to customers, resulting in late delivery times. With consolidation, a van delivers the required products to a micro-hub closely located to the sinks. Consequently, consolidation enables one to speed-up deliveries by shortening cargo-bikes routes and facilitating faster vehicles on long distances.

4. Decision support system

To investigate the introduced problem setting, a DSS was developed. It is designed to assist decision-makers, who consider the usage of cargo-bikes and urban consolidation in highly dynamic settings, to investigate various distribution strategies. Furthermore, it enables one, among others, to study tactical questions such as the required vehicle fleet size, utilisation of sources and sinks as well as the impact of offering various guaranteed delivery times on logistics operations.

Based on the system architecture presented in Fikar, Gronalt, and Hirsch (2016), the DSS contains an agent-based simulation, dynamic vehicle routing procedures and the integration of geographic information system (GIS) data. Figure 2 shows an overview of the developed system. The user defines parameters and input data specifying the available vehicle fleet, locations as well as network and inventory data to calculate driving durations and product availability, respectively. Based on these data, an agent-based simulation is initiated, which simulates demand and the availability of cargo-bikes. At a predefined scheduling interval during a simulation run, heuristic optimisation procedures are called to schedule requests to vehicles and to perform routing and transshipment decisions. To facilitate interpretation of results, vehicle movements and various statistics are visualised in a graphical user interface. The individual components are introduced in the following subsections.

4.1. Agent-based simulation

To dynamically generate demand and to model uncertainty in the availability of cargo-bikes, an agent-based simulation was developed. Locations, vehicles and shipments are individually modelled as agents. Locations represent nodes in the network where sources, sinks, depots or hubs are based. Vehicles are categorised by the vehicle classes, i.e. vans and cargo-bikes. The latter are generated by

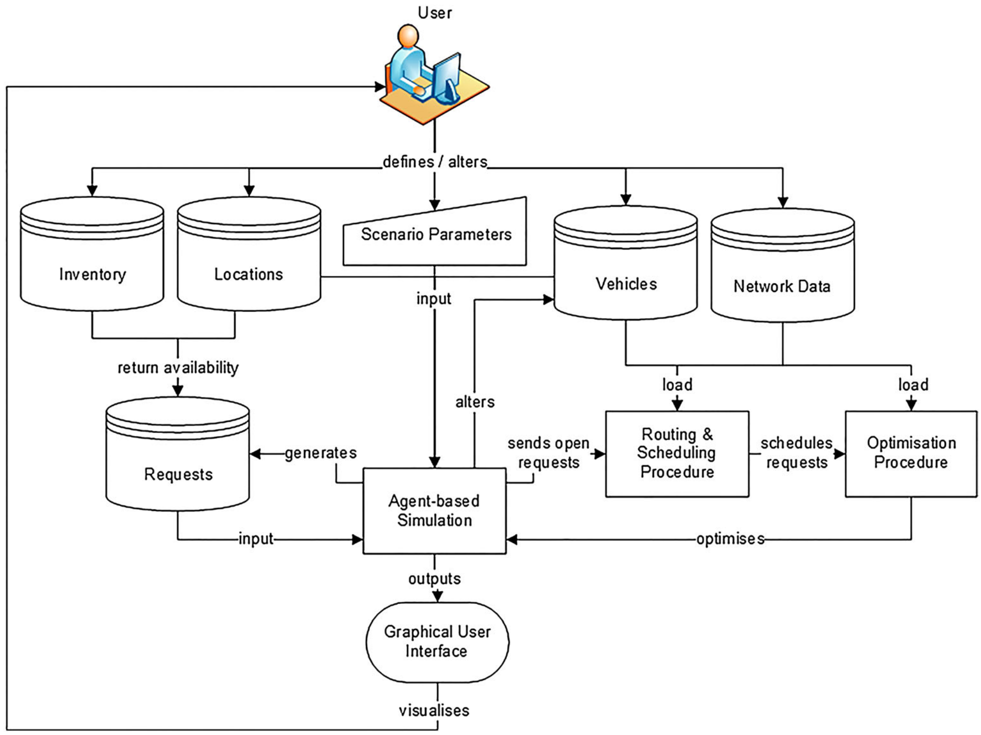

Figure 2. A DSS to investigate dynamic last-mile distribution facilitating cargo-bikes and micro-hubs.

events based on a Poisson-distributed arrival rate for each depot location and are active for a random time duration. The generated system considers the option of freelancers to dynamically log in and out of the system. Consequently, it is assumed that the logistics provider has no prior information of when and for how long cargo-bikes occur in the system. Nevertheless, if a vehicle becomes inactive (i.e. a freelancer stops operation), all scheduled requests are delivered to the sinks, i.e. customers, before ending the shift. This agent behaviour and additional shipping operations are modelled with a statechart as shown in Figure 3. An individual vehicle is either inactive, i.e. it is not available to perform any shipments, or active. If activated, the vehicle becomes idle and checks if shipments are assigned. If so, the vehicle starts moving and is marked as busy. It continues performing waiting, pickup or delivery tasks until no further stops are scheduled. At this point, the vehicle returns to the depot. At arrival, the vehicle either turns inactive or waits until a new shipment request is assigned.

Shipment requests occur dynamically at each sink based on Poisson-distributed arrival rates. During the simulation, shipments are assigned with one of the following five states: ‘at source’, ‘in transit to hub’, ‘at hub’, ‘in transit to sink’ or ‘at sink’. At a fixed time interval, an event is called to start the scheduling of requests.

4.2. Routing and scheduling procedure

As execution time of the solution procedure is of major focus to enable real-time solutions in urban settings (Mangiaracina et al. 2017), a two-stage procedure to schedule requests at a predefined scheduling interval, e.g. every two simulated minutes, was developed. In the first stage, all new requests, i.e. requests which occurred between the current point-in-time and the last time the optimisation procedure was called, are scheduled to cargo-bikes ignoring the option of consolidation. To find the best position of a request within a vehicle route, a best insertion heuristic is run. It evaluates

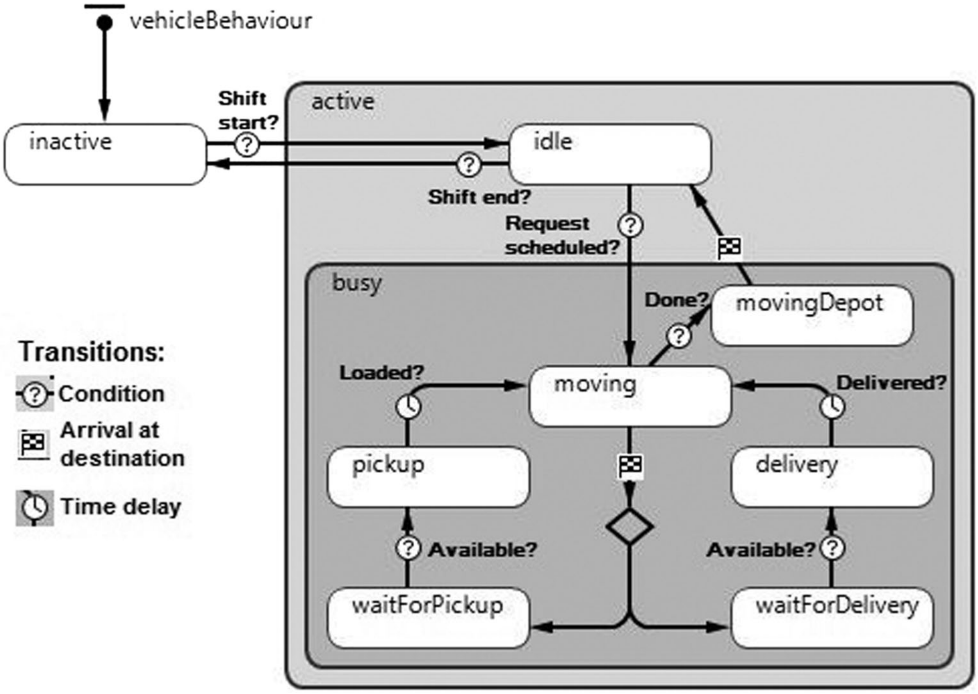

Figure 3. Statechart representing the agent behaviour of a vehicle.

all potential positions on all feasible vehicle routes considering each potential source of a shipment. The best option is scheduled. Various scheduling rules were investigated to indicate in which order the open requests are inserted to the vehicles' schedules. These priority rules included sorting open requests by urgency, regret value (Ropke and Pisinger 2006) as well as grouping requests by the respective demand zones. Nevertheless, based on a wide range of computational experiments, none of these sorting operations showed significant advantages. Consequently, request are scheduled in the order of occurrence in the DSS.

After all new requests are inserted, the solution procedure begins optimising routes with a local search procedure. It checks if relocating a shipment to another position, vehicle or changes in the selected source leads to improvements. The best improvement in the current neighbourhood is performed and this procedures is repeated until no further improvements are found. This procedure is further called each time a new cargo-bike appears in the system to initiate the vehicle.

In the second stage, each scheduled request is checked if transshipping the goods at a hub is beneficial to reduce the objective value. Therefore, the evaluation has to consider the impact of relocating the request to a hub and changes in related last-mile delivery routes to sinks. An example of such interdependencies between routes of a van and of cargo-bikes is shown in Figure 4. Consequently, performing changes to a van's route impacts delivery times and travel distances of all related cargo-bike routes. Furthermore, the feasibility concerning temporal synchronisation has to be checked by updating arrival times.

If a relocation is feasible and results in an improvement, the request is scheduled to the van. Additionally, the pickup point for the cargo-bike is altered from the source to the hub. All requests are sequentially tested and, if a consolidation is scheduled, the optimisation procedure is rerun to test if further improvements by relocating shipments or altering sources and hubs are possible.

The solution procedure is summarised in Algorithm 1. Due to the various combinations of sources and hubs to deliver requests, testing all options is time-consuming. To speed-up the procedure, a restricted granular neighbourhood is implemented, inspired by the work of Toth and

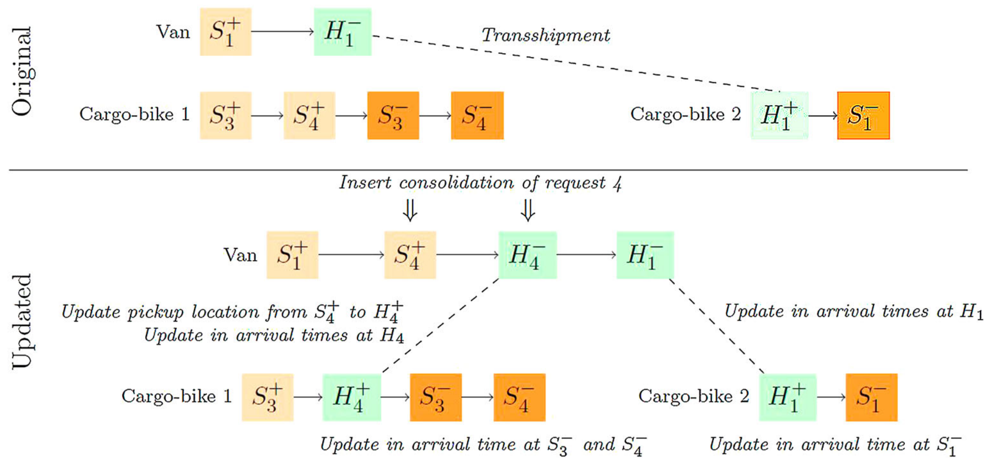

Figure 4. Feasibility check and solution evaluation of a consolidation insertion for request 4. S^+ and S^- denote sources and sinks respectively; H^+ indicates a pickup from and H^- a delivery to a hub.

Algorithm 1 Pseudocode: routing and scheduling procedure

```
procedure SCHEDULEREQUESTS(requests, vehicles)
    openRequests ← getAllOpenRequests(requests)            ▷ get all requests not yet scheduled
    for Request request: openRequests do
        request.bestInsertion(vehicles);                   ▷ sequentially insert open requests at best position
    end for
    performLocalSearch(vehicles);                          ▷ optimise routes of all vehicles
    atSourceRequests ← getAllRequestsAtSource(requests)    ▷ get all requests in state 'at source'
    for Request request : atSourceRequests do
        if request.consolidationIsBeneficial(vehicles) then    ▷ tests if transfer to hub is beneficial
            request.performConsolidation(vehicles);
            performLocalSearch(request.getVehicles());     ▷ re-optimise routes of altered vehicles
        end if
    end for
end procedure
```

Vigo (2003). Consequently, not all feasible combinations are evaluated, but only a set of the most promising ones. While shipping goods from the closest source is beneficial in many cases, multiple requests can be consolidated to be picked up from a single source or hub to reduce driving distances. As a result, the user-defined parameter *candidateListSize* $\in [0, 1]$ was implemented. It indicates what percentage of all potential candidates is evaluated. Therefore, sources and hubs are sorted in ascending order by the distance to the sink. Locations, which are already visited in the current vehicle route, are additionally considered. In case of a *candidateListSize* of 0, only the nearest location to the sink is evaluated.

5. Computational experiments

The DSS was developed with AnyLogic 7.3.6 (AnyLogic 2016) and coded in Java. Travel routes are calculated with the open-source routing library GraphHopper 0.5 (GraphHopper 2016) and based on OpenStreetMap (2016) network data. All computational experiments were run on an Intel Core i7-4930K, 64 GB RAM with MS-Windows 10. Input data are loaded from a database connected to the DSS. During a single simulation run, vehicle movements and various statistics, e.g. average delays as well as utilisations of hubs, sources and vehicles, are visualised. Additionally, the DSS provides the possibility to report aggregated results of multiple runs to compare the impact of varying input parameters and investigated stochastic factors. During the entire developing process, a special focus was set on providing decision-makers with a high degree of flexibility. Consequently, all parameters can be adjusted by the user, if required. To promote comparison of results and to facilitate future research, input data and solution files are available as supplemental files.

5.1. Study region

To test the developed solution method and derive implications, a sample setting in Vienna, Austria, is analysed. It is motivated from restaurant delivery services, an industry where short delivery times are of high importance and demand occurs dynamically. A logistics provider delivers for multiple restaurant operators, where each operator owns one or more sources from which an order can be served. To model demand and to cluster potential customer locations, the study area was categorised into zones according to the electoral districts in Vienna (Stadt Wien 2016). Each zone is associated with the corresponding population figures to estimate demand, i.e. a zone with a higher population generates more shipment requests. In total, the city is clustered into 1525 zones. Of these, 123 zones, with a total population of 117,378, were selected to include sinks, representing an area with partly restricted motorised traffic. Sources are based on a major food provider totalling 255 locations. To enable transshipping orders, 59 hubs are available in or close to the demand area. These are based on secured parking lots in the study area. Driving distances and durations are calculated on real-world street and cycling networks between the zones' centroids considering the fastest connection. If no connection for a certain vehicle-type exists, e.g. due to driving restrictions, the travel time is set to ∞. Figure 5 visualises the performed zoning and plots the demand area as well as zones which include sources, hubs and sinks.

5.2. Data and parameters

The parameters of the DSS are summarised in Table 2. These are grouped in four categories to define settings related to simulation, optimisation, demand and vehicles. For each parameter, the

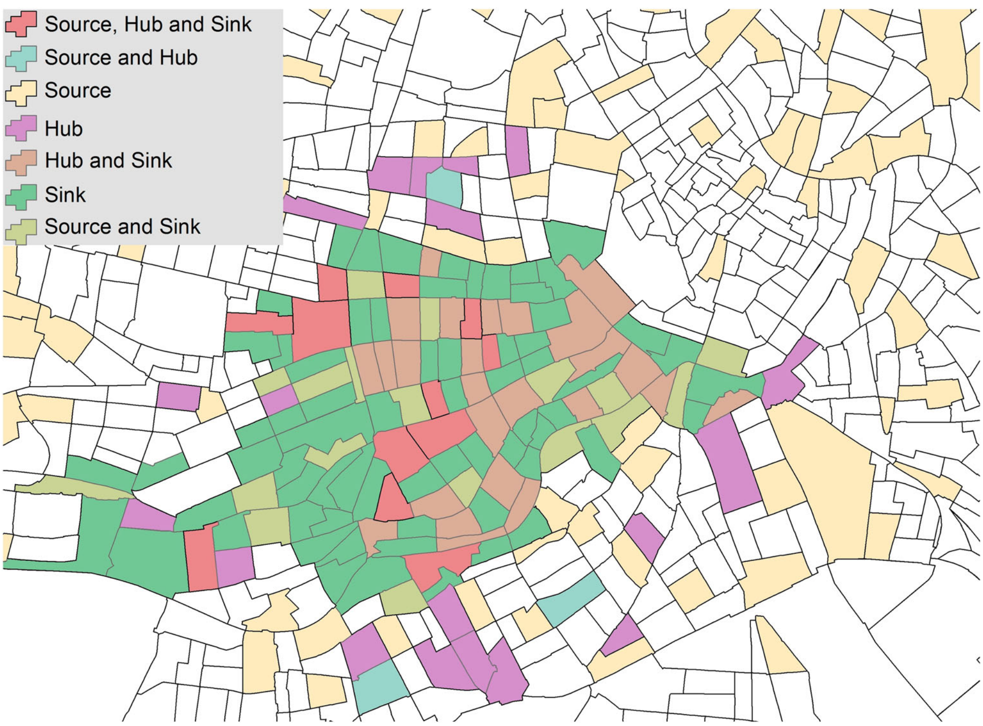

Figure 5. Visualization of the demand area with zoning based on electoral districts.

Table 2. Parameters of the computational experiments.

Group	Parameter	Base scenario	Variation	Experiment
Simulation	replications	100		
	warmupPeriodInHours	7		
	simulationHorizoninHours	31		
Optimisation	candidateListSize	0.40	{0.00,0.10,…,1.00}	(6.1)
	schedulerIntervalInMin	2	{1,2,…,10}	(6.1)
	enableLocalSearch	*true*	{*false,true*}	(6.2)
	enableConsolidation	*true*	{*false,true*}	(6.3)
	enableStorageAtHub	*false*	{*false,true*}	(6.4)
Demand	averageOrderPerPersonPerDay	0.015	{0.010,0.011,…,0.025}	(6.2;6.3;6.4)
	maxDeliveryTimeInMin	45	{30,31,…,75}	(6.5)
	orderPreparationDelayInMin	15		
	probabilityGoodAvailableAtStore	0.0125		
	loadFactorOfOrder	*uniform*(10,50)		
	loadingDelayInMin	2.5		
Vehicles	averageBikesPerPersonPerDay	0.0020	{0.0015,0.0016,…,0.0050}	(6.6)
	maxCapacityVan	500		
	maxCapacityBike	100		
	maxDistanceBikeInKm	100		
	averageShiftLengthOfBikeInMin	180		

standard value is stated, which is used as a base scenario in each of the performed computational experiments. Additionally, the variation column states which minimum and maximum value is used as well as the considered steps. These ranges are used in the subsequent computational experiment subsections, indicated in the experiment column, to investigate the impact of specific parameters.

For each experiment, 100 replications were run to consider stochasticity. Each run reports the total delay in delivery and the total distance driven. Furthermore, statistics on the delay distribution of all arrived shipments are given. To initialise the simulation, a warm-up period is included in which the simulation is run, however, no statistics are collected. The simulation ends at a fixed point in time and all shipments that have not yet arrived at the sinks are evaluated with the current scheduled routes, i.e. scheduled delivery times and distances. To run the implemented routing and scheduling procedures, the scheduling interval and the size of the candidate list have to be set. Furthermore, the option to enable or disable the local search module, consolidation of shipments at micro-hubs and the possibility to store goods at micro-hubs is provided.

Demand occurs based on the population living in a single zone and a demand rate per day. It is further defined with a uniformly distributed average load factor of the shipment to consider weight and dimensions of the order. Within the computational experiments, the expected number of orders per day range between 1174 and 2935 from the lowest to the highest setting. Furthermore, the user defines the probability that a good is available at a single source to simulate inventory. In the computational experiments, this value is set to 0.0125, indicating that an average order is available at approximately three sources. The maximum delivery time indicates the time from when the order is placed until the moment a vehicle arrives at the client, i.e. the start point of the unloading operations. Additionally, both order preparation delays and loading durations are set for the experiments.

The logistics provider owns 24 vans. Cargo-bikes are activated in any zone within the demand area, i.e. a zone with a sink, based on a daily arrival rate per person living in the zone. Each vehicle is defined with a maximum capacity, indicating that a cargo-bike and a van can carry a maximum of 10 and 50 shipments, respectively. Additionally, the maximum travel distance for a cargo-bike is set. The end of a cargo-bike shift is randomly selected based on an average shift length. Within the experiments, the expected number of cargo-bikes varies between 176 and 587 per day, equalling 528 and 1761 operating hours, respectively.

5.3. Limitations

The following assumptions have to be considered when interpreting results. Population figures originate from electoral registers and do not consider age and income distributions. Consequently, actual geographic demand distribution may differ. Likewise, due to a lack of reliable data, the computational experiments do not consider demand peaks during a day of operations. Accordingly, the computational experiments assume a peak scenario for which the system needs to be designed. If additional data are available, such information can be easily integrated by adjusting population or demand rates of single zones individually. Furthermore, derived implications are subject to the operational area and the geographic distribution of hubs, sources and sinks. Consequently, implications derived within this work from urban operations in Vienna may considerably vary from settings in rural areas where average travel distances are greater.

6. Results and discussion

6.1. Impact of scheduling parameters

In the first step, experiments are performed to set up the DSS. Various scheduling intervals and candidate list sizes are investigated for the base scenario concerning the trade-off between computational times and solution quality. Figure 6 plots the results.

While larger candidate lists improve the solution quality, run times are substantially increased. Longer scheduling intervals, however, negatively impact solution quality. Particularly, if a high interval is selected, the systems takes longer to react to dynamic changes in the system and, consequently, solution quality decreases substantially. Based on these results, for the subsequent experiments, a candidate list size for the neighbourhood of 0.4 was selected, i.e. the top 40% of all sources and hubs are evaluated. The scheduling of new requests is done every two simulated minutes.

6.2. Impact of optimisation

Moreover, the simulation experiments were run with the local search module enabled and disabled. Results are shown in Figure 7. If disabled, requests are scheduled to vehicles by a best insertion rule, however, once scheduled, requests cannot be altered or relocated. The advantages of such a strategy is that less changes to the system occur, simplifying real-world implementations as routes stay stable for drivers, hubs and sources. In contrast, potentials to improve the solution quality are lost.

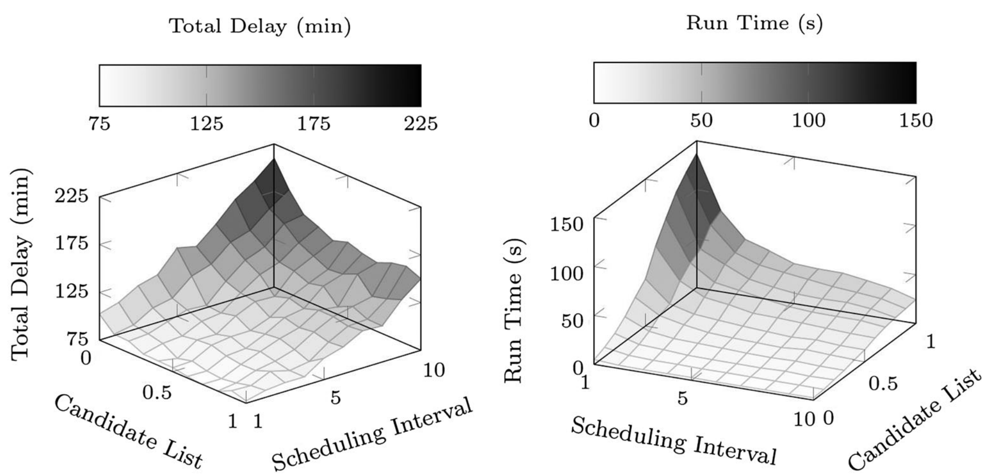

Figure 6. Impact of varying the selected candidate list size and scheduling interval on solution quality (left) and run times (right).

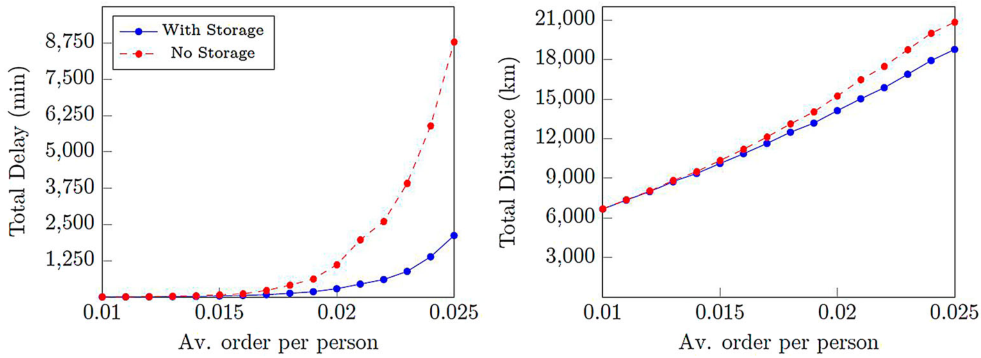

Figure 7. Impact of the local search module on the total delay and distance driven.

Dynamically optimising requests by adjusting vehicle routes to updated information enables one, in all test settings, to reduce the average distance driven. Furthermore, the total delay can be reduced, particularly if the system is highly utilised, i.e. a low number of cargo-bikes is available or demand is high.

6.3. Impact of urban consolidation

Figure 8 plots the impact of enabling consolidation at micro-hubs. As shown, consolidation is particularly beneficial concerning reducing the delay of shipments if a high amount of demand occurs, even though additional loading and unloading operations are required. In a high demand setting, cargo-bikes are highly utilised and, consequently, save time by picking up multiple consolidated shipments from micro-hubs. Nevertheless, average travel distances per shipment increase as detours to reach consolidation points occur.

The average number of shipments per day transshipped at the given hubs is shown in Figure 9. Particularly, hubs located at the periphery of the demand zone are highly utilised. This indicates the potential of using vans to bring shipments close to the demand area and facilitating cargo-bikes for the last-mile distribution in areas where motorised restrictions are present.

6.4. Impact of providing storage at micro-Hubs

Figure 10 further shows the impact of enabling storage of goods at micro-hubs. If enabled, wait times and utilisation of cargo-bikes are reduced, resulting in less delays and shorter travel distances in high

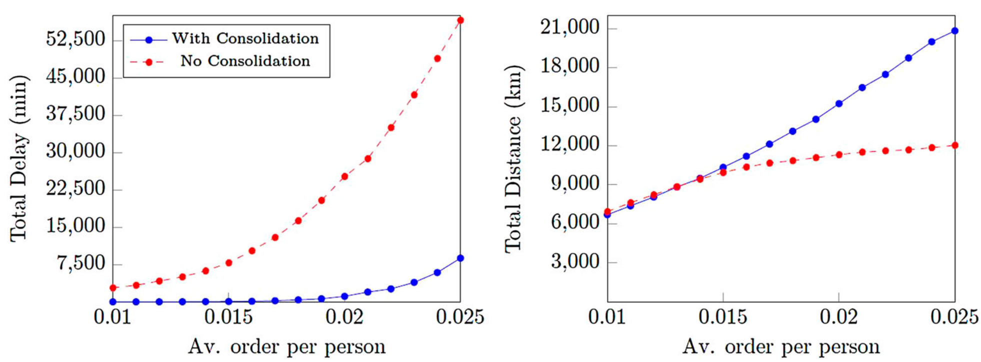

Figure 8. Impact of enabling urban consolidation on the total delay and distance driven.

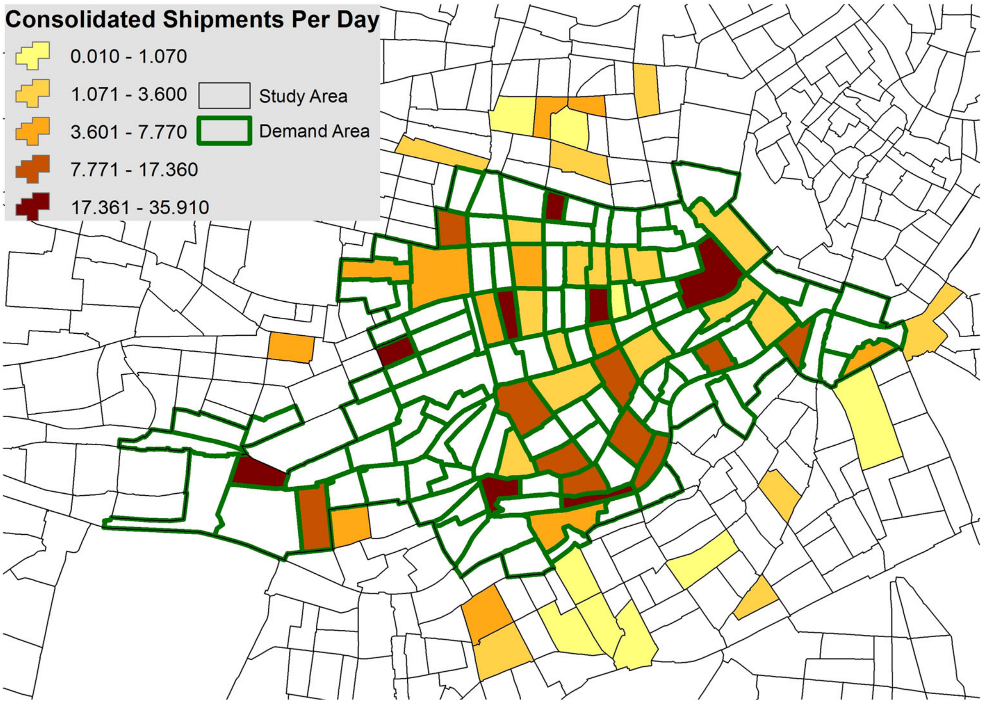

Figure 9. Utilisation of micro-hubs in the base scenario.

demand settings. Implementation of such a strategy, however, is complex as it requires close cooperation with the hub provider as well as additional organisational and legal considerations such as spatial constraints, theft protection, liability and food safety-related factors.

6.5. Impact of maximum delivery times

In Figure 11, the impact of offering various guaranteed delivery times is investigated. The total delay of shipments decreases with an increase in offered delivery times to a point where nearly all shipments can be delivered on time. Moreover, offering shorter delivery times results in higher travel distances and less options to consolidate shipments, potentially increasing logistics costs.

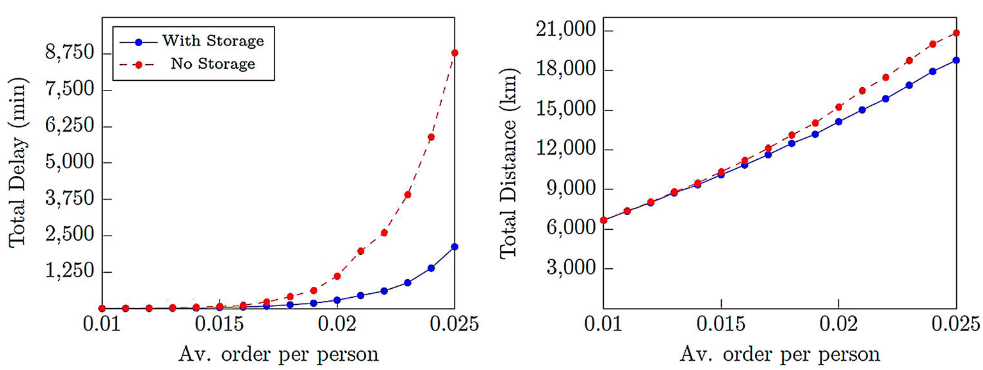

Figure 10. Impact of enabling storage at micro-hubs on the total delay and distance driven.

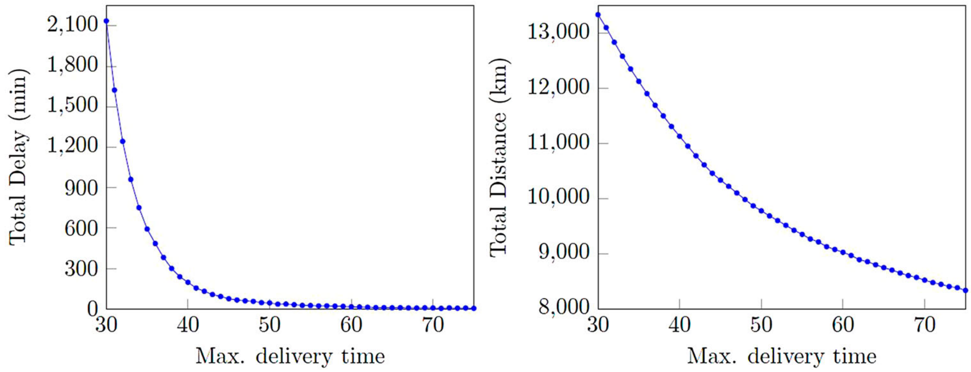

Figure 11. Impact of varying guaranteed delivery times on the total delay and distance driven.

As customers prefer fresh and fast deliveries (Chen et al. 2014) and on-time delivery is an important factor for building customer trust and loyalty (Reichheld and Schefter 2000), the guaranteed delivery time offered to customers is an important consideration from both a service and logistics perspective.

6.6. Impact of the availability of cargo-Bikes

The impact of the arrival rate of cargo-bikes is shown in Figure 12. The DSS gives indications on how many cargo-bikes are required for successful operations. If too few cargo-bikes are available, the average delay of shipments increases substantially. In contrast, having more cargo-bikes operating than required to fulfil all requests on time enables providers to decrease the total distance driven. Nevertheless, at a certain threshold, only minor further improvements are achieved as additional cargo-bikes are little utilised.

Consequently, if the number of potential freelancers is low or availability differs substantially throughout a day, providers are required to have additional back-up solutions to guarantee on-time deliveries.

6.7. Impact on source utilisation

An increase in home deliveries further impacts the amount of work load at the individual source locations. This may require highly utilised restaurants to either focus on delivery services or to

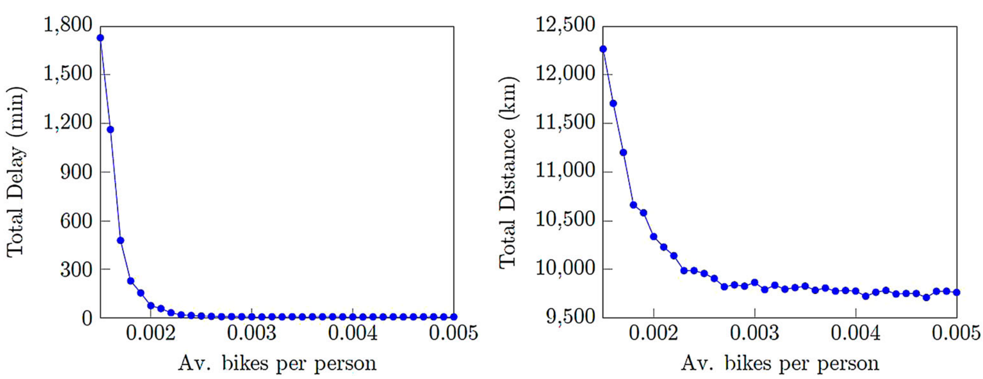

Figure 12. Impact of the availability of cargo-bikes on the total delay and distance driven.

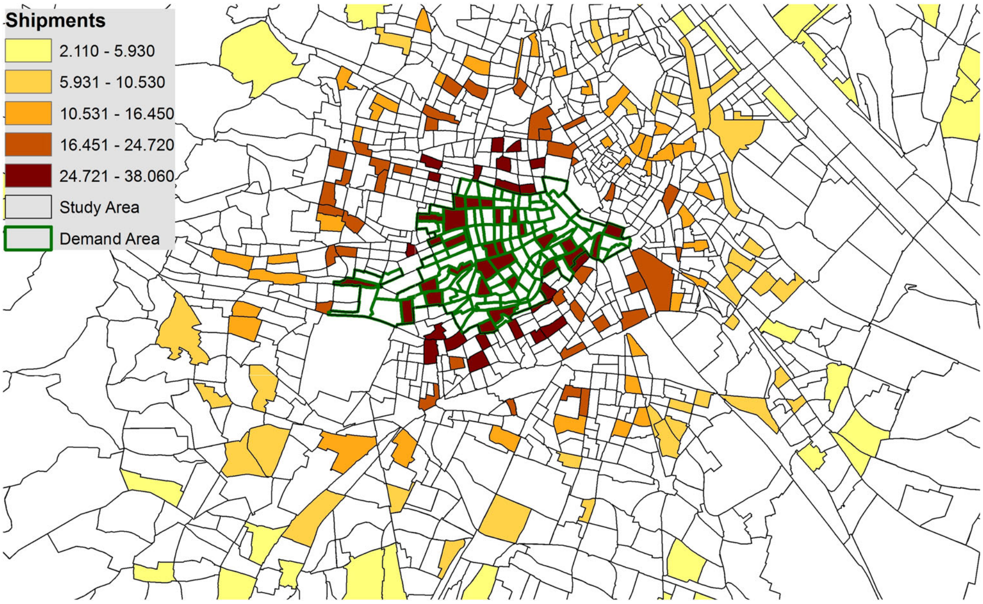

Figure 13. Impact on the individual source locations in the base scenario.

expand operations. Figure 13 plots the average number of shipment requests fulfilled from each individual source per day. As the result shows, utilisation differs substantially among the various sources. Such findings enable decision-makers to consider dedicating specific locations for delivery services, while enabling others to focus on walk-in customers.

7. Conclusions

The presented DSS supports both accuracy and velocity of decision-making by enabling the investigation of different problem settings and various impacts of facilitating cargo-bikes and consolidation in an urban food delivery context. It enables decision-makers to design, test and adapt urban last-mile distribution concepts for highly dynamic settings in a flexible and risk-free environment. This is achieved by the combination of an agent-based simulation with dynamic optimisation procedures. The former models dynamic demand and uncertainty in the system, while the latter enables one to derive order assignments to vehicles, driving routes and transshipment points. Results indicate the potential of facilitating micro-hubs and the importance of having a sufficient number of cargo-bikes available to guarantee timely deliveries.

Future research fields to enhance the DSS include the implementation of real-time traffic data, backhauls as well as the development of interfaces to online ordering and inventory management systems. Therefore, an integration of the delivery strategies with picking, handling or processing processes at sources and hubs is of interest to jointly optimise operations. Furthermore, this enables one to put a focus on total costs. Studies investigating policy implications and legal frameworks to use idle urban space for consolidation as well as cost-utility analysis support future real-world implementations. To extend the scope of the DSS to related fields such as e-groceries, various specific challenges of food logistics operations such as recommended temperature ranges and food safety consideration (Fredriksson and Liljestrand 2015) have to be included. Additionally, while the DSS optimises routing decisions, it does not consider the willingness of cargo-bike drivers to follow such instructions. Consequently, incorporating various behavioural factors of drivers to study the impact of incentives is worth further investigation.

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