Modeling and Calibration of Last-Mile Logistics to Study Smart-City Dynamic Space Management Scenarios

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ABSTRACT

This contribution presents a base case modeling and calibration for simulation studies of last-mile parcel delivery in urban areas to be compared with future sustainable and livable alternative scenarios. We formulate a two-stage mixed-integer programming optimization framework. In the first stage, stopping points are identified using a facility location problem. In the second stage, these stopping points are served through multiple vehicle tours by solving a capacitated vehicle routing problem. The parameterization and calibration are based on real data for a part of the Hanover Linden-Nord district, which includes the street network, the parcel demand of a large logistics service provider, and stopping distances derived from trajectories. The model is the basis for follow-up work in the area of 5G-enabled dynamic space management.

CCS CONCEPTS

• **Computing methodologies → Model development and analysis**; • **Applied computing → Transportation**.

KEYWORDS

Urban Logistics, MILP, Optimization, Parking Space Management

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1 INTRODUCTION

There are many factors to consider in urban planning, but the effective management of public space remains a significant yet underemphasized challenge, especially as global shifts in climate, energy paradigms, and mobility emerge. Reimagining these spaces is essential. As just one example, the 5GAPS (research project) platform utilizes 5G mobile communications for mapping and representing public space and its occupancy virtually in a digital-twin framework. The developed database backend with continuous state updates from crowd-sourced mapping vehicles [4] will allow a dynamic booking for various purposes. One application area for such a framework is urban logistics and what innovative delivery concepts would be enabled by a corresponding smart city platform and technology, highlighted as further research direction in Bäßmann et al. [1].

Urban logistics, commonly associated with courier, express, and parcel (CEP) services, is a multifaceted domain spanning freight forwarding, retail logistics, and waste disposal. At the same time, new companies are entering the market, especially in the area of spontaneous and small-scale deliveries, such as e-grocery and meal services. Particularly in recent years, there has been an increased interest amongst established stakeholders and policymakers to test sustainable alternative concepts. Along with continued high levels of private car ownership, there is an increasing demand for urban (parking) infrastructure, fostering the need for efficient space utilization and strategic land allocation. Dynamic space management could enable more diverse access to these and (temporarily) utilize existing parking spaces for other purposes, enabling innovative and sustainable urban logistics concepts (e.g., delivery zones, micro-hubs, pick-up locations, or UAV landing zones).

In the city of Hanover (Germany), Linden-Nord has been designated as a pilot area for CEP logistics. Since 2019, 21 double parking bays have been reserved during the day as static logistics stops, along with two permanently blocked bays for micro-hubs [2]. A corresponding simulation study by Trott et al. [6] reveals service and environmental benefits, but indicates insufficiently provided bays. The designation of these additional bays intersects with established functions such as residents' parked cars and bicycles, construction sites, and outdoor restaurant areas. However, logistics bays usually require only temporary allocation rather than permanent occupancy. Here, a dynamic booking system could make unused space resources usable and manage various temporary uses.

This work contributes with the development and calibration of a basic model for simulating last-mile parcel logistics at neighborhood level including parking. It serves as a basis for follow-up studies to optimize logistics parking bay allocation in order to minimize risky and obstructive second-row parking.

2 PROBLEM FORMULATION

The objective of the simulation is to model how last-mile delivery vehicles meet customer parcel demands in the study area. The vehicles' current on-demand second-row parking is represented in this base case. For alternative scenarios, those will be substituted by simulating parking bay usage, minimized in number and with

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respect to conflicts with other occupations. The problem is formulated in two sub stages (see Figure 1). The selection of parking spots is done by optimizing walking distances to served customer's buildings, formulated as a facility location problem (FLP). A capacitated vehicle routing problem (CVRP) is adapted for routing the last-mile delivery vans serving a district's parking spots (and thus customers) from a central hub. This two-stage optimization is modeled via mixed-integer programming and solved in Gurobi, to benefit from the integrated approximation algorithms.

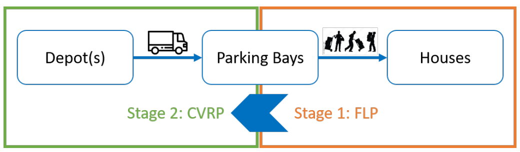

Figure 1: Problem separation into two stages.

Besides trade-offs in global optimality, the two-stage architecture reduces computational complexity and allows an separated implementation and processing of the carrier-spanning strategic facility definition component (handled by a higher-level entity, e.g. a booking system for dynamic space management) and the carrier-specific operational tour planning and scheduling (solved individually by carriers). Further carriers and their demands can be integrated as additional stage 2 instances.

2.1 Stage 1: facility location

In the first stage, an FLP is formulated to select used parking spots (as facilities) from the candidate set to optimize walking distances to buildings with a reasonable number of stops.

A specific scenario is configured by the parameters:

parking spot candidates $P = 1, 2, ..., p$
customer buildings $H = 1, 2, ..., h$
facility cost [sec. equivalent] D
walk time [sec.] $c_{ij} = 2 \cdot \text{dist(i, j)} \quad \text{with } i \in P, j \in H$

Parking spot candidates and customer buildings are prepared as geographic locations to estimate the required walking times based on distances with 1 m/s speed and visualization of results. All costs are estimated non-monetary by times, accordingly the facility fixed costs as (synthetic) seconds equivalent.

In the optimization process, two model variables are used to track spot-building assignments and active spots (facilities):

spot serves building $x \leftarrow P, H$
used spots $y \leftarrow P$

The stage's model objective minimizes the used link's costs, quantified by walking time, and the facility cost, to control their density. Further, to minimize conflicts with other parking demands, this basic objective can be extended by a penalty term for high parking load or probability.

$$\min \sum_{i \in P} \sum_{j \in H} c_{ij} \cdot x_{ij} + D \sum_{i \in P} y_i \tag{1}$$

While minimizing the objective, several model constraints need to be fulfilled. Namely, both model variables x and y are binary. Every building must be covered by one parking spot, while used spots need to be set up.

$$\sum_{i \in P} x_{ij} = 1 \quad \text{with } j \in H \quad \text{and} \quad x_{ij} \le y_i \quad \text{with } i \in P, j \in H \tag{2}$$

2.2 Stage 2: capacitated vehicle routing

Next, the vehicle tours are optimized to serve the previously selected spots with multiple same-sized vehicles from a single hub.

The adjustable problem parameters include all possible origin-destination nodes based on parking spots and hub, linking edges, related costs, different limits and the parcel demand pooled by spot.

parking spots $B = 1, 2, ..., b$
nodes $V = \{0\} \cup B$
edges $E = (i, j) \in V^2 : i \ne j$
edge cost [sec.] $c_{ij} \quad \text{with } (i, j) \in E$
node service time
$s_i = (i = 0 \rightarrow L) \land (i \ne 0 \rightarrow d_i + S + q_i \cdot S) \quad \text{with } i \in V$
vehicle capacity [parcels] U
spot demand [pcs.] $Q = \sum_{i \in B} q_i$
walking time [sec.] $d_i \quad \text{with } i \in B$
loading time [sec.] L
shift time limit [sec.] T
service time duration [sec.] S
minimal utilization G

Model variables are used to keep track of used edges, nodes' parcel flow and time.

used edges $x \leftarrow E$
parcel flow $u \leftarrow B$
time flow $f \leftarrow V$

The model objective minimizes the used edges' time cost plus the nodes' service time.

$$\min \sum_{i,j \in E} x_{ij} \cdot (c_{ij} + s_i) \tag{3}$$

While x is constrained to binary, the in- and outgoing visits of parking spots are fixed to one and the common 'flow formulation' is used to connect vehicle routes implicitly by preserving the parcel flow. In addition, the time flow is formulated analog to this.

$$\sum_{i \in V, j \ne i} x_{ij} = 1 \text{ with } j \in B \quad \text{and} \quad \sum_{j \in V, j \ne i} x_{ij} = 1 \text{ with } i \in B \tag{4}$$

$$\begin{aligned} x_{ij} = 1 &\Rightarrow u_i + q_j = u_j \quad \text{with } i, j \in E : j \ne 0, i \ne 0 \\ x_{ij} = 1 &\Rightarrow f_i + c_{ij} + s_i = f_j \quad \text{with } i, j \in E : j \ne 0 \end{aligned} \tag{5}$$

Further, the initial flows are forced to the first demands and the flow in nodes needs to satisfy their demand.

$$x_{0j} = 1 \Rightarrow \quad u_j = q_j \quad \text{and} \quad u_i \ge q_i \quad \text{with } i, j \in B \tag{6}$$

The parameterized limits are applied as upper parcel and time flow bounds.

$$u_i \le U \quad \text{and} \quad f_i + c_{i0} \le T \quad \text{with } i \in B \tag{7}$$

The vehicle number is bound for easier convergence, and vehicle utilization and duration are balanced.

$$\sum_{j \in B} x_{0j} \ge \frac{1}{U} \sum_{i \in B} q_i \tag{8}$$

$$x_{i0} = 1 \Rightarrow \quad f_i + c_{i0} \ge G \cdot T \quad \text{and} \quad u_i \ge G \cdot U \quad \text{with } i \in B \tag{9}$$

3 CASE STUDY: DATA INPUT AND PROBLEM PARAMETRIZATION

The densely populated Hanover district of Linden-Nord, with its industrial working-class history, serves as this study's case. Bordered by rivers Leine and Ihme, the Fössestraße main road, and the Westschnellweg freeway, its unique zip code (30451) aids in data filtering. Limmerstraße diagonally bisects the area with several one-way and restricted zones. This study focuses on the northeast part. Used data sources and processing, as well as design decisions for the base model parameterization, are described in the following.

3.1 Infrastructure network

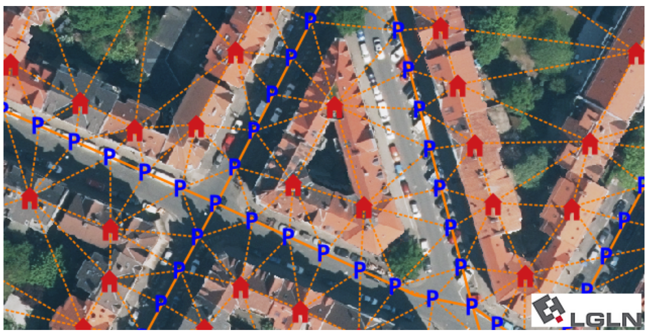

Figure 2: Generated network structure in the study area with streets (lines), foot links (dashed), parking spots (P) and buildings (houses). [aerial imagery by LGLN, 2023]

All infrastructure objects are modeled in a combined and georeferenced network structure (see Figure 2), so different levels of detail and processing can be derived. The study area's street network and building center points were extracted from OSM [5]. The building points were revised via aerial images and the streets were extended by links to the carrier hub. In this base case scenario, parking spot candidates are sampled along the street every 10 m to simulate current on-street stopping, resulting in 1763. For future logistic bay studies, those can be replaced by automatically extracted bays [3] and connected to the closest street. Parking spots and buildings are connected by a Delaunay Triangulation, representing ways by foot.

Based on this, abstracted origin-destination graphs are prepared and routed individually for both problems.

3.2 Carrier parametrization

Not only does the infrastructure vary between different areas, but also the studied CEP carrier needs to be parameterized based on local characteristics like vehicle fleet and shipping demand. In this study, the focus is put exemplarily on a major carrier operating in Germany, adjusted to the local characteristics in the study area based on provided data and information.

One aspect already mentioned in the previous section is the location of respective city or regional hubs, which can be researched online. For the delivery vehicles, a capacity of 180 parcels is set based on expert knowledge, as the maximum tour duration to 8 hours (incl. 1 h pre- and follow-up work as loading time). Further, a service time duration of 1 min. per parcel and stop is assumed. Walking times result from the stage 1 FLP based on spot-building distances in the network. The minimal utilization is adjusted to 66 %. The driving time costs for each edge are estimated from their length and 40 % of the speed limit. This factor was derived from the real average speed of 12 km/h in several delivery trajectories compared to the dominant limit of 30 km/h in the study area.

The parcel demand of buildings (and customers, respectively) is based on provided real data for the area of one carrier. The given average number of parcels over 34 working days in autumn 2022 indicates a daily demand of 589 parcels in the defined study area. Those are randomly assigned to the prepared building nodes, which can be used to simulate daily variations via different random seeds.

3.3 Facility calibration

As a fundamental parameter, the facility cost needs to be quantified. In the presented approach it is not a known (time) cost for facility setup or stopping but a fictitious one to keep the number of facilities under control. To not under- or overestimate the parking spot demand, a parameter study is carried out to calibrate the facility cost, reproducing realistic stop distances in the final tours. As a target value, a median distance of 65 m between subsequent stops was observed in several analyzed delivery trajectories in the area.

4 RESULTS AND DISCUSSION

Since several optimization runs in different configurations were necessary for the following results, we decided to use a 1 % gap to the estimated optimum (MIPGap) as a consistent termination criterion for stage 2, resulting in a 'several-minutes run time' on a office computer. Thus, these are near-optimal solutions but not less realistic due to varying human decisions in reality. Stage 1 is solved within seconds despite the large number of candidates.

With all other model parameters set, the facility cost was varied between 30 and 140 for calibrating resulting stop distances in the final tours. Additionally, ten different random seeds are used for the initial parcel distribution to simulate the influence of different configurations. A higher facility cost results in a lower number of parking spots, as one can see an increase in median stop distances in Figure 3 (top). From the plot, 70 (sec. equivalent) can be read as the appropriate facility cost to achieve the stop distance reference of 65 m. Despite clear level differences in objective values between runs, a consistent minimum range supports the choice. In addition, the number of tours, or vehicles required, consistently remains at four, aligning with field observations.

Table 1: Resulting delivery tour measures of stage 2 CVRP.

tour	stops [#]	load [#]	duration [h]	drive dist. [km]	walk dist. [km]
1	25	151	7.8	7.8	4.3
2	24	139	7.4	6.3	4.0
3	24	138	7.7	8.9	4.2
4	26	161	8.0	8.0	4.3
Σ	99	589	30.9	31.0	16.8

With all parameters set, we take a closer look at one of the resulting passes as an illustrative example. The parcels are distributed to 390 houses on this synthetic day. Stage 1 returns an optimum of

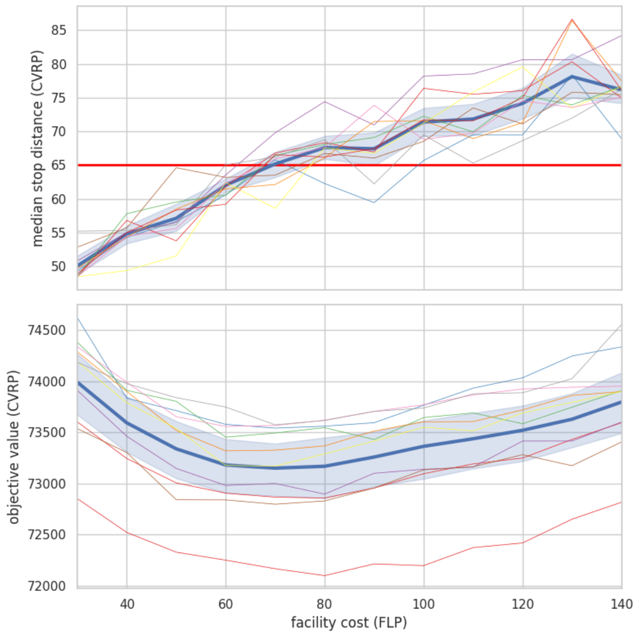

Figure 3: Parameter study on median stop distances (top) with 65 m reference and objective value (bottom) resulting from varying facility cost.

Figure 4: Resulting parking spots and vehicle tours. [map tiles by Stamen Design and OpenStreetMap contributors, 2023]

99 picked parking spots, mapped as bullets in Figure 4 connected by the resulting four tours from stage 2. The resulting median stop distance in this case is 65.6 m, which is very close to the targeted 65 m regarding GNSS positioning inaccuracy and model variations. More tour details are given in Table 1, showing a quite balanced number of 24-26 stops, loads of 138-161 and 7.4-8.0 h trip duration of the vehicles. There is still capacity for parcels in all vehicles, so the area and demand could be adjusted upwards. However, it is also important to consider the time limit, which is almost reached. It is more important than tearing out all the tours to keep the general conditions constant when comparing them later with alternative scenarios. As a notable feature of the area, the tour lengths benefit from comparatively short access routes. The high population density also results in short distances within the area. This explains the driving distances, which at first glance appear to be quite short in relation to the walking distances.

5 CONCLUSION AND OUTLOOK

This study presents a base case model and calibration process for simulating last-mile CEP deliveries in urban areas via a two-stage MIP optimization, beginning with the identification of stopping points through an FLP and subsequently serving them with multiple vehicle tours via a CVRP. The model is parameterized and calibrated using real data from the Hanover Linden-Nord district, providing a realistic foundation for simulating alternative scenarios. In particular, the distance between subsequent stops of about 65 m was determined as a target from real delivery trajectories, which was closely achieved with the selected parameterization at 65.6 m.

This contribution provides a base model for future scenario studies of alternative last-mile delivery concepts in urban areas. For this reason, it is designed to be extendable to parking bay management and current on-street parking spots can be supplemented or replaced easily by parking bays. The optimality trade-off resulting from two stages could be investigated by comparison with an integrated approach. Existing parking areas and their utilization during the day will be determined from mobile mapping LiDAR data in order to investigate the resulting effects of different planning strategies in a simulation study. A dynamic parking reservation system enables further innovative and sustainable logistics concepts, such as cargo-bike facilitating micro-hubs, mobile parcel pick-up points or UAV landing zones.

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