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An Optimisation Approach to Planning Micro-logistics Centers for On-demand Food Delivery Service with A Mixed Operational Model

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An Optimisation Approach to Planning Micro-logistics Centers for On-demand Food Delivery Service with A Mixed Operational Model

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Abstract

This work presents a comprehensive framework to assist on-demand meal delivery platforms with the decision-making of delivery model choice and the planning of the micro-logistics centers within a mixed operational model. We consider two prevalent delivery models: (a) the owner-operator model operating with independent contractors (IC); and (b) the company-vehicle model with micro-logistics centers (CV). These centers serve as the place to accommodate company-owned vehicles. Assuming platforms have operated with independent contractors for some time, we aim to determine the necessity of micro-logistics centers, indicating whether to maintain the IC model or adopt a hybrid approach, and optimize the planning of necessary centers. We propose a mixed integer optimisation problem to minimize the total costs while considering the convenience for couriers. It combines strategic decisions for locating micro-logistics centers considering the dimensions of the centers (number, locations and vehicle stock) with operational considerations (the impact of couriers' distribution and shifts on repositioning company vehicles). For the CV model, two operational policies are considered: fixed coverage with return-to-origin requirement, and time-variant coverage with global redistribution considering the spatial-temporal variation of demand. Our findings suggest that diverse market conditions and operational approaches can lead to different strategies. We also applied the model for the city of Amsterdam, and it reveals that multiple centers are needed and the platform may invest in courier convenience by choosing center locations with great accessibility.

Keywords: On-demand meal delivery; Delivery model; Independent contractors; Facility planning; Cost minimisation

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List of Abbreviation

ODFD: On-Demand Food Delivery
IC: delivery model, the owner-operator model operating with independent contractors (using their personal vehicles)
CV: delivery model, the company-vehicle model with micro-logistics centers

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1
Introduction

Over the past few years, there has been a substantial worldwide expansion of on-demand food delivery (ODFD) services, which are made possible by online meal delivery platforms like Uber Eats, Meituan, and Just Eat Takeaway.com. These platforms enable customers to conveniently order meals from a wide range of restaurants, choosing their desired time and location. The worldwide consumer base utilizing online meal delivery systems has surpassed three billion by 2022, due to a consistent growth in user engagement over the previous few years [1]. This development is largely related to the convenience and accessibility provided by these services. ODFD has attracted the attention of industry experts, politicians, and academic researchers because of its growing market and unique features (Seghezzi et al., 2021).

The meal order arrival flow is highly unpredictable and fluctuating, with a typical order delivered just after the dish is ready (Van Lon et al., 2016). Short delivery windows and frequent new orders limit consolidation chances and require the use of many couriers simultaneously (Reyes et al., 2018), compared to other last-mile services, such as parcel delivery, which may operate on more stable and predictable routes. Customers' growing demands, desire for relatively short delivery times, and price sensitivity pose challenges to the logistics process of these ODFD platforms: they must control costs while maintaining a certain level of responsiveness time and competitive price to attract and retain customers and ensure the company's profitability (Seghezzi and Mangiaracina, 2021).

One of the important cost components comes from the delivery operations. The delivery models of meal delivery platforms fall into two main categories (Furlan, 2021; Scheiwe, 2022; Zambetti et al., 2017). The first involves platforms that match diners with restaurants but do not handle delivery logistics. The second type, a more common model, utilizes its own networks of freelance couriers to handle deliveries as well as order processing and management. In the second category, certain organizations, like Uber Eats, permit their couriers, referred to as independent contractors, to utilize their personal vehicles from any location and at any desired hour. Meituan operates offline stores using company-owned motorcycles and couriers. On the other hand, companies such as Just Eat Takeaway.com employ a hybrid approach by allowing couriers either to use company-owned vehicles (e.g., e-bikes) from specific facilities or operate as independent contractors with their personal vehicles and receive an allowance [2].

The performance of different delivery models under various logistics contexts is discussed. Ballare and Lin (Ballare and Lin, 2020) stated that network size and customer density will influence the performance of the microhub delivery paradigm in the context of last-mile parcel delivery and that it is better suited to cities with medium to high customer densities, with performance measured in terms of labour costs associated with travel time, number of trucks or crowdshippers dispatched, total vehicle miles travelled (VMT), and total daily operating costs. Ai et al (Ai et al., 2021) indicated that, while crowd-sourcing services are easily accessible in high-density areas, they may not be the best solution for restaurant meal delivery, where trips start and are organised by restaurants, and the most cost-effective delivery choice varies with different scenarios of restaurant density, customer density, demand distribution, and other neighbourhood-specific characteristics. Despite brand opportunities and better control of vehicle maintenance and delivery reliability with parking spaces and company-owned vehicles, little is said about the economic evaluation of the

[1] https://www.statista.com/topics/9212/online-food-delivery/
[2] https://www.thuisbezorgd.nl/en/courier/the-inside-track/delivering-with-us/choosing-ride-shift-starting-location

company-vehicle model in the on-demand meal delivery industry, particularly in diverse market contexts and in a mixed delivery structure mentioned earlier, where platforms can choose between (a) an owner-operator model with independent contractors (IC), (b) a company-vehicle model (CV), or an integrated approach combining both. This makes it challenging for platforms to make informed decisions about whether to adopt a company-vehicle model or not.

This paper addresses this challenge by focusing on a critical aspect of implementing the company-vehicle model: the evaluation and planning of micro-logistics centers. These centers serve as facilities to accommodate company-owned vehicles, where couriers in the company-vehicle model pick up and return these vehicles to start or end their shifts. The planning of micro-logistics centers involves several interconnected decisions: first, it needs to determine 1) whether establishing micro-logistics centers is economically viable, which indicates whether a hybrid model or an IC-only model is preferable. If micro-logistics centers are necessary, the planning process extends to 2) identifying the optimal number and locations of these centers, 3) defining their respective service areas, and 4) determining the appropriate inventory of company-owned vehicles to be operated.

Current economic viability discussions of such infrastructures focus on telecom and transport (e.g., airline, cargo, and parcel delivery) industries, where a hub is used as consolidation and dissemination points in many-to-many flow networks and consolidation generates economies of scale (Mahmutogullari and Kara, 2016), which is different from the logistics practices in on-demand food delivery industry, in terms of specific functions and operations. Existing research in on-demand meal delivery largely focuses on operational aspects such as order batching and routing optimization, while limited literature addresses the strategic planning of facilities in this context. It also lacks comprehensive studies that include optimising the inventory of company vehicles - a crucial initial investment - and integrating the impact of facilities on operations into long-term planning. This integration is critical because operations, including company vehicle usage patterns, vehicle distribution locations, and courier shift arrangements, directly influence both facility running costs and the calculation of optimal fleet size.

Due to market challenges, ODFD platforms must examine their delivery strategy and carefully choose necessary facility locations, which influences operational dynamics, cost structures, and service efficiency. The choice of delivery model and smart placement of parking facilities, particularly in varying markets and delivery environments, are critical to the ODFD platforms' expenses. Furthermore, it is strongly tied to the company's expansion goals to provide new services beyond restaurants [3] or deliver other higher-margin categories of products [4] and it is critical to meeting the increasing demand for on-demand meal delivery [5].

We propose a comprehensive planning framework for micro-logistics centers in on-demand meal delivery service. Our approach considers interconnected strategic and operational factors, using historical data on courier shift start and end locations. We employ a cost-minimization strategy to evaluate trade-offs between delivery models and determine the optimal delivery plan. It also assesses the necessity of micro-logistics centers, identifies the number and locations of these centers, defines their coverage areas, and determines the stock for company-owned vehicles. We interpret the operational impact as the costs of vehicle distribution between centers and delivery points and present two models representing different operational policies: Model I assumes a fixed coverage area with a return-to-origin requirement for vehicles, while Model II incorporates time-variant coverage with global redistribution optimization. Beyond costs, the convenience of center locations for courier commutes is also considered.

The remainder of this report is organized as follows: Chapter 2 presents a comprehensive literature review. Chapter 3 outlines the key research questions, while Chapter 4 describes the system and defines problem objectives and scope. Chapter 5 introduces the mathematical models, including formulations of Model I and II. Chapter 6 presents the results, including instance descriptions, computational findings, managerial insights derived, and a case study of Amsterdam City. Finally, Chapter 7 concludes the paper with a summary of findings and directions for future work.

[3] https://www.wsj.com/articles/doordash-and-uber-eats-are-hot-theyre-still-not-making-money-11622194203

[4] https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/ordering-in-the-rapid-evolution-of-food-delivery

[5] https://www.jll.co.uk/en/newsroom/jll-appointed-by-just-eat-takeaway-dot-com-to-find-inner-city-space-across-europe

2

Literature Review

This research reviews the literature in four related directions: operations and optimization in the on-demand meal delivery, decisions including facility location, fleet sizing and rebalancing in shared mobility system, facility location problem, and districting.

2.1 On-demand Food Delivery

The on-demand meal delivery sector is booming. It is expected to generate $200 billion in gross sales by 2025. UberEats, Doordash, and Grubhub emerged due to rising demand for meal delivery. The platform-to-customer meal delivery market saw a 27% revenue rise from 2019 to 2020 (Jahanshahi et al., 2022).

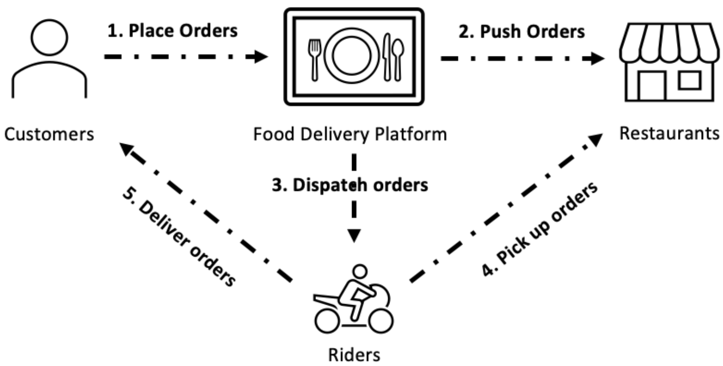


Figure 2.1. A typical process of on-demand meal delivery

Figure 2.1 illustrates the standard process for food ordering, pickup, and delivery facilitated by these platforms, involving various actors including the platform, delivery riders (couriers), restaurants, and customers. The sequence begins when a customer places an order through the online platform. Subsequently, the platform forwards this order to the selected restaurant and assigns a courier according to availability. The courier then picks up the meal from the restaurant and delivers it to the customer's location (Gao et al., 2021).

The operation of on-demand meal delivery is dynamic, capacitated, and stochastic with limited customer time windows and a limited number of couriers. It stands apart from typical delivery services mainly because of several features: its narrower delivery time windows, commitment to fulfilling almost all order requests immediately upon receipt rather than turning them down, the highly variable nature of meal orders and the involvement of couriers with variable working hours. The problem of optimizing logistics in this area is currently viewed as the most significant challenge in last-mile logistics (Michalopoulou et al., 2023). Such optimization includes considering the delivery area size, efficiently allocating resources such as manpower and fleet, order batching and routing optimization (Seghezzi et al., 2021).

Most of the current optimization studies focus on order batching and routing optimization, while few studies address the delivery model choice and involve facility configuration for on-demand meal delivery service from the perspective of strategic planning. Reyes et al. (Reyes et al., 2018) propose a dynamic deterministic framework to solve the courier assignment and capacity management problems in meal delivery routing operations dealing with challenges faced by meal delivery networks, such as the need for fast and reliable delivery within tight time constraints, and the ability to respond to fluctuations in demand. Jahanshahi et al. (Jahanshahi et al., 2022) propose a novel Markov decision process model for the meal delivery problem and provide valuable insights into the courier assignment process and the optimal number of couriers for different order frequencies. Studies like the one by Zambetti et al., 2017 consider the depot in on-demand meal service as the place for couriers to wait for delivery and seek to maximize the demand coverage where a customer is considered covered if they can be reached by at least one restaurant taking into account a limited length of the full path (depot - restaurant - customer). However, since they don't distinguish between personal and company-owned vehicles, the associated fleet costs are overlooked. They assume couriers start each delivery from the depot, which doesn't reflect the reality of multiple deliveries per shift, and their considerations on specific restaurant-customer distances are unpredictable in the complex real practices. In contrast, we propose focusing on deadhead trips at the start and end of shifts, considering only trips between centers and potential restaurant/customer clusters, to better reflect realistic operational costs influenced by center locations.

2.2 Shared Mobility System Design

When a company considers the design of a shared mobility system, such as bike-sharing, car-sharing, or scooter-sharing, especially for a station-based one, the key design decisions considered include the number and locations of the stations, the transportation infrastructure and network, fleet sizing and inventory levels of sharing vehicles to be held at the stations and rebalancing operations among stations, with consideration for both total cost and service levels (measured both by the availability rate for requests and coverage of the origins and destinations) (Angelelli et al., 2022; Lin and Yang, 2011; Lin et al., 2013).

For the station location problem, the goal is determining the optimal number and placement of stations by minimizing impedance (p-median) (the average distance to the demand points covered from the stations to be allocated is minimized) or maximising coverage (the amount of reachable demand within a certain coverage area is maximized) (Mix et al., 2022). The main inputs for this problem typically include user demand patterns, population density, points of interest, and existing transportation infrastructure.

Regarding fleet sizing decision, it refers to determining the optimal number of vehicles needed to be deployed in the whole system and the initial number of vehicles at each station (Shui and Szeto, 2020). It should be considered as a strategic decision as the investment costs of vehicles are not negligible. This problem is often solved using simulation-based optimization techniques or queuing theory models. Benjaafar et al., 2022 model the system as a closed queueing network and develop a novel approach to approximate the minimum number of vehicles needed to meet a target service level. They highlight key differences between round-trip systems (where vehicles always return to their origin) and one-way systems (where vehicles can roam), and indicate that one-way systems require more buffer capacity due to the randomness in vehicle distribution across locations.

Rebalancing means how to redistribute vehicles efficiently to deal with the spatial and temporal imbalanced demands and usage patterns. Common rebalancing strategies can be broadly categorized into operator-based and user-based approaches. Operator-based strategies involve manual redistribution of vehicles using rebalancing trucks, which can be further divided into static and dynamic rebalancing based on timing. User-based strategies, on the other hand, focus on incentivizing users to self-rebalance the system (Pal and Zhang, 2017).

The differences between on-demand meal delivery platforms and shared mobility systems can lead to distinct operational challenges. Shared mobility systems treat customer rental requests as input for facility planning, while our problem considers courier usage of company vehicles as a decision variable controlled by the company's cost trade-off between company-vehicle and independent contractor models. Moreover, the criteria for location selection in our model (courier accessibility via public transport, minimizing repositioning costs) differ from shared mobility systems' focus on customer convenience and geographic coverage to include their key origins and destinations within walking distance for profitability maximization. Also, the timing of vehicle pick-up and drop-off tied to courier shifts introduces unique logistical characteristics.

2.3 Facility Location Problem

Facility location is a critical strategic decision in operations management and logistics, including the determination of facility numbers, locations, and demand point allocations. The complexity of these problems varies based on capacity constraints, time horizons, and data certainty. Objectives can range from cost minimization to distance reduction, coverage maximization, or balancing multiple goals. Recent research has expanded to integrate facility location with inventory and routing decisions, known as the location-routing-inventory problem. This integrated approach has proven instrumental in designing efficient supply networks (Govindan et al., 2014; Zhalechian et al., 2016; Zheng et al., 2019). The cost components typically considered in these models include facility setup, inventory holding, and transportation costs (Hiassat et al., 2017; S. Liu and Lin, 2005; S.-C. Liu and Lee, 2003). Ahmadi-Javid and Seddighi, 2012 also revealed that combining short-term decisions on vehicle routing and inventory planning with facility location optimization yields cost savings.

Notably, our study first examines the economic viability of a company-vehicle delivery model based on micro-logistics centers within a mixed delivery model structure, which differs from traditional facility location problems with an implication of a single model. Also, we include the consideration of courier accessibility to these micro-logistics centers using public transport. This factor is not typically included in traditional facility location literature. Furthermore, due to the unique nature of on-demand meal delivery, the cost components in our problem require new interpretations.

2.4 Districting

The districting problem is often applied in service and distribution contexts to define pickup and delivery districts prior to developing daily routing solutions (Kalcsics and Ríos-Mercado, 2019). This approach helps reduce the complexity of routing problems (Defryn and Sörensen, 2017), and improve drivers' familiarity with customer locations and route organization (Haugland et al., 2007; Zhong et al., 2007). When dividing areas into service districts, specific criteria such as compactness and contiguity are employed to meet operational needs. Compactness ensures reasonable travel times within districts, while contiguity guarantees physical connectivity without isolated areas (Kalcsics et al., 2005).

The application of districting concepts to on-demand meal delivery service areas remains relatively unexplored. The accessibility in our study uniquely focuses on courier convenience in accessing facilities before delivery, departing from traditional districting's emphasis on unobstructed vehicle travel within districts. In the context of this paper, districts can be viewed as service areas for micro-logistics centers. The compactness criterion can be incorporated into the objective function to limit travel time and distance between demand points and centers. Also, the continuity criterion can ensure coverage meets geographic or administrative restrictions.

2.5 Summary and Discussion

The literature review highlights several gaps and unique aspects in the research on on-demand meal delivery systems. Most studies of optimisation in the on-demand meal delivery sector concentrate on operational aspects, neglecting courier assignment, delivery model selection, and economic considerations of parking facilities. ODFD platforms face different operational challenges compared to other logistics practices, e.g., parcel delivery, or shared mobility systems, which require new interpretations of cost components and methods to describe the system. There is also little discussion on courier convenience in accessing facilities before delivery and the application of districting concepts when considering service areas in this industry.

This study introduces the examination of economic viability for a company-vehicle delivery model based on micro-logistics centers within a mixed delivery model structure. Also, we propose a novel method to provide a comprehensive planning framework integrating the operational considerations and considering multiple dimensions of centers.

3
Research Questions

This study aims to create a model that can assess the necessity of setting up micro-logistics centers to adopt the company-vehicle delivery model and optimise their locations in urban regions in the on-demand meal delivery sector. And the main question is:

How can we assess the economic viability and optimal planning of micro-logistics centers within a mixed structure of delivery models?

This question will be explored and answered by breaking it down into the following specific sub-questions:

- Sub-question (1): Identifying Criteria - 'What criteria are crucial for evaluating the economic viability of centers in on-demand meal delivery?'

  This involves the identification and analysis of specific criteria to guide the decision-making process. It offers a measurable way to evaluate the need for and influence on operations to have centers.

- Sub-question (2): Economic Viability and Optimal Locations - 'Under what conditions is the company-vehicle delivery model economically advantageous, and how can we determine the optimal locations, coverage of these centers, as well as the inventory of company vehicles?'

  This sub-question examines the economic factors that justify implementing centers in meal delivery systems. It aims to develop a method for identifying different dimensions of optimal centers, considering courier activities and accessibility.

By addressing these sub-questions, the study attempts to provide a thorough and practical strategy for determining a cost-effective delivery model and necessary distribution of centers in urban meal instant delivery services.

4

Problem Scope and Objective

We consider an on-demand meal delivery platform that dispatches couriers to deliver orders from restaurants to customers and aims to minimize its total operational cost. We assume that the platform has been in operation with independent-contractor couriers for a long time and has collected historical data on where and when couriers start/end their shifts, indicating their first/last delivery locations, and their shift schedules.

4.1 System Description

Graph Representation The platform's service area is divided into uniform hexagonal zones, offering uniform adjacency among zones in the network. Each zone ($i \in I$, where I is the set of zones in the network) is centered at r_i. A graph $G = \{I, A\}$ represents the connectivity of the service region, where each vertex corresponds to a zone, and an edge $(i, j) \in A$ exists between adjacent zones having a common border. The travel time t_{ij} between any two zones i and j is defined based on couriers' travel time on the shortest path between zone centers.

Time Space Let $\mathscr{T}$ represent a typical operation day in our planning horizon. This horizon is discretized into equal time intervals, where $\mathscr{T} = \{\tau_0, \tau_1, \ldots, \tau_n, \ldots, \tau_N\}$ to capture the variation of couriers' movements during the day. Each $\tau \in \mathscr{T}$ represents the time stamp at the beginning of the period.

Delivery Model We consider a hybrid operational model, which incorporates two approaches: (a) the owner-operator model with Independent Contractors (IC) and (b) the Company-Vehicle model (CV) with micro-logistics centers.

In (a) the owner-operator model, IC couriers use their personal vehicles and start/end their shifts at their first/last delivery locations. They receive a basic hourly salary (C_h^O), plus an additional allowance (C_a^O) for the use of their personal vehicles.

For (b) the company-vehicle model, CV couriers use vehicles provided by the company and are required to start and end their shifts at designated micro-logistics centers. They also receive the same basic hourly salary (C_h^O). Unlike IC couriers, CV couriers must travel between centers and delivery zones at shift start and end. And the company covers the cost of these non-productive trips by including compensation for this travel time in the couriers' pay.

We assume either IC or CV couriers, are using the same type of transport modes for delivery (e.g., vehicles, e-mopeds etc). Both types of couriers earn the same hourly basic salary (C_h^O) and travel at a homogeneous, constant speed throughout the service area.

We assume that the platform aims to re-consider the delivery model choice in an area for which historical operation data exists. Based on the historical data, we can obtain observations of courier activities, particularly their starting and ending times and locations, which indicate their historical first and last delivery zones. We define $\tilde{S}_i^\tau$ as the number of couriers starting their shift at zone i at time τ and $n_{ij}^{\tau\tau'}$ as the probability for a courier starting at zone i at time τ to end their shift at zone j at time τ'.

For a hybrid delivery model, to introduce micro-logistics centers and provide CV service in such an area, we assume that the platform considers a service level, denoted by α. The service level represents the percentage of time that a given number of couriers can adequately cover the observed courier activity patterns in a specific zone based on historical data. We use S_i^τ to denote the number of couriers at a certain service level desired by the platform. And S_i^τ can be determined at a given service level (α) by Equation 4.1. For zone i at time τ, for example, we have 400 days of historical data on couriers' starting records where 200 days with 0 couriers, 100 with 1, and 100 with 2. Thus, 0 couriers cover 50% of demand, 1 covers 75% and 2 for 100%. And if the platform's desired service level α is 75%, then S_i^τ would be 1. Table 4.1 shows how the number of couriers (S_i^τ) is determined based on the chosen service level and historical data for zone i at time τ in this example.

$$S_i^\tau = \min \xi_i^\tau : F_i^\tau(\xi_i^\tau) \geq \alpha, \qquad \forall i \in I, \tau \in \mathscr{T} \tag{4.1}$$

$$\xi_i^\tau \in \mathbb{N}, \qquad \forall i \in I, \tau \in \mathscr{T} \tag{4.2}$$

where F_i^τ is the cumulative distribution function of courier counts for zone i at time τ; α is the desired service level and $0 \geq \alpha \leq 1$.

Table 4.1. Example of determination of the values of S_i^τ

Couriers	Days	Cumulative	%Service Level (α)	S_i^τ
0	200	50%	0-50%	0
1	100	70%	50-75%	1
2	100	100%	75-100%	2

When determining the possible CV service needs of zone i in terms of the number of couriers, S_i^τ is considered and the remaining required number of couriers will be assigned as IC couriers, denoted by $\overline{S}_i^\tau$. The historical starting and ending records of these S_i^τ couriers are treated as their first and last delivery locations, which will result in 'non-productive legs' - the trips from potential centers to these delivery points.

Furthermore, in the context of CV model, the starting and ending shift activities of CV couriers impact vehicles' inventory at centers through pickup and drop-off activities. To maintain system balance, all vehicles that are picked up must be returned to designated centers.

Accessibility Measure We introduce the **accessibility score** for each zone, A_i, as a quantitative measure to evaluate public transport conditions for each zone in a network, reflecting the convenience for couriers to access the zone. We assume that couriers use public transportation for their commutes. And a higher accessibility score suggests that a zone is well-connected to public transport networks, implying a lower effort for couriers to reach these locations. While the exact commute costs are challenging to quantify due to the privacy concerns and variability of couriers' residences, the accessibility score serves as a practical alternative to assess a zone's potential for easy access. By considering this score when selecting center locations, companies can provide convenience for couriers who commute to these centers using company vehicles, potentially improving job satisfaction and employee retention, as well as the attractiveness of their company-vehicle model to potentially increase its adoption among couriers.

A_i is calculated based on the public transportation condition within zone i, including the availability and frequency of transport options within it and the zone's connectivity to others. Specifically, the accessibility score A_i of zone i consists of three components, the number of public transport modes available within a certain walking distance from the center of the zone, the number of lines of the corresponding mode, and the number of zones it can connect to represent each zone's accessibility and make sure the chosen location of center meets the requirement of accessibility. Let $\Omega = \{1,2,3,4\}$ be the set of different modes, with 1,2,3 and 4 denoting bus, metro, tram, and train, respectively. Particularly, since each mode contributes to the overall accessibility by offering different options for commuters, the number of public transport modes available within 350m walking distance from the centroid of zone i is counted with the denotation of PT_i^1. The number of lines in the corresponding mode is denoted by $PT_i^{2m}, m \in \Omega$, respectively. To some extent, it represents the frequency of service for each mode of public transport, and higher frequencies generally mean shorter waiting times, improving accessibility. Also, the number of zones connected via public transport $PT_i^{3m}, m \in \Omega$ reveals the coverage of key destinations that can be reached from zone i. It is important for the candidate zone for the location of center to be accessible by couriers living in different zones.

The overall accessibility score A_i of zone i can be interpreted in terms of the weighted sum of these critical factors:

$$A_i = u_1 * PT_i^1 + u_2 * \sum_{m \in \Omega} u_{2m} * PT_i^{2m} + u_3 * \sum_{m \in \Omega} u_{3m} * PT_i^{3m} \tag{4.3}$$

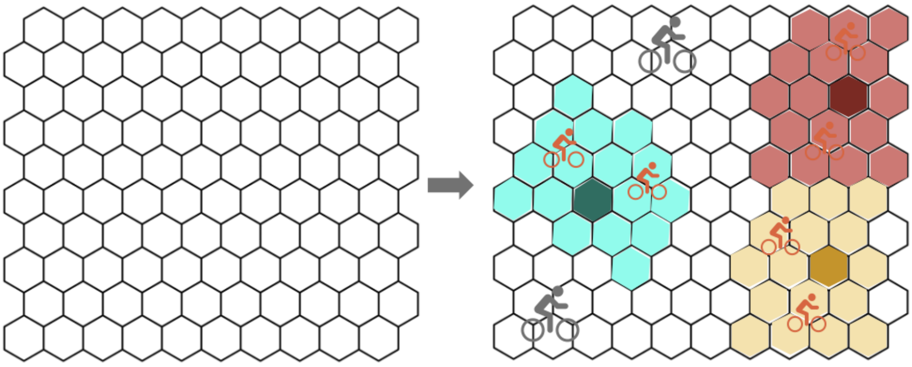


Figure 4.1. Illustration of key decisions

4.2 Objectives

Our study aims to develop a strategic model that provides insights into the following key decisions for the platform to optimize the costs:

1. Delivery model selection: choose between maintaining operations with independent contractors (IC) or adopting a hybrid model that includes both IC and company-vehicle (CV) couriers operating with micro-logistics centers, to minimize total costs;
2. Micro-logistics center placement: select strategic locations for micro-logistics centers to support CV operations, ensuring accessibility to couriers;
3. Coverage area and vehicle allocation: define the service zones allocated to each micro-logistics center for CV operations (coverage area consists of zones where center provides company vehicles for CV couriers to start), and determine the optimal number of company vehicles to be stationed at each micro-logistics center.

In particular, the coverage area of a center consists of multiple zones where the company provides vehicles for CV couriers to start their routes. Each zone serves as a starting point for several couriers beginning at different times throughout the day. Couriers use these company-owned vehicles for their delivery routes, which may end at different locations. The coverage is defined by these starting zones associated with a center, not the entire delivery area.

For the total costs, we consider four cost components:

- Facility-related costs: to construct necessary micro-logistics centers;
- Vehicle depreciation costs: to purchase and operate company fleet;
- Operational costs of CV model: labor cost for CV couriers; and vehicle repositioning costs (including distribution from centers to their first delivery locations and collection from last delivery locations back to centers);
- Operational costs of IC model: labor costs for independent contractors.

As explained in Section 4.1, we assume both types of couriers receive the same basic hourly salary while independent contractors receive an additional allowance for using their personal vehicles. And the common labor costs are omitted in the following cost minimization problem and our focus is on repositioning costs for the CV model and additional payments for the IC model respectively. Figure 4.1 illustrates our decisions to divide a uniform hexagonal grid according to the delivery model choice. Colored zones represent different coverage areas for centers with CV couriers (in orange), with darker ones indicating potential center placements. The white areas suggest they are assigned to be served by IC couriers (in grey).

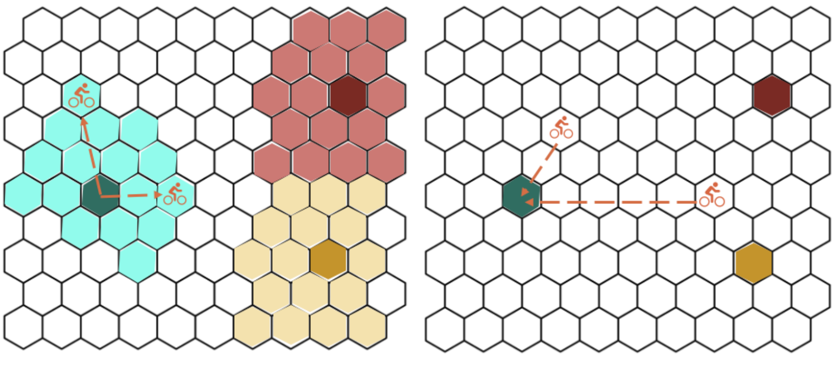
5

Mathematical Models

In this section, we will introduce two models: Model I considers a fixed-coverage problem with the return-to-origin operational policy, in hybrid delivery operations where centers, if needed, have fixed coverage areas for CV service. These areas remain constant over time, considering geographic connectivity constraints imposed by physical or administrative requirements. Also, CV couriers need to return company-owned vehicles to their original centers at the end of their shifts, regardless of their final locations.

Model II addresses a problem with time-variant coverage and global redistribution optimisation to obtain more efficient resource allocation. It allows for flexible coverage areas of centers that can change with time τ. It also optimizes the returns for CV couriers based on overall cost trade-offs and maintains a system-wide balance in company-owned vehicles' inventory.

Figure 5.1 and Figure 5.2 show the illustration of the requirements and decisions included in Model I and II respectively.



(a) Model I - Coverage & Vehicles' Supply

(b) Model I - Returns

Figure 5.1. Illustration of Model I

5.1 Model I

This section provides a complete description of Model I, where the centers, if needed, have fixed coverage over periods during the operation with geographic continuity constraints. The notation and definition of sets, parameters, and variables involved in this mathematical model can be found in Table 5.1.

Table 5.1. Sets, Variables, and Parameters in Model I

Set	
I	Set of zones;

Continued on next page

Table 5.1 – Continued from previous page

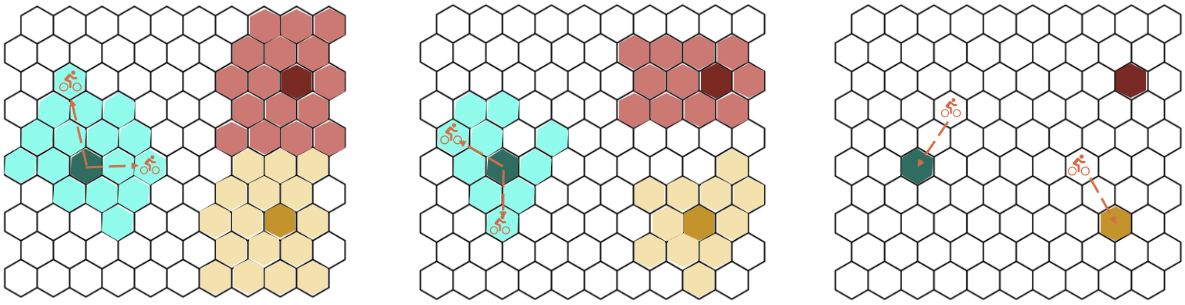
I_c	$I_c \subseteq I$, Set of candidate zones for center location whose accessibility score meets the minimum threshold;
A	$A = \{(i,j) \mid i,j \in I$, and i is adjacent to $j\}$;
P	Set of candidate center and its coverage;
$\mathscr{T}$	set of time steps during operation period, and $\mathscr{T} = \{\tau_0, \tau_1, \ldots, \tau_n, \ldots, \tau_N\}$;
$G = \{I, A\}$	Graph of the network;
Variable	
x_i^p	equals 1 if zone $i, i \in I$ is covered by center p, 0 otherwise;
y_i^p	equals 1 if the center p is located at zone i, 0 otherwise;
z_{ij}^p	equals 1 if zone j is covered by center p located at zone i, 0 otherwise;
v_i	equals 1 if zone i is assigned to be served by IC couriers, 0 otherwise;
$q^{p\tau}$	inventory in terms of the number of vehicles in center p at time τ;
q_0^p	stock of vehicles needed for the CV couriers within the coverage area of center p;
$e_i^{p\tau}$	number of CV couriers ending their shift at zone i at time τ that need to return to center p ;
f_{ij}^p	variable representing continuity on arc $(i,j) \in A$ within the coverage area of center p;
Parameter	
$n_{ij}^{\tau\tau'}$	the probability of couriers starting their shift at zone i at time τ and ending their shift at zone j at time τ'
$\tilde{S}_i^\tau$	the total number of couriers starting their shift at zone i at time τ, and $S_i^\tau = \overline{S}_i^\tau + S_i^\tau$
S_i^τ	the number of couriers needed as CV couriers for a certain service level α starting at zone i at time τ
$\overline{S}_i^\tau$	the remaining number of couriers hired as IC couriers to start at zone i at time τ if zone i is assigned to be served by CV service
$E_{ji}^{\tau'\tau}$	the number of CV couriers ending at zone i at time τ who start their shift at zone j at time τ', with $E_{ji}^{\tau'\tau} = S_j^{\tau'} * n_{ji}^{\tau'\tau}$
t_{ij}	travel time between zone i and j (h) by company vehicles assuming free flow speed;
C_i^F	fixed costs of locating a center in the center of zone i (expressed in euros per day);
C_h^O	couriers' basic hourly salary (expressed in euros per hour);
C_b^F	depreciation costs for each vehicle (expressed in euros per day);
C_a^O	the allowance paid for one IC courier using their personal vehicles (expressed in euro per person);
U_0	maximum number of vehicles that fit in each center;

Model I with the objective of cost minimisation is formulated as follows:

$$\min \quad \sigma_b^F + \gamma_b^F + \zeta_b^O + \theta_a^O \tag{5.1}$$

The objective function (5.1) aims to minimize the total investment and operation costs of the delivery model adopted for one typical business day. Specifically, the investment refers to the construction (σ_b^F) and vehicle-depreciation costs (γ_b^F) for centers to provide CV service. The operation cost includes the cost of non-productive legs for CV couriers (ζ_b^O) that they are required to travel between the center and their starting and ending delivery locations, and the labour costs for IC couriers (θ_a^O). The same part of labor cost calculated on the basic hourly salary for couriers in both IC and CV plans is omitted.

The model also seeks the optimal number of centers needed. We explain each item of objectives separately in (5.2)-(5.8). Constraints on districting and capacity of centers are presented by (5.10)-(5.31). The



(a) Model II - Coverage & Vehicles' Supply at time 1

(b) Model II - Coverage & Vehicles' Supply at time 2

(c) Model II - Returns at certain time

Figure 5.2. Illustration of Model II

following sections elaborate on each category of constraints.

Investment Cost: Facility-related cost. Let $p \in P$ be the set of centers. Each center has a coverage area in which CV service is provided. We introduce the binary variable y_i^p, and it equals 1 when the center p is located at the zone i. Also, the center locations can only be selected from the candidate zones in set $I_c, I_c \subseteq I$, whose accessibility score meets the minimum threshold. If center p is required and it is selected to be placed in zone i, the associated facility cost is determined by dividing the total cost of setting up a center in zone i over the duration of planning to estimate the daily cost (C_i^F). We define σ_b^F as the fractional variable to represent the facility-related cost.

$$\sigma_b^F = \sum_{p \in P} \sum_{i \in I_c} C_i^F * y_i^p \tag{5.2}$$

$$\sigma_b^F \in \mathbb{R} \tag{5.3}$$

Investment Cost: Vehicle depreciation costs. To provide CV couriers with company-owned vehicles, there are costs for purchasing these vehicles. C_b^F is introduced to reflect this term of cost, which is also broken down across the planning time horizon into one-day cost. q_0^p denotes the initial inventory (which also is the total vehicles needed for the CV couriers within the coverage areas) at center p. Fractional variable γ_b^F is calculated to purchase all vehicles needed.

$$\gamma_b^F = \sum_{p \in P} C_b^F * q_0^p \tag{5.4}$$

$$\gamma_b^F \in \mathbb{R} \tag{5.5}$$

Operation Costs: Costs for non-productive legs. CV couriers' shifts include time spent travelling between the centers and zones where they have the first and last delivery. We use z_{ij}^p to denote the non-productive legs and it equals 1 if zone j is covered by center p located at zone i. C_h^O represents the hourly salary paid to couriers, and fractional variable ζ_b^O calculates the costs for these non-productive trips when repositioning couriers between the centers and their starting (or ending) point over an operational day.

$$\zeta_b^O = \sum_{p \in P} \sum_{\tau \in \mathcal{T}} \sum_{i \in I_c} \sum_{j \in I} C_h^O * z_{ij}^p * (t_{ij} * S_j^\tau + \sum_{k \in I} \sum_{\tau' \in \mathcal{T}} t_{ik} * E_{jk}^{\tau'\tau}) \tag{5.6}$$

$$\zeta_b^O \in \mathbb{R} \tag{5.7}$$

Operation Costs: Costs for Owner-operator Couriers IC couriers will also receive an extra allowance C_a^O for using their personal vehicles. Thus, the labor cost for an IC courier is C_a^O. v_i indicates whether zone i is served by IC couriers or not, and the fractional variable θ_a^O calculates the labor costs for zones included in the owner-operator plan for daily operation.

$$\theta_a^O = \sum_{i \in I} \sum_{\tau \in \mathcal{T}} C_a^O * \tilde{S}_i^\tau * v_i + C_a^O * \overline{S}_i^\tau * (1 - v_i) \tag{5.8}$$

$$\theta_a^O \in \mathbb{R} \tag{5.9}$$

The constraints consist of two interdependent parts: **Allocation** and **Vehicle Inventory**. 'Allocation' determines center numbers, locations, and coverage, with an additional 'Continuity' constraint in Model I. 'Vehicle Inventory' optimizes fleet size and initial center inventories.

$$v_i + \sum_{p\in P} x_i^p = 1, \qquad \forall i \in I \tag{5.10}$$

$$e_i^{p\tau} = \sum_{j\in I}\sum_{\tau'\in\mathcal{T}} E_{ji}^{\tau'\tau} * x_j^p, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.11}$$

$$\sum_{i\in I_c} y_i^p \le 1, \qquad \forall p \in P \tag{5.12}$$

$$y_i^p = 0, \qquad \forall i \in I \setminus I_c, \forall p \in P \tag{5.13}$$

$$\sum_{p\in P} y_i^p \le 1, \qquad \forall i \in I_c \tag{5.14}$$

$$z_{ij}^p \le y_i^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{5.15}$$

$$z_{ij}^p \le x_j^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{5.16}$$

$$1 + z_{ij}^p \ge x_j^p + y_i^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{5.17}$$

$$x_i^p \in \{0,1\}, \qquad \forall i \in I, \forall p \in P \tag{5.18}$$

$$y_i^p \in \{0,1\}, \qquad \forall i \in I_c, \forall p \in P \tag{5.19}$$

$$z_{ij}^p \in \{0,1\}, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{5.20}$$

$$v_i \in \{0,1\}, \qquad \forall i \in I \tag{5.21}$$

$$e_i^{p\tau} \in \mathbb{R}^+, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.22}$$

Allocation. Constraint (5.10) determines whether a zone is included in CV service or not. Constraint (5.11) determines the value of the vehicles' return $e_i^{p\tau}$. It depends on $E_{ji}^{\tau'\tau}$, the number of CV couriers for center p ending their shift in this zone time τ, where $E_{ji}^{\tau'\tau} = S_j^{\tau'} * n_{ji}^{\tau'\tau}$. Constraints (5.12) - (5.13) ensure that if center p is needed, exactly one location is assigned to it, and this location must meet the accessibility requirement. Constraints (5.14) guarantee that each potential candidate location can be used for at most one center. Constraints (5.15) - (5.17) ensure z_{ij}^p equal 1 only when zone j is within the coverage of center p and meanwhile zone i serves as its location.

$$\sum_{j|(i,j)\in A} f_{ij}^p - \sum_{j|(j,i)\in A} f_{ij}^p \ge x_i^p - (|I|+1) * y_i^p, \quad \forall i \in I, \forall p \in P \tag{5.23}$$

$$\sum_{j|(j,i)\in A} f_{ij}^{pt} \le |I| * x_i^p, \quad \forall i \in I, \forall p \in P \tag{5.24}$$

$$f_{ij}^p \ge 0, \qquad \forall (i,j) \in A, \forall p \in P \tag{5.25}$$

Continuity. If a center is needed, the compactness and continuity of its coverage area are incorporated into the construction of the network and the minimising objective of the distance-based travel time. The following constraints provide an enhanced version of the continuity requirement. Constraints (5.23) - (5.24) ensure the overall continuity within the coverage area of center p, where variable f_{ij}^p representing continuity on arc $(i,j) \in A$ within the coverage area of center p.

$$q^{p\tau_0} = q^{p\tau_N}, \qquad \forall p \in P \tag{5.26}$$

$$q^{p\tau} = q^{p(\tau-1)} - \sum_{i\in I} S_i^\tau * x_i^p + \sum_{i\in I} e_i^{p\tau}, \qquad \forall p \in P, \forall \tau \in \mathcal{T} \setminus \{\tau_0\} \tag{5.27}$$

$$q^{p(\tau_0)} \le q_0^p \qquad \forall p \in P \tag{5.28}$$

$$q_0^p \le U_0 * \sum_{i\in I_c} y_i^p, \qquad \forall p \in P \tag{5.29}$$

$$q^{p\tau} \in \mathbb{R}^+, \qquad \forall p \in P \tag{5.30}$$

$$q_0^p \in \mathbb{N} \tag{5.31}$$

Vehicle Inventory. Constraints (5.26) - (5.27) determine the inventory level of vehicles in each center at time τ ($q^{p\tau}$) and ensure its balance after a one-day operation. Particularly, the inventory of each center varies with the pick-up needs and returns at time τ. Constraint (5.28) determines the total stock of vehicles of each center p needed for CV couriers within its coverage. Constraint (5.29) also ensures that if the CV service is needed, there must be a center to accommodate the vehicles required, with maximum capacity restriction considering the center limitation U_0.

5.2 Model II

Model II considers the starting distribution of couriers changing throughout the day, their possible ending locations varying based on starting point and time (reflecting different customer clusters for various restaurants and times), and their impact on the non-productive costs related to the travel times spent on vehicles pickup and return trips, as well as vehicle inventory determined based on vehicles' demands and turnover. Allocation decisions in the Model II adapt over time. Moreover, vehicles are not required to return to their original centers. Instead, return locations are optimized based on the distance to available centers and overall system balance.

Model II considers the spatial-temporal distribution of courier shifts changing with time τ as well as the balance of vehicles in the whole network and each center. And the allocation-related variables are updated to x_i^{pt} and v_i^t, compared with Model I (the location of centers remains unchanged over time in both models, as indicated by y_i^p). In addition, Model II introduces variables $z_{ij}^{(S)p\tau}$ and $z_{ij}^{(E)p\tau}$ to denote the non-productive legs of distribution and collection, respectively. Detailed variable description of Model II can be found in Table 5.2.

Table 5.2. Additional Parameters and Variables for Model II

Parameter	
M	big number;
Variable	
$x_i^{p\tau}$	equals 1 if zone i is covered by center p at time τ, 0 otherwise;
y_i^p	equals 1 if the center p is located at zone i, $i \in I_c$, 0 otherwise;
$z_{ij}^{(S)p\tau}$	the number of CV couriers to travel from center p located at zone i to zone j within its coverage to start their shift at time τ;
$z_{ij}^{(E)p\tau}$	the number of CV couriers to travel from zone j to end their shift at time τ to center p located at zone i;
v_i^τ	equals 1 if zone i is assigned to be served by IC couriers at time τ;
$q^{p\tau}$	the inventory state in center p, in terms of the number of vehicles;
q_0^p	the total vehicles needed in center p to provide CV couriers;
$e_i^{p\tau}$	number of CV couriers ending their shift at zone i at time τ that need to return center p

The objective function in Model II includes updated operational costs:

$$\min \quad (\sigma_b^F + \gamma_b^F + \zeta_b^O) + \theta_a^O \tag{5.32}$$

$$\sigma_b^F = \sum_{p\in P}\sum_{i\in I_c} C_i^F * y_i^p \tag{5.33}$$

$$\gamma_b^F = \sum_{p\in P} C_b^F * q_0^p \tag{5.34}$$

$$\zeta_b^O = \sum_{\tau\in\mathcal{T}}\sum_{p\in P}\sum_{i\in I_c}\sum_{j\in I} C_h^O * t_{ij} * (z_{ij}^{(S)p\tau} + z_{ij}^{(E)p\tau}) \tag{5.35}$$

$$\theta_a^O = \sum_{i\in I}\sum_{\tau\in\mathcal{T}} C_a^O * \tilde{S}_i^\tau * v_i^t + C_a^O * \overline{S}_i^\tau * (1 - v_i^t) \tag{5.36}$$

$$v_i^\tau + \sum_{p\in P} x_i^{p\tau} = 1, \qquad \forall i \in I, \forall \tau \in \mathcal{T} \tag{5.37}$$

$$\sum_{p\in P} e_i^{p\tau} = \sum_{p\in P}\sum_{j\in I}\sum_{\tau'\in\mathcal{T}} E_{ji}^{\tau'\tau} * x_j^{p\tau'}, \qquad \forall i \in I, \forall \tau \in \mathcal{T} \tag{5.38}$$

$$\sum_{i\in I_c} y_i^p \leq 1, \qquad \forall p \in P \tag{5.39}$$

$$\sum_{p\in P} y_i^p \leq 1, \qquad \forall i \in I_c \tag{5.40}$$

$$x_j^{p\tau} \leq \sum_{i\in I_c} y_i^p, \qquad \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.41}$$

$$z_{ij}^{(S)p\tau} \leq M * y_i^p, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.42}$$

$$z_{ij}^{(S)p\tau} \leq S_j^\tau * x_j^{p\tau}, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.43}$$

$$z_{ij}^{(S)p\tau} \geq S_j^\tau * x_j^{p\tau} - M * (1 - y_i^p), \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.44}$$

$$z_{ij}^{(E)p\tau} \leq M * y_i^p, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.45}$$

$$z_{ij}^{(E)p\tau} \leq e_j^{p\tau}, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.46}$$

$$z_{ij}^{(E)p\tau} \geq e_j^{p\tau} - M * (1 - y_i^p), \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.47}$$

$$x_i^{p\tau} \in \{0,1\}, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.48}$$

$$y_i^p \in \{0,1\}, \qquad \forall i \in I_c, \forall p \in P \tag{5.49}$$

$$z_{ij}^{(S)p\tau} \in \mathbb{N}, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.50}$$

$$z_{ij}^{(E)p\tau} \in \mathbb{R}^+, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.51}$$

$$v_i^\tau \in \{0,1\}, \qquad \forall i \in I, \forall \tau \in \mathcal{T} \tag{5.52}$$

$$e_i^{p\tau} \in \mathbb{R}^+, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.53}$$

Allocation. Constraint (5.37) determines whether a zone is included in CV service or not. Constraint (5.38) vehicle returns are based on pickup demand, without restrictions on specific centers. Constraint (5.39) ensures that if center p is needed, exactly one location, that meets the accessibility requirement, is assigned to it. Constraints (5.40) guarantees each potential candidate location can be used for at most one center. Constraint (5.41) ensures that if a zone is assigned to be served by center p, there should be a location for this center. Constraints (5.42) - (5.44) ensure $z_{ij}^{(S)p\tau}$ equals the number of CV couriers to travel from zone i to zone j to start their first delivery at time τ only if one center p is located at zone i and zone j is within its coverage. Constraints (5.45) - (5.47) ensure $z_{ij}^{(E)p\tau}$ determines the number of CV couriers to travel from zone j to center p located at zone i to end their shift at time τ.

$$q^{p(\tau_0)} = q^{p(\tau_n)}, \qquad \forall p \in P \tag{5.54}$$

$$q^{p\tau} = q^{p(\tau-1)} - \sum_{i\in I} S_i^\tau * x_i^{p\tau} + \sum_{i\in I} e_i^{p\tau}, \qquad \forall p \in P, \forall \tau \in \mathcal{T}/\{\tau_0\} \tag{5.55}$$

$$q^{p(\tau_0)} \leq q_0^p, \qquad \forall p \in P \tag{5.56}$$

$$q_0^p \leq U_0 * \sum_{i\in I_c} y_i^p, \qquad \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.57}$$

$$q^{p\tau} \in \mathbb{R}^+, \qquad \forall p \in P, \forall \tau \in \mathcal{T} \tag{5.58}$$

$$q_0^p \in \mathbb{N} \tag{5.59}$$

Vehicle Inventory. Constraint (5.54) ensures the balance of the number of vehicles provided by each center after a one-day of operation. Constraint (5.55) determines the inventory level of vehicles at each center at each time τ as the result of pickups and returns. Constraint (5.56) determines the total stock of vehicles of each center p to satisfy the needs for CV service within its coverage. Constraint (5.57) restricts the number of vehicles within each center (maximum capacity) considering its space limitation.

6
Results

In the following sections, we describe the instances and case study in Amsterdam and investigate the managerial insights that can be provided by our model.

6.1 Instance Description

Network Settings Three network configurations are considered to simulate either entire cities of varying sizes or core operational areas within larger metropolitan regions, depending on the specific characteristics of the on-demand platform's service region and the concentration of courier activities. Furthermore, we employ a hexagonal network generated using the H3 spatial indexing system with a resolution of 8 to these areas. Each hexagon covers an average area of 0.737 km^2[1], offering a granular representation of urban landscapes and uniform adjacency among zones in the network.

- 6x6 network (36 zones): Representing smaller urban areas (e.g., Delft, Netherlands) or compact business districts;
- 9x9 network (81 zones): Representing medium-sized cities or expanded central business areas;
- 12x12 network (144 zones): Representing large cities (e.g., Den Haag, Netherlands) or extensive business areas of major metropolitan cities.

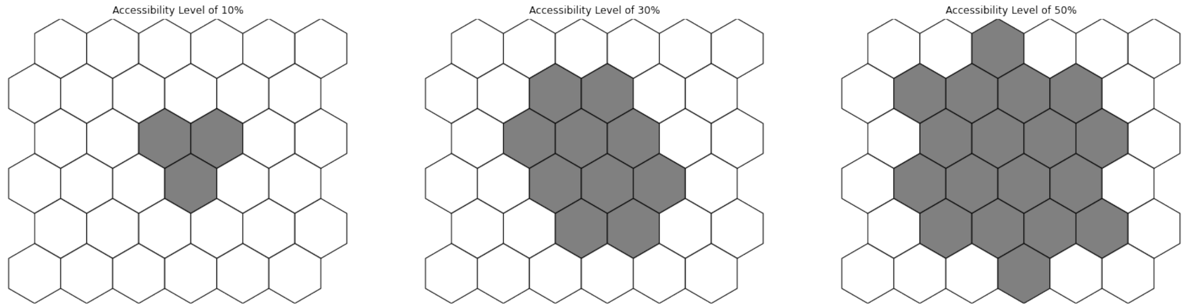
Accessibility Levels We introduce three accessibility levels: 10%, 30%, and 50%. These percentages represent the proportion of zones within the network whose accessibility scores exceed a defined threshold, making them eligible as candidate locations for centers. This can reflect cities with different rates of transportation infrastructure connectivity. In the following instances, we assume accessibility decreases with distance from the city center, reflecting typical urban patterns where central areas have more diverse and frequent public transportation options, and the proportion, e.g., 10%, means the top 10% zones closest to the city center. Figure 6.1 shows the eligible candidates (indicated in grey) under these three different accessibility levels on a 6x6 network.

Temporal Distribution of Couriers We consider a one-day operation period spanning from 08:30 AM to 22:00 PM. We segment this period into 1.5-hour intervals, each represented by a timestamp in the set $T = \{0,1,2,3,...,7,8,9\}$, where each number indicates the start of an interval. We suppose that couriers start their shift between 11:00 AM and 20:00 PM and this period is further categorized into operational periods that reflect typical meal delivery patterns:

- Lunch peak period [1, 2]: Hours from 11:00 AM to 14:00 PM;
- Normal period [3, 4]: Hours from 14:00 PM to 17:00 PM;
- Dinner peak period [5, 6]: Hours from 17:00 PM to 20:00 PM.

The number of active couriers fluctuates throughout the day. We use courier density, measured in 'couriers/km^2', to describe the number of available couriers relative to the size of the market or service area. Based on industry observations, we have the following assumption to represent a higher courier density during meal times to handle increased order volume, which is a pattern commonly observed in food delivery operations.

[1] https://h3geo.org/docs/core-library/restable/



(a) 10% Accessibility Level: Top 10% of zones closest to city center

(b) 30% Accessibility Level: Top 30% of zones closest to city center

(c) 50% Accessibility Level: Top 50% of zones closest to city center

Figure 6.1. Visualization of different urban accessibility Levels

- Peak hours (lunch and dinner): 0.3 couriers/km^2;
- Normal period: 0.075 couriers/km^2.

To illustrate, consider a 6x6 network (36 zones, covering approximately 26 km^2) as shown in Figure 6.2, during peak hours (time stamp 1, 2, 5 or 6) is 0.3 couriers/km^2 * 26 km^2 ≈ 8 couriers start their shift; and during off-peak hours (times 3 or 4) 0.075 * 26 ≈ 2 courier starts their shift. This results in a total of 36 active couriers over a full day.

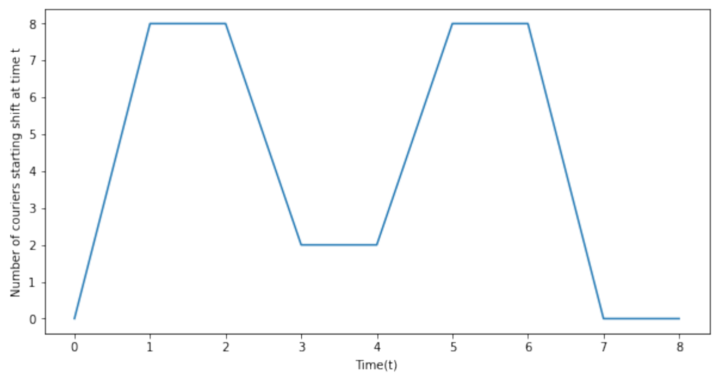


Figure 6.2. Number of couriers starting at different times on the 6x6 network instance

Courier shift lengths are modelled using a normal distribution with a mean of 2 time units (3 hours) and a standard deviation of 1 unit (1.5 hours), with a maximum of 3 units (4.5 hours) and a minimum of 1 unit (1.5 hours).

Spatial Distribution of Couriers We assume a uniform random spatial distribution for both the starting and ending locations of couriers in the following instances.

Examples Based on the settings introduced above, Table 6.1 shows a sample of couriers' starting records indicating the values of $\tilde{S}_i^\tau$, the total number of couriers starting at a specific zone at any given time. S_i^τ refers to the CV couriers needed at service level 0.7, and, $\overline{S}_i^\tau$, the number of IC couriers required if CV service is provided for that zone, is determined by $\tilde{S}_i^\tau - S_i^\tau$. And Table 6.2 provides an overview of the $n_{ij}^{\tau\tau'}$ matrix, indicating the observations that, for given zone i and time τ, the probability of couriers starting their shift at zone i at time τ, to end their shift at zone j at time τ'.

We use this example to illustrate the data we consider: couriers' starting records and the couriers' movement matrix $n_{ij}^{\tau\tau'}$. For instance, the total number of couriers starting at Zone 2 at time 5 is 2 and $\tilde{S}_2^5 = 2$. And $S_2^5 = 1$ indicating the CV couriers needed at service level 0.7, and thus, $\overline{S}_2^5 = 1$ as the number of IC couriers required if CV service is provided for Zone 2 at time 5. Moreover, couriers starting at Zone 2 at Time 5, have a 0.2 chance of ending their shift at Zone 5 at Time 6, 0.14 chance of ending at Zone 7 at Time 6, and 0.66 to end at Zone 4 at Time 7, where $n_{25}^{56} = 0.2$, $n_{27}^{56} = 0.14$, $n_{24}^{57} = 0.66$.

Table 6.1. $\tilde{S}_i^\tau$, S_i^τ, and $\overline{S}_i^\tau$ values for each zone and time τ

Starting Zone i	τ	$\tilde{S}_i^\tau$	S_i^τ	$\overline{S}_i^\tau$
1	0	0	0	0
1	1	3	2	1
⋮	⋮	⋮	⋮	⋮
2	5	2	1	1
⋮	⋮	⋮	⋮	⋮
36	6	1	1	0
36	7	0	0	0
36	8	0	0	0

Table 6.2. $n_{ij}^{\tau\tau'}$ values for each zone

Start Zone i	Start Time τ	End Zone j	End Time τ'	$n_{ij}^{\tau\tau'}$
2	1	4	3	0.2
2	1	4	4	0.658
2	1	13	4	0.142
2	5	5	6	0.2
2	5	7	6	0.14
2	5	4	6	0.66
⋮	⋮	⋮	⋮	⋮
8	2	23	4	0.207
8	2	23	5	0.146
8	6	7	7	0.142
8	6	22	8	0.2
⋮	⋮	⋮	⋮	⋮
35	5	30	7	0.325

We assume the vehicles couriers are using are e-bikes with a speed of 15-16 km/h within urban areas. The distance between centers of two adjacent zones is 0.92 km and then the travel time is 0.06 h. And other parameters we used in the instances are listed in 6.3.

Table 6.3. Parameters of the test instances.

Parameters	Value	Remark
C_i^F	60 (€/day)	for all locations
C_b^F	1 (€/e-bike)	
C_b^O	15 (€/hour)	
C_a^O	8 (€/person)	
TT_{ij}	0.06 (hour)	for adjacent zones $(i, j) \in A$
TT_{ij}	shortest path	for non-adjacent zones i and j
$\|P\|$	3	Maximum centers allowed

6.2 Computational Results

We conduct our experiments using Python 3.9 and Gurobi Optimizer version 9.5.2 build v9.5.2rc0 (mac64[arm]). Computational time mainly depends on two factors: network size and the number of candidate locations, which are determined by the accessibility level. Table 6.4 and Table 6.5 show the settings and results for instances with varying network sizes and accessibility levels.

The largest case '12-R-A3-Model II' requires 11755.7(s) to solve and it indicates our model can solve a real-world size case with an exact solution within a reasonable time. Moreover, computation time increases exponentially with both network size and accessibility levels. This is due to the growing number of nodes and candidate locations, respectively. Instances for Model II generally require more computation time than Model I ones.

Table 6.4. Settings of computation test.

Network Size \ Accessibility Level (Instance Name)	10%	30%	50%
6x6	6-R-A1	6-R-A2	6-R-A3
9x9	9-R-A1	9-R-A2	9-R-A3
12x12	12-R-A1	12-R-A2	12-R-A3

Table 6.5. Computation results of the test instances.

Instance Name	Time(s)	Initial Solution	Initial Bound	Best Solution	Best Bound	# Node Explore	Gap(%)
6-R-A1-Model I	0.17	400	167.16	342.7	342.7	1	0.0
6-R-A1-Model II	0.38	400	192.0	342.2	342.2	1	0.0
6-R-A2-Model I	0.74	400	166.93	342.7	342.7	99	0.0
6-R-A2-Model II	2.22	400	192.0	342.2	342.2	111	0.0
6-R-A3-Model I	2.12	400	166.93	342.7	342.7	365	0.0
6-R-A3-Model II	6.76	400	192.0	342.2	342.2	343	0.0
9-R-A1-Model I	3.3	864	371.5	812.4	812.4	75	0.0
9-R-A1-Model II	26.4	864	470	799	799	195	0.0
9-R-A2-Model I	3.49	864	371.5	812.4	812.4	403	0.0
9-R-A2-Model II	100.1	864	470	799	799	1636	0.0
9-R-A3-Model I	23.5	864	371.5	812.4	812.4	6275	0.0
9-R-A3-Model II	928.9	864	470	799	799	24189	0.0
12-R-A1-Model I	20.79	1520	659.5	1508	1508	940	0.0
12-R-A1-Model II	100.21	1520	680.1	1464	1464	960	0.0
12-R-A2-Model I	980.7	1520	659.5	1508	1508	56591	0.0
12-R-A2-Model II	3132	1520	583.5	1359	1359	44288	0.0
12-R-A3-Model I	1709.1	1520	694.3	1508	1508	175121	0.0
12-R-A3-Model II	11755.7	1520	583.5	1336.8	1336.8	54271	0.0

6.3 Topics Based on Insights

Our experimental design aims to provide insights for on-demand meal delivery platforms optimizing logistics strategies across diverse urban environments and market conditions.

We begin by examining market size and maturity, reflecting different stages of market development and levels of demands (see Section 6.3.1).

We also assess the impact of diverse urban structures on optimal delivery strategies and micro-logistics center planning. Combining the dynamics of the logistics for on-demand meal delivery, our scenarios assume that couriers typically start near restaurant clusters for their first delivery and end their shifts/last delivery closer to customer areas. In Section 6.3.2, we investigate how varying restaurant distributions and distances between commercial and residential zones influence platform decisions.

Our study also compares decisions under different economic conditions, including infrastructure costs and courier compensations (see Section 6.3.3).

Lastly, we evaluate various transport options to gain insights into optimal vehicle fleet configuration (see Section 6.3.4).

For each scenario, we generate 3 random sets of initial distributions (R1, R2, R3) due to the random distribution assumption introduced earlier. We test each setting across three accessibility levels (A1, A2, A3) as shown in Table 6.3. If the results are identical for different accessibility levels, we use a compact format to illustrate, e.g., '6-R1-A1/2/3-Model I'.

6.3.1 Market

As shown in Table 6.6, Scenario M0 simulates emerging markets with low courier density, reflecting areas new to food delivery services. Scenario M1 represents established markets with moderate courier density, typical of stable urban areas. Scenario M2 depicts high-demand metropolitan environments with dense courier networks. The variations are tested on both 6x6 and 12x12 networks. By varying courier density from low to high across these scenarios, we aim to examine how market size and maturity influence optimal delivery strategies. The model results are presented in Table 6.7.

Table 6.6. Scenarios settings with different markets.

Network	Scenarios	Number of Total Couriers	Courier Density
6x6	Scenario M0	22	Peak Hours: 0.2 Normal Hours: 0.05
	Scenario M1	36	Peak Hours: 0.3 Normal Hours: 0.075
	Scenario M2	50	Peak Hours: 0.4 Normal Hours: 0.1
12x12	Scenario M0	94	Peak Hours: 0.2 Normal Hours: 0.05
	Scenario M1	144	Peak Hours: 0.3 Normal Hours: 0.075
	Scenario M2	190	Peak Hours: 0.4 Normal Hours: 0.1

Table 6.7. Results under different market scenarios.

Instance Name	#C	#Bikes	# Couriers			Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC	CSR		σ_b^F	γ_b^F	ζ_b^O	
Scenario M0										
6-R1-A1/2/3-Model I	1	8	18	4	100%	171.5	60	8	71.5	32
6-R1-A1/2/3-Model II	1	8	18	4	100%	171.5	60	8	71.5	32
6-R2-A1/2/3-Model I	0	0	0	22	0.0	176	0	0	0	176
6-R2-A1/2/3-Model II	0	0	0	22	0.0	176	0	0	0	176
6-R3-A1/2/3-Model I	0	0	0	22	0.0	176	0	0	0	176
6-R3-A1/2/3-Model II	0	0	0	22	0.0	176	0	0	0	176
12-R1-A1/2/3-Model I	0	0	0	94	0.0	752	0	0	0	752
12-R1-A1/2/3-Model II	0	0	0	94	0.0	752	0	0	0	752
12-R2-A1/2/3-Model I	0	0	0	94	0.0	752	0	0	0	752
12-R2-A1/2/3-Model II	0	0	0	94	0.0	752	0	0	0	752
12-R3-A1/2/3-Model I	0	0	0	94	0.0	752	0	0	0	752
12-R3-A1/2/3-Model II	0	0	0	94	0.0	752	0	0	0	752
Scenario M1										
6-R1-A1/2/3-Model I	1	12	26	10	100%	254	60	12	102	80
6-R1-A1/2/3-Model II	1	12	26	10	100%	254	60	12	102	80
6-R2-A1/2/3-Model I	1	11	25	11	96.2%	268	60	11	109	88
6-R2-A1/2/3-Model II	1	11	25	11	96.2%	268	60	11	109	88
6-R3-A1/2/3-Model I	1	11	24	12	96.2%	276	60	11	109	96
6-R3-A1/2/3-Model II	1	11	24	12	92.3%	272	60	11	105	96
12-R1-A1/2/3-Model I	0	0	0	144	0.0	1152	0	0	0	1152
12-R1-A1-Model II	0	0	0	144	0.0	1152	0	0	0	1152

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Table 6.7 continued

Instance Name	#C	# Bikes	# Couriers			Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC	CSR		σ_b^F	γ_b^F	ζ_b^O	
12-R1-A2-Model II	3	41	89	55	89%	1097	180	41	436	440
12-R1-A3-Model II	3	42	89	55	89%	1089	180	42	427	440
12-R2-A1/2/3-Model I	0	0	0	144	0.0	1152	0	0	0	1152
12-R2-A1-Model II	2	33	73	71	73%	1146	120	33	425	568
12-R2-A2-Model II	3	45	98	46	98%	1080	180	45	487	368
12-R2-A3-Model II	3	43	97	47	97%	1064	180	43	465	376
12-R3-A1/2/3-Model I	0	0	0	144	0.0	1152	0	0	0	1152
12-R3-A1-Model II	0	0	0	144	0.0	1152	0	0	0	1152
12-R3-A2-Model II	3	41	95	49	95%	1107	180	41	494	392
12-R3-A3-Model II	3	40	92	52	92%	1088	180	40	452	416
Scenario M2										
6-R1-A1/2/3-Model I	1	13	25	25	69.4%	378	60	13	105	200
6-R1-A1/2/3-Model II	1	13	28	22	77.8%	365	60	13	116	176
6-R2-A1/2/3-Model I	1	13	28	22	77.8%	355	60	13	106	176
6-R2-A1/2/3-Model II	1	14	30	20	83.3%	346	60	14	112	160
6-R3-A1/2/3-Model I	1	16	35	15	97.2%	342	60	16	146	120
6-R3-A1/2/3-Model II	1	16	35	15	97.2%	342	60	16	150	120
12-R1-A1/2/3-Model I	1	21	47	143	35.6%	1508	60	21	283	1144
12-R1-A1-Model II	3	45	104	86	78.8%	1464	180	45	551	688
12-R1-A2-Model II	3	50	111	79	84.1%	1379	180	50	517	632
12-R1-A3-Model II	3	47	108	82	81.8%	1376	180	47	493	656
12-R2-A1/2/3-Model I	0	0	0	190	0.0	1520	0	0	0	1520
12-R2-A1-Model II	2	39	89	101	67.4%	1492	120	39	525	808
12-R2-A2-Model II	3	54	124	66	93.9%	1386	180	54	624	528
12-R2-A3-Model II	3	54	120	70	90.9%	1370	180	54	576	560
12-R3-A1/2/3-Model I	0	0	0	190	0.0	1520	0	0	0	1520
12-R3-A1-Model II	2	39	88	102	66.7%	1480	120	39	505	816
12-R3-A2-Model II	3	53	124	66	93.9%	1360	180	53	599	528
12-R3-A3-Model II	3	52	123	67	93.2%	1337	180	52	569	536

Table 6.8. Average results under different market scenarios.

Instance Name	#C	#Bikes	# Couriers			Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC	CSR		σ_b^F	γ_b^F	ζ_b^O	
Scenario M0										
Avg-6-A1	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-A2	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-A3	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-Model I	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-Model II	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-12-A1	0	0	0	94	0.0	752	0	0	0	752
Avg-12-A2	0	0	0	94	0.0	752	0	0	0	752
Avg-12-A3	0	0	0	94	0.0	752	0	0	0	752
Avg-12-Model I	0	0	0	94	0.0	752	0	0	0	752
Avg-12-Model II	0	0	0	94	0.0	752	0	0	0	752
Scenario M1										
Avg-6-A1	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-A2	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-A3	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-Model I	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-Model II	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-12-A1	0.3	5.5	12.2	131.8	0.1	1151	20	5.5	70.8	1054.7
Avg-12-A2	1.5	21.2	47	97	0.5	1123.3	90	21.2	236.2	776
Avg-12-A3	1.5	20.8	46.3	97.7	0.5	1116.2	90	20.8	224.0	781.3
Avg-12-Model I	0	0	0	144	0.0	1152	0	0	0	1152
Avg-12-Model II	2.2	31.7	70.3	73.7	0.7	1108.3	133.3	31.7	354	589.3

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Table 6.8 continued

Instance Name	#C	# Bikes	# Couriers			Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC	CSR		σ_b^F	γ_b^F	ζ_b^O	
Scenario M2										
Avg-6-A1	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-A2	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-A3	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-Model I	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-Model II	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-12-A1	1.3	24	54.7	135.3	0.4	1497.3	80	24	310.7	1082.7
Avg-12-A2	1.7	29.7	67.7	122.3	0.5	1445.5	100	29.7	337.2	978.7
Avg-12-A3	1.7	29	66.3	123.7	0.5	1438.5	100	29	320.2	989.3
Avg-12-Model I	0.3	7	15.7	174.3	0.1	1516	20	7	94.3	1394.7
Avg-12-Model II	2.8	48.1	110.1	79.9	0.8	1404.9	166.7	48.1	551	639.1

We use indicators: the number of micro-logistics centers needed ($\#C$), the number of e-bikes needed ($\#Bikes$), the number of CV couriers included to provide CV service and IC couriers needed, and the costs of CV (particularly, the center construction costs σ_b^F, the bicycle purchasing costs γ_b^F, and the operational costs for non-productive legs ζ_b^O) and IC service (θ_a^O) respectively to evaluate different scenarios. We also use the indicator, CV Courier Supply Ratio (CSR), to denote the ratio of the optimal number of CV couriers, as determined by the cost-minimization delivery plan model, divided by the maximum potential CV courier demand based on the desired service level across all zones.

Table 6.7 shows the results for each instance and Table 6.8 calculates the average results of the three random cases under different accessibility levels and the models.

When the courier density is quite low, which indicates the market size is small (Scenario M0), the IC model is optimal (there are approximated 0 or 0 centers needed for both 6*6 and 12*12 networks and almost all the couriers are hired as independent contractors).

As markets grow and courier density increases, a hybrid model becomes preferable (the average values of CSR increase from 0 to approximated 1). For smaller areas, a single center is sufficient, while larger networks with expanded operations benefit from multiple centers (some average values of '#C' are greater than 1 for the 12x12 network in both M1 and M2 scenarios). The model also demonstrates good scalability, allowing companies' transition from medium market M1 to larger market M2 to maintain their existing infrastructure while simply increasing the number of e-bikes to meet growing demand (with maintaining the optimal number of centers as 1, the average number of e-bikes needed grows from 11.3 to 14.2 on 6x6 network).

Moreover, Model II generally leads to lower costs compared to Model I. Also, as compared to adopting all IC couriers with the operational strategy as Model I for the 12x12 network in M1, Model II implies an average of 2.2 centers needed, suggesting a varied delivery model choice and center plan under different operating strategies.

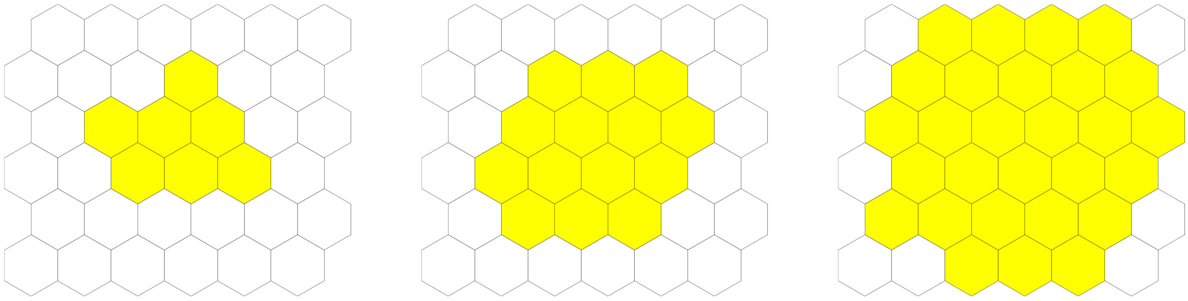
Also, as accessibility levels increase (from A1 to A3), the changes in the optimal solution (in M1 the average value of total costs under A1 1151 euro as indicated in 'Avg-12-A1' decreases to 1116.2 euro under A3 level, also it drops from 1497.3 euro of A1 to 1438.5 euro of A3 in M2) suggests that sometimes a wider range of center options offers more opportunities to optimize operations.

6.3.2 Urban Structures

A. We developed three scenarios representing varied restaurant distributions, as shown in Table 6.9 and Figure 6.3. These scenarios range from highly concentrated (inner 20% of the city) to widely dispersed, reflecting diverse city layouts or the scope of platform-partnered restaurants. It also reflects how couriers might begin their shifts in different areas of the city. Moreover, we assume random ending locations across all scenarios, simulating a typical situation with more deterministic restaurant placements and stochastic customer distributions.

Table 6.9. Scenarios settings with different starting/restaurant areas.

Scenarios	Starting Areas
Scenario S1	0% - 20 %
Scenario S2	0% - 40 %
Scenario S3	0% - 80 %



(a) S1: 0% - 20 % Areas from Center (b) S2: 0% - 40 % Areas from Center (c) S3: 0% - 80 % Areas from Center

Figure 6.3. Visualization of different starting/restaurant areas

Table 6.10. Results under different starting/restaurant areas.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
Scenario S1									
6-R1-A1/2/3-Model I	1	8	18	4	158	60	8	58	32
6-R1-A1/2/3-Model II	1	8	18	4	158	60	8	58	32
6-R2-A1/2/3-Model I	1	7	14	8	170	60	7	39	64
6-R2-A1/2/3-Model II	1	7	16	6	163	60	7	46	48
6-R3-A1/2/3-Model I	1	8	15	7	166	60	8	42	56
6-R3-A1/2/3-Model II	1	8	16	6	160	60	8	44	48
Avg	1	7.7	16.2	5.8	162.5	60	7.7	47.8	46.7
Scenario S2									
6-R1-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R1-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model I	1	6	14	8	169	60	6	39	64
6-R2-A1/2/3-Model II	1	8	16	6	163	60	8	47	48
6-R3-A1/2/3-Model I	1	8	16	6	168	60	8	52	48
6-R3-A1/2/3-Model II	1	8	17	5	163	60	8	55	40
Avg	0.7	5	10.5	11.5	169.2	40	5	32.2	92
Scenario S3									
6-R1-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R1-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
Avg	0	0	0	22	176	0	0	0	176

As illustrated in Table 6.10, as restaurants' distribution becomes more decentralized (moving from S1 to S3), the IC model becomes more cost-effective (the average number of IC couriers needed increases from the 5.8 in S1, 11.5 in S2 to 22 in S3). Moreover, total costs generally rise from S1 to S3 (from 162.5 euro to 176 euro), indicating as higher operational costs for spread-out distributions. This suggests that urban structure and its restaurants' distribution will influence the choice of delivery model.

B. We designed scenarios to simulate diverse urban layouts with varing distances between central business districts and residential areas to investigate its impact on the decisions. As shown in Table 6.11, we assume restaurants are clustered within the inner 20% of the city center. We then vary the distributions of residential areas from 20-40% from the center (D1) to 80-100% from center (D3), which also indicates the couriers' shift-ending locations.

Table 6.11. Scenarios settings with different ending/customer areas.

Scenarios	Ending Areas
Scenario D1	20-40%
Scenario D2	40-60%
Scenario D3	80-100%

Table 6.12 shows, generally, as the distance between couriers' starting points (restaurant clusters) and ending points (residential areas) increases, the IC model becomes more economically advantageous (the average number of IC couriers needed rises from 9.3 in D1, 8.2 in D2, to 19.2 in D3 while the average number of centers needed decreases from 0.8 to 0.2). It suggests that, in practice, more concise decisions should be made on company-specific historical data related to the geographic distribution of restaurants and customers.

Table 6.12. Results under different ending/customer areas.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
Scenario D1									
6-R1-A1/2/3-Model I	1	6	10	12	184	60	6	22	96
6-R1-A1/2/3-Model II	1	7	16	6	152	60	7	37	48
6-R2-A1/2/3-Model I	1	8	18	4	142	60	8	42	32
6-R2-A1/2/3-Model II	1	8	18	4	142	60	8	42	32
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	1	8	14	8	165	60	8	33	64
Avg	0.8	6.2	12.7	9.3	160.2	50.0	6.2	29.3	74.7
Scenario D2									
6-R1-A1/2/3-Model I	1	7	16	6	161	60	7	46	48
6-R1-A1/2/3-Model II	1	8	17	5	158	60	8	50	40
6-R2-A1/2/3-Model I	1	8	18	4	151	60	8	51	32
6-R2-A1/2/3-Model II	1	8	18	4	151	60	8	51	32
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	1	7	14	8	169	60	7	38	64
Avg	0.8	6.3	13.8	8.2	161.0	50.0	6.3	39.3	65.3
Scenario D3									
6-R1-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R1-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	1	8	17	5	176	60	8	68	40
Avg	0.2	1.3	2.8	19.2	176.0	10.0	1.3	11.3	153.3

6.3.3 Costs

Table 6.13 outlines three economic scenarios designed to test delivery model adaptability under varying cost structures. Scenario C0 serves as our baseline (M1 from Table 6.7). C1 simulates higher facility costs, particularly common in dense urban areas or strict regulations on commercial spaces. C2 introduces lower independent contractor (IC) compensation, representing markets with abundant gig workers. By testing these key economic variables, we aim to understand how cost dynamics influence the optimal choice between company-owned vehicles (CV) and IC couriers, and the necessity of centers across different urban economic landscapes. And the results of different indicators under these scenarios are listed in Table 6.14.

Table 6.13. Scenarios settings with different costs.

Scenarios \ Costs	C_i^F (€/day)	C_b^F (€/bike)	C_h^O (€/hour)	C_a^O (€/person)
Scenario C0	60	1	15	8
Scenario C1	100	1	15	8
Scenario C2	60	1	15	6

Table 6.14. Results under different cost scenarios.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
Scenario C0									
6-R1-A1/2/3-Model I	1	12	26	10	254	60	12	102	80
6-R1-A1/2/3-Model II	1	12	26	10	254	60	12	102	80
6-R2-A1/2/3-Model I	1	11	25	11	268	60	11	109	88
6-R2-A1/2/3-Model II	1	11	25	11	268	60	11	109	88
6-R3-A1/2/3-Model I	1	11	24	12	276	60	11	109	96
6-R3-A1/2/3-Model II	1	11	24	12	272	60	11	105	96
6-R3-A1/2/3-Model II	1	11	24	12	272	60	11	105	96
Avg	1	11.3	25	11	265.3	60	11.3	106	88.0
Scenario C1									
6-R1-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R1-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
Avg	0	0	0	36	288	0	0	0	288
Scenario C2									
6-R1-A1/2/3-Model I	0	0	0	36	216	0	0	0	216
6-R1-A1/2/3-Model II	0	0	0	36	216	0	0	0	216
6-R2-A1/2/3-Model I	0	0	0	36	216	0	0	0	216
6-R2-A1/2/3-Model II	0	0	0	36	216	0	0	0	216
6-R3-A1/2/3-Model I	0	0	0	36	216	0	0	0	216
6-R3-A1/2/3-Model II	0	0	0	36	216	0	0	0	216
Avg	0	0	0	36	216	0	0	0	216

It shows when facility costs are substantially higher (C1), it becomes economically unfavorable to adopt a CV delivery model with centers (the average number of IC couriers needed increases from 11 to 36). When the compensation for IC couriers is relatively lower in C2, companies can optimize costs by increasing their reliance on IC couriers (compared to the hybrid one in market condition C0 with an average of 25 CV couriers and 11 for IC, it shows in C2 that the platform should better hire all 36 couriers as IC one).

The results suggest that companies need to adapt their strategies - favoring IC models in high-facility-cost urban areas and leveraging lower IC rates when available.

6.3.4 Couriers' Transport Mode

To assess how vehicle types impact the trade-off between delivery models, we tested 5 scenarios, as shown in Table 6.15, to inform platforms' choices when equipping their company fleet.

- Scenario T0: Baseline - E-bikes;
- Scenario T1: Standard bicycles, slow but cheaper;
- Scenario T2: Slower regular bicycles, potentially in congested areas;
- Scenario T3: Fast scooters, increasing speed at a higher cost;
- Scenario T4: Premium Scooters, better quality but at a higher cost.

Table 6.15. Scenarios settings with different modes.

Scenarios	Unit Travel Time	Purchasing Costs C_b^F
Scenario T0	0.06	1
Scenario T1	0.072	0.5
Scenario T2	0.09	0.5
Scenario T3	0.042	4
Scenario T4	0.042	7

Vehicle speed influences travel time and thus operational costs, especially in high labor cost markets, and a balance exists between vehicle speed and cost when considering the choice of vehicle type. As shown in Table 6.16, in scenarios with low-speed vehicles (T1, T2), despite a lower vehicle purchasing cost, we observe an increase in total costs (from an average of 265.3, 280.6 to 288 euro), as well as a trend toward more IC couriers rejecting CV models. In comparison, despite higher purchasing costs, faster modes (T3) show similar total costs to the baseline (T0) (267.8 euro in T3, compared to 265.3 euro in T0), suggesting that the speed gain offsets the higher vehicle cost. However, there's a tipping point where more costly vehicles should be excluded from company vehicle configuration options, indicated by the preference for IC models over owned fleets in T4 and higher overall total costs (288 euro).

Table 6.16. Results under different mode scenarios.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
Scenario T0									
6-R1-A1/2/3-Model I	1	12	26	10	254	60	12	102	80
6-R1-A1/2/3-Model II	1	12	26	10	254	60	12	102	80
6-R2-A1/2/3-Model I	1	11	25	11	268	60	11	109	88
6-R2-A1/2/3-Model II	1	11	25	11	268	60	11	109	88
6-R3-A1/2/3-Model I	1	11	24	12	276	60	11	109	96
6-R3-A1/2/3-Model II	1	11	24	12	272	60	11	105	96
Avg	1	11.3	25	11	265.3	60	11.3	106	88.0
Scenario T1									
6-R1-A1/2/3-Model I	1	12	26	10	269	60	6	123	80
6-R1-A1/2/3-Model II	1	12	26	10	269	60	6	123	80
6-R2-A1/2/3-Model I	1	12	26	10	285	60	6	138	80
6-R2-A1/2/3-Model II	1	12	26	10	285	60	6	138	80
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	1	11	24	12	287.5	60	5.5	126	96
Avg	0.8	9.8	21.3	14.7	280.6	50	4.9	108	117.3
Scenario T2									
6-R1-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R1-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
Avg	0	0	0	36	288	0	0	0	288
Scenario T3									
6-R1-A1/2/3-Model I	1	12	26	10	260	60	48	72	80
6-R1-A1/2/3-Model II	1	12	26	10	260	60	48	72	80
6-R2-A1/2/3-Model I	1	11	25	11	270	60	44	78	88
6-R2-A1/2/3-Model II	1	11	25	11	268	60	44	76	88
6-R3-A1/2/3-Model I	1	11	24	12	276	60	44	76	96
6-R3-A1/2/3-Model II	1	11	24	12	273	60	44	73	96
Avg	1	11.3	25	11	267.8	60	45.3	74.5	88
Scenario T4									
6-R1-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R1-A1/2/3-Model II	0	0	0	36	288	0	0	0	288

Continued on next page

Table 6.16 continued

Instance Name	#C	# Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
6-R2-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
Avg	0	0	0	36	288	0	0	0	288

6.4 Case Study: Amsterdam City

In this section, we look at the potential of using the models proposed above in practice by conducting a case study using historical data from one of the OMFD operators in Amsterdam.

We consider an operation period from 10:00 AM to 23:00 PM, covering the main meal delivery hours in Amsterdam. We assumed that zones generating more orders are more likely to serve as starting locations for courier shifts. Also, since couriers tend to end their shifts after completing their last deliveries, courier shift end locations were determined based on the distribution of delivery zones in the historical data. Combining data on the total number of couriers starting at each time slot, and courier shift records with our derived starting and ending location distributions, we determined the number of couriers starting their shift in each zone at each time slot, the possibility of their shift length and possible destinations.

Using h3 spatial index and Amsterdam map[2], the city is divided into 415 hexagons. Regarding the accessibility scores for each zone, the public transportation network (including train, bus, metro, and tram) in Amsterdam is considered. Specifically, 15 tram lines with 139 tram stations, 5 metro lines with 11 metro stations, 81 bus lines (bidirectional) with 893 bus stations (those on different sides of the road are counted as 2), and 4 train lines with 13 train stations are considered. The relative data are obtained from the municipality of Amsterdam website[3] and via OpenStreetMap API[4]. Then, the accessibility score of each zone according to the equation (4.3) is calculated. Figure 6.4 shows the accessibility score calculation results of each zone in Amsterdam.

Figure 6.4. Accessibility Score of Amsterdam City

Table 6.17 shows a different number of potential candidates for center locations that meet accessibility requirements under varying levels of threshold. When the threshold becomes lower, it means more zones can meet the requirement of accessibility to serve as center location candidates.

[2]https://maps.amsterdam.nl/gebiedsindeling/
[3]https://maps.amsterdam.nl/trammetro/
[4]https://overpass-turbo.eu/

Table 6.17. Different accessibility thresholds and the corresponding candidate locations

Accessibility Threshold	Number of Candidate Locations
2.8	8
2.2	33
1.7	41
1.3	53
1.2	63
1.12	95
1.08	123
0.2	163

Considering the planning horizon of 5 years (1825 days), for all places, the construction or leasing cost of a company-owned center is 25,000 euro per year and then C_i^F is around 69 euro per day. And the purchasing cost for company-owned e-bikes C_b^F is 1 euro (about 900 euro for purchasing and 900 euro for maintaining a bicycle for 5 years). Assume the hourly salary for both types of couriers C_h^O is 15 euro per hour[5], and the extra bicycle allowance C_a^O is 13 euro per day for a IC courier. The estimated parameters are listed in Table 6.18.

Table 6.18. Parameters of Amsterdam Case.

Parameters	Value	Remark
C_i^F	69 (€/day)	for all locations
C_b^F	1 (€/bicycle)	
C_h^O	15 (€/hour)	
C_a^O	13 (€/person)	
TT_{ij}	0.06 (hour)	for adjacent zones $(i, j) \in A$
$\|P\|$	3	Maximum centers allowed

Table 6.19. Results of Amsterdam case using Model I and II.

Accessibility Threshold	#PL	#Bikes	# Couriers			Total Costs	Reduction	CV Costs			IC Costs θ_a^O
			CV	IC	CSR			σ_b^F	γ_b^F	ζ_b^O	
2.8 (Model I)	3	119	222	49	100%	2474		207	119	1511	637
2.8 (Model II)	3	119	222	49	100%	2104	15%	207	119	1141	637
2.2 (Model I)	3	119	222	49	100%	2458		207	119	1495	637
2.2 (Model II)	3	119	222	49	100%	2096	15%	207	119	1133	637
1.3 (Model I)	3	119	222	49	100%	2458		207	119	1495	637
1.3 (Model II)	3	119	222	49	100%	2096	15%	207	119	1133	637

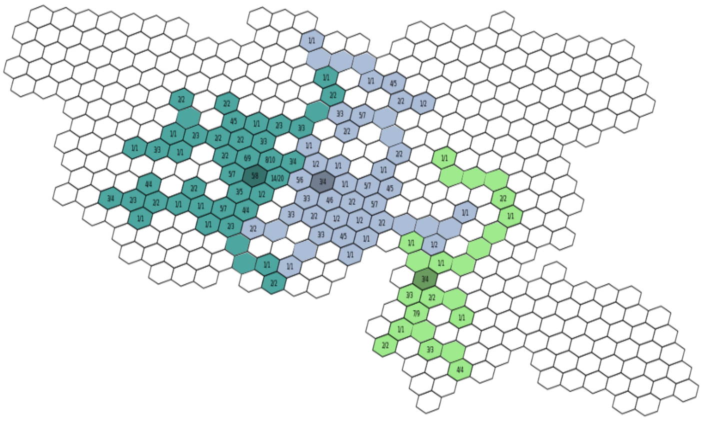


Figure 6.5. Illustration of Model I result on Amsterdam case

Table 6.19 presents the results of center location decisions using Model I and Model II considering various accessibility requirements in Amsterdam city. The data shows that multiple centers are necessary for cities of Amsterdam's scale, based on given historical data. Notably, Model II results in a significant 15% reduction in operational costs compared to Model I. It suggests that while both models fully satisfy courier vehicle (CV) needs in Amsterdam, the Model II approach offers additional benefits. It leads to the reduction in the average cost for couriers to access centers when picking up and returning e-bikes by adjusting service coverage based on temporal fluctuations in couriers' starting and ending distribution (varying by their starting location and starting time of the day) and flexible returning choices.

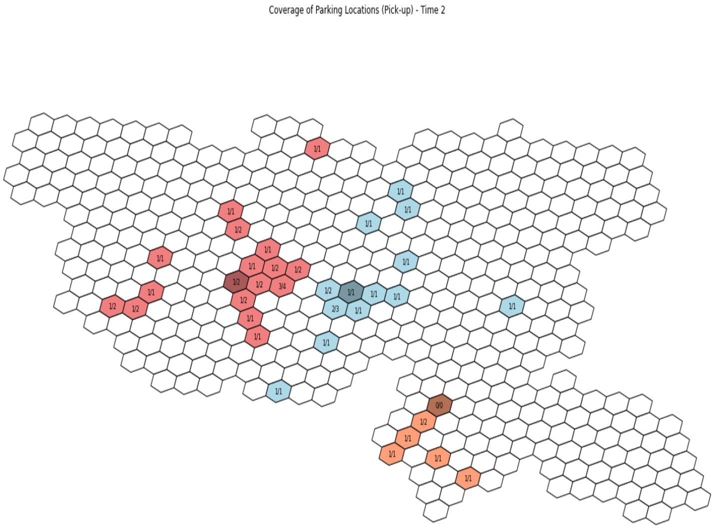
Figure 6.5 and Figure 6.6 show the final courier assignment decision and the coverage of each center according to Model I and Model II (at certain times) respectively. Different colors illustrate different centers and its coverage. The darker colored zones indicate the location of each center and the lighter color shows its coverage. The labels on each zone show the number of CV couriers and the total number of couriers starting at that zone. The white zones are the ones assigned to IC couriers.

The results shown in Table 6.20 illustrate the relationship between accessibility thresholds and operational costs in the Amsterdam case study. As the accessibility threshold increases from 0.2 to 2.8, there's a slight increase in total costs (from 2440 to 2474 euro, 14% increase), mainly due to increased operational costs related to the cost to pick up and drop off e-bikes at centers. Since higher accessibility thresholds mean greater convenience for a larger population to commute between their home and these centers, it suggests that, in this case, the company can consider investing a marginal amount to provide better courier convenience.

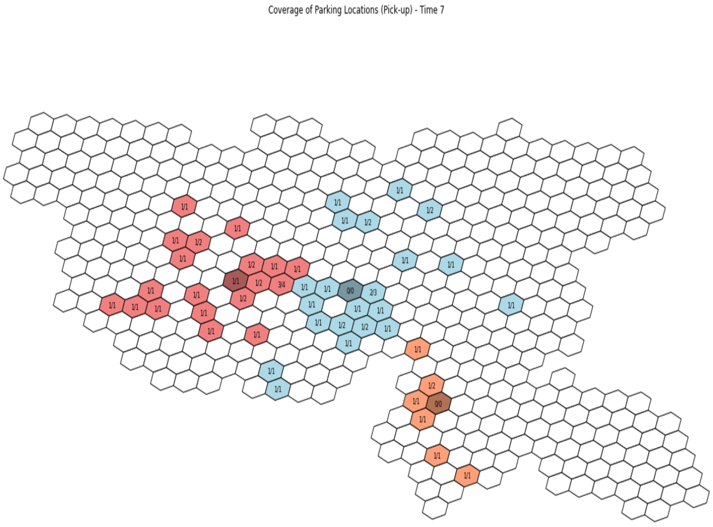
Table 6.20. Results of Amsterdam case under different accessibility requirements.

Accessibility Threshold	#PL	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
0.2 (Model I)	3	119	222	49	2440	207	119	1477	637
1.08 (Model I)	3	119	222	49	2440	207	119	1477	637
1.12 (Model I)	3	119	222	49	2440	207	119	1477	637
1.2 (Model I)	3	119	222	49	2442	207	119	1479	637
1.3 (Model I)	3	119	222	49	2458	207	119	1495	637
1.7 (Model I)	3	119	222	49	2458	207	119	1495	637
2.2 (Model I)	3	119	222	49	2458	207	119	1495	637
2.8 (Model I)	3	119	222	49	2474	207	119	1511	637

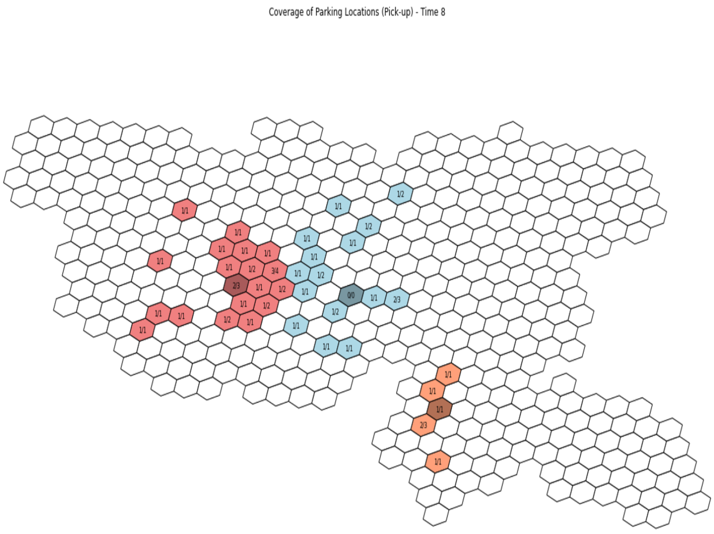
[5]https://www.thuisbezorgd.nl/en/courier



(a) Model II Coverage - Time 2 (11:00AM)



(b) Model II Coverage - Time 7 (16:00PM)



(c) Model II Coverage - Time 8 (17:00PM)

Figure 6.6. Model II results at different times of Amsterdam case

7 Conclusion

7.1 Summary

This study presents a comprehensive framework for planning and optimizing micro-logistics centers in on-demand meal delivery services. We consider the economic viability of these centers within a mixed delivery structure, and optimize multiple dimensions of center planning including the number, location and inventory of company vehicles. We also integrate the operational considerations when evaluating the costs of centers by using historical data on couriers' shift patterns and introducing Model I and II to deal with different coverage and vehicle distribution requirements for varying operational policies.

Specifically, the proposed solution evaluates the costs of delivery options by facility and vehicle investment of the CV model with centers, as well as operational expenses for both IC and CV models. By minimizing the total cost, it determines the necessity of centers and the optimal delivery plan. Moreover, by considering interconnected factors, it strikes a balance between competing objectives across different planning dimensions, including investment costs related to the number of centers, vehicle fleet investment based on CV courier needs and shifts, and operational costs of vehicle repositioning tied to demand distribution and center locations. Notably, the setting of maximum p centers allows for the automatic determination of the optimal number of centers. We also factor in the trade-off between costs and the accessibility of candidate centers to ensure convenience for CV couriers.

Experiments under various scenarios are conducted to highlight our model's stability and adaptability to different market conditions. The findings suggest that the IC model proves more cost-effective in several situations: sparse or new markets; areas with low allowances for IC couriers; regions with high real estate costs for infrastructure; environments with long travel times due to slow transport or congestion coupled with high labor costs; markets where restaurants are widely dispersed; and cases where business and residential areas (or main restaurant and customer clusters) are geographically distant. Furthermore, a hybrid delivery model incorporating CV service with micro-logistics centers optimizes costs in more established, dense markets. When considering vehicle configuration for the CV model, platforms must balance speed and cost, noting that slower transport modes in markets with high labor costs or more expensive options are economically unfavorable. Regarding the specific models proposed, Model I is particularly suitable when geographic continuity is a strict requirement and couriers' spatial and temporal distributions remain relatively stable. In contrast, Model II with flexible coverage and parking adapts better to fluctuating courier distributions, potentially reducing total costs. The optimal locations for centers, when necessary, depending on specific courier activity patterns and the platform's desired accessibility level.

Overall, these insights provide valuable guidance for on-demand meal delivery platforms to make informed decisions tailored to their unique market conditions and operational requirements, optimizing their delivery strategies for maximum efficiency and cost-effectiveness.

7.2 Future Work

In our model, when considering the allocation of a specific zone, we assume to satisfy all the needs for CV service under a certain service level in terms of couriers starting at that zone at a given time if a zone is assigned to a certain center. Future research could extend this framework to explore partial CV courier allocation within zones to obtain greater optimisation.

Moreover, considering facility cost variations based on fleet size and exploring the implications of buffer capacity in flexible return scenarios in the results using Model II would enhance the model's practicality.

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An Optimisation Approach to Planning Micro-logistics Centers for On-demand Food Delivery Service with A Mixed Operational Model

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***Abstract*—This work presents a comprehensive framework to help with the decision-making of delivery model choice and the planning of the micro-logistics centers within a mixed delivery structure: operating with independent contractors or the company-vehicle model with micro-logistics centers. We aim to determine the necessity of micro-logistics centers, indicate the optimal choice of delivery model, and optimize the planning of necessary centers. We propose a mixed integer optimisation problem to minimize the total costs while considering the convenience for couriers. It combines strategic decisions for locating micro-logistics centers considering the dimensions of the centers (number, locations and vehicle stock) with operational considerations (the impact of couriers' distribution and shifts on repositioning company vehicles). Particularly, two operational policies are considered: fixed coverage requiring return-to-origin and time-variant coverage with global redistribution, taking into account spatial-temporal variation of demand. Our findings suggest that diverse market conditions and operational approaches can lead to different strategies. We also applied the model for the city of Amsterdam, and it reveals that multiple centers are needed and the platform may invest in courier convenience by choosing center locations with great accessibility.**

***Index Terms*—on-demand food delivery, delivery model, independent contractors, facility planning, cost minimisation**

I. Introduction

Over the past few years, there has been a substantial worldwide expansion of on-demand food delivery (ODFD) services, which are made possible by online meal delivery platforms like Uber Eats, Meituan, and Just Eat Takeaway.com. These platforms serve as intermediaries, connecting customers, restaurants, and couriers in a complex ecosystem. As the industry evolves, these ODFD platforms' logistical processes face numerous challenges.

One of the most critical aspects of ODFD platforms is their delivery model. Currently, two primary models dominate the industry ([1]–[3]). The first involves platforms that match diners with restaurants but do not handle delivery logistics. The second type, more prevalent, utilizes its own networks of couriers to handle deliveries as well as order processing. Within the second model, platforms adopt various courier engagement strategies: UberEats utilizes independent contractors who use their personal vehicles with flexible schedules; Meituan operates with company-owned motorcycles and couriers with offline stores; Just Eat Takeaway.com adopts a hybrid approach, offering couriers the choice between using company-owned vehicles (e.g., e-bikes) from specific facilities or operating as independent contractors with their own vehicles and receiving an allowance ([4]).

There is little discussion on the economic evaluation of the company-vehicle model in the on-demand meal delivery industry, particularly in diverse market contexts and in a mixed delivery structure, where platforms can choose between (a) an owner-operator model with independent contractors (IC), (b) a company-vehicle model (CV), or an integrated approach combining both. This makes it challenging for platforms to make informed decisions about whether to adopt a company-vehicle model or not. This paper addresses this challenge by focusing on a critical aspect of implementing the company-vehicle model: the evaluation and planning of micro-logistics centers. These centers serve as facilities to accommodate company-owned vehicles, where couriers in company-vehicle model pick up and return these vehicles to start or end their shifts. The planning of micro-logistics centers involves several interconnected decisions: first, they need to determine 1) whether establishing micro-logistics centers is economically viable, which indicates whether a hybrid model or an IC-only model is preferable. If micro-logistics centers are necessary, the planning process extends to 2) identifying the optimal number and locations of these centers, 3) defining their respective service areas, and 4) determining the appropriate inventory of company-owned vehicles to be operated.

Existing research in on-demand meal delivery largely focuses on operational aspects such as order batching and routing optimization, while limited literature addresses the strategic planning of facilities in this context. It also lacks comprehensive studies that optimize the inventory of company vehicles - a crucial initial investment - and integrate the impact of facilities on operations into long-term planning. This integration is critical because operations, including company vehicle usage patterns, vehicle distribution locations, and courier shift arrangements, directly influence both facility running costs and the calculation of optimal fleet size.

We propose a comprehensive planning framework for micro-logistics centers in on-demand meal delivery service. Our approach considers interconnected strategic and operational factors, using historical data on courier shift start and end locations. We employ a cost-minimization strategy to evaluate trade-offs between delivery models and determine the optimal delivery plan. It also assesses the necessity of micro-logistics centers, identifies the number and locations of these centers, defines their coverage areas, and determines the stock for company-owned vehicles. We interpret the operational impact as the costs of vehicle distribution between centers and delivery points and present two models representing different operational policies: Model I assumes a fixed coverage area with a return-to-origin requirement for vehicles, while Model II incorporates time-variant coverage with global redistribution optimization. Beyond costs, the convenience of center locations for courier commutes is also considered.

The remainder of this paper is organized as follows: Section II presents a comprehensive literature review. Section III describes the system and defines problem objectives and scope. Section IV introduces the mathematical models, including formulations of Model I and II. Section V presents the results of computational findings and managerial insights derived from instances and a case study of Amsterdam City. Finally, Section VI concludes the paper with a summary of findings and directions for future work.

II. Literature Review

This research reviews the literature in four related directions: operations and optimization in the on-demand meal delivery, decisions including facility location, fleet sizing and rebalancing in shared mobility system, facility location problem, and districting.

A. On-demand Food Delivery

The operation of on-demand meal delivery is dynamic, capacitated, and stochastic with limited customer time windows and a limited number of couriers. It stands apart from typical delivery services mainly because of several features: its narrower delivery time windows, commitment to fulfilling almost all order requests immediately upon receipt rather than turning them down, the highly variable nature of meal orders and the involvement of couriers with variable working hours. The problem of optimizing logistics in this area is currently viewed as the most significant challenge in last-mile logistics ([5]). Such optimization includes considering the delivery area size, efficiently allocating resources such as manpower and fleet, order batching and routing optimization ([6]).

Few studies address the delivery model choice and involve facility configuration for on-demand meal delivery service from the perspective of strategic planning. Studies like the one by [1] consider the depot in on-demand meal service as the place for couriers to wait for delivery and seek to maximize the demand coverage where a customer is considered covered if they can be reached by at least one restaurant taking into account a limited length of full path (depot - restaurant - customer). However, since they don't distinguish between personal and company-owned vehicles, the associated fleet costs are overlooked. They assume couriers start each delivery from the depot, which doesn't reflect the reality of multiple deliveries per shift, and their considerations on specific restaurant-customer distances are unpredictable in the complex real practices. In contrast, we propose focusing on deadhead trips at the start and end of shifts, considering only trips between centers and potential restaurant/customer clusters, to better reflect realistic operational costs influenced by center locations.

B. Economic Viability Analysis of Delivery Models and Infrastructure

The choice of an optimal delivery model can be evaluated and influenced by various factors across different logistics practices. [7] stated that network size and customer density influence the performance of the microhub delivery paradigm in the context of last-mile parcel delivery, with performance measured by labour costs based on travel time, number of trucks dispatched, total vehicle miles travelled, and total daily operating costs. [8] found that while crowd-sourcing services are easily accessible in high-density areas, they may not always be the most cost-effective solution for restaurants who organised deliveries themselves. Their research indicates that the optimal delivery choice varies with restaurant density, customer density, and demand distribution.

Current economic viability discussions of infrastructures associated with delivery process focus on telecom and transport (e.g., airline, cargo, and parcel delivery) industries, where a hub is used as consolidation and distribution points in many-to-many flow networks and consolidation generates economies of scale ([9]), which is different from the logistics practices in on-demand food delivery industry, in terms of specific functions and operations.

C. Shared Mobility System Design

When a company considers the design of a shared mobility system, such as bike-sharing, car-sharing, or scooter-sharing, especially for a station-based one, the key design decisions considered include the number and locations of the stations, the transportation infrastructure and network, fleet sizing and inventory levels of sharing vehicles to be held at the stations, and rebalancing operations among stations, with consideration for both total cost and service levels (measured both by the availability rate for requests and coverage of the origins and destinations) ([10]–[12]).

For the station location problem, the goal is determining the optimal number and placement of stations by minimizing impedance (p-median) (the average distance to the demand points covered from the stations to be allocated is minimized) or maximising coverage (the amount of reachable demand within a certain coverage area is maximized) ([13]). The main inputs for this problem typically include user demand patterns, population density, points of interest, and existing transportation infrastructure.

Regarding fleet sizing decision, it refers to determining the optimal number of vehicles needed to be deployed in the whole system and the initial number of vehicles at each station ([14]). It should be considered a strategic decision as the investment costs of vehicles are not negligible. This problem is often solved using simulation-based optimization techniques or queuing theory models. [15] model the system as a closed queueing network and develop a novel approach to approximate the minimum number of vehicles needed to meet a target service level. They highlight key differences between round-trip systems (where vehicles always return to their origin) and one-way systems (where vehicles can roam), and indicate that one-way systems require more buffer capacity due to the randomness in vehicle distribution across locations.

Rebalancing means how to redistribute vehicles efficiently to deal with the spatial and temporal imbalanced demands and usage patterns. Common rebalancing strategies can be broadly categorized into operator-based and user-based approaches. Operator-based strategies involve manual redistribution of vehicles using rebalancing trucks, which can be further divided into static and dynamic rebalancing based on timing. User-based strategies, on the other hand, focus on incentivizing users to self-rebalance the system ([16]).

The differences between on-demand meal delivery platforms and shared mobility systems can lead to distinct operational challenges. Shared mobility systems treat customer rental requests as input for facility planning, while our problem considers courier usage of company vehicles as a decision variable controlled by the company's cost trade-off between company-vehicle and independent contractor models. Moreover, the criteria for location selection in our model (courier accessibility via public transport, minimizing repositioning costs) differ from shared mobility systems' focus on customer convenience and geographic coverage to include their key origins and destinations within walking distance for profitability maximization. Also, the timing of vehicle pick-up and drop-off tied to courier shifts introduces unique logistical characteristics.

D. Facility Location Problem

Facility location is a critical strategic decision in operations management and logistics, including the determination of facility numbers, locations, and demand point allocations. The complexity of these problems varies based on capacity constraints, time horizons, and data certainty. Objectives can range from cost minimization to distance reduction, coverage maximization, or balancing multiple goals. Recent research has expanded to integrate facility location with inventory and routing decisions, known as the location-routing-inventory problem. This integrated approach has proven instrumental in designing efficient supply networks ([17]–[19]). The cost components typically considered in these models include facility setup, inventory holding, and transportation costs ([20]–[22]). [23] also revealed that combining short-term decisions on vehicle routing and inventory planning with facility location optimization yields cost savings.

Notably, our study first examines the economic viability of a company-vehicle delivery model based on micro-logistics centers within a mixed delivery model structure, which differs from traditional facility location problems with the implication of a single model. Also, we include the consideration of courier accessibility to these micro-logistics centers using public transport. This factor is not typically included in traditional facility location literature. Furthermore, due to the unique nature of on-demand meal delivery, the cost components in our problem require new interpretations.

E. Districting

The districting problem is often applied in service and distribution contexts to define pickup and delivery districts prior to developing daily routing solutions ([24]). This approach helps reduce the complexity of routing problems ([25]), and improve drivers' familiarity with customer locations and route organization ([26], [27]). When dividing areas into service districts, specific criteria such as compactness and contiguity are employed to meet operational needs. Compactness ensures reasonable travel times within districts, while contiguity guarantees physical connectivity without isolated areas ([28]).

The application of districting concepts to on-demand meal delivery service areas remains relatively unexplored. The accessibility in our study uniquely focuses on courier convenience in accessing facilities before delivery, departing from traditional districting's emphasis on unobstructed vehicle travel within districts. In the context of this paper, districts can be viewed as service areas for micro-logistics centers. The compactness criterion can be incorporated into the objective function to limit travel time and distance between demand points and centers. Also, the continuity criterion can ensure coverage meets geographic or administrative restrictions.

III. Problem Description

We consider an on-demand meal delivery platform that dispatches couriers to deliver orders from restaurants to customers and aims to minimize its total operational cost. We assume that the platform has been in operation with independent-contractor couriers for a long time and has collected historical data on where and when couriers start/end their shifts, indicating their first/last delivery locations, and their shift schedules. The delivery models and the historical data we considered are explained in Section III-A.

Our study aims to develop a strategic model that provides insights into the following key decisions for the platform to optimize the costs:

1) Delivery model selection: choose between maintaining operations with independent contractors (IC) or adopting a hybrid model that includes both IC and company-vehicle (CV) couriers operating with micro-logistics centers, to minimize total costs.
2) Micro-logistics center placement: select strategic locations for micro-logistics centers to support CV operations, ensuring accessibility to couriers (as the detailed explanation in Section III-B).
3) Coverage area and vehicle allocation: define the service zones allocated to each micro-logistics center for CV operations, and determine the optimal number of company vehicles to be stationed at each micro-logistics center.

In particular, coverage consists of zones where a center provides company vehicles for couriers to start their first deliveries. Multiple couriers may begin from each zone at different times. The coverage area is defined by these starting zones, not the entire region where deliveries occur.

For the total costs, we consider four cost components:

- Facility-related costs: to construct necessary micro-logistics centers;
- Vehicle depreciation costs: to purchase and operate company fleet;
- Operational costs of CV model: labor cost for CV couriers; and vehicle repositioning costs (including distribution from centers to their first delivery locations and collection from last delivery locations back to centers);
- Operational costs of IC model: labor costs for independent contractors.

In this study, we assume both types of couriers receive the same basic hourly salary while independent contractors receive an additional allowance for using their personal vehicles. And the common labor costs are omitted in the following cost minimization problem and our focus is on repositioning costs for the CV model and additional payments for the IC model respectively.

The platform's service area is divided into uniform hexagonal zones, offering uniform adjacency among zones in the network. Each zone ($i \in I$, where I is the set of zones in the network) is centered at r_i. A graph $G = \{I, A\}$ represents the connectivity of the service region, where each vertex corresponds to a zone, and an edge $(i, j) \in A$ exists between adjacent zones having a common border. The travel time t_{ij} between any two zones i and j is defined based on couriers' travel time on the shortest path between zone centers.

Let $\mathcal{T}$ represent a typical operation day in our planning horizon. This horizon is discretized into equal time intervals, where $\mathcal{T} = \{\tau_0, \tau_1, \ldots, \tau_n, \ldots, \tau_N\}$ to capture the variation of couriers' movements during the day. Each $\tau \in \mathcal{T}$ represents the time stamp at the beginning of the period.

A. Delivery Model

We consider a hybrid operational model, which incorporates two approaches: (a) the owner-operator model with Independent Contractors (IC) and (b) the Company-Vehicle model (CV) with micro-logistics centers.

In (a) the owner-operator model, IC couriers use their own vehicles and start/end their shifts at their first/last delivery locations. They receive a basic hourly salary (C_h^O), plus an additional allowance (C_a^O) for the use of their personal vehicles.

For (b) the parking-dependent company-vehicle model, CV couriers use vehicles provided by the company and are required to start and end their shifts at designated company centers. They also receive the same basic hourly salary (C_h^O). Unlike IC couriers, CV couriers must travel between centers and delivery zones at shift start and end. And the company covers the cost of these non-productive trips by including compensation for this travel time in the couriers' pay.

We assume either IC or CV couriers, are using the same type of transport modes for delivery (e.g., vehicles, e-mopeds etc). Both types of couriers earn the same hourly basic salary (C_h^O) and travel at a homogeneous, constant speed throughout the service area.

We assume that the platform aims to re-consider the delivery model choice in an area for which historical operation data exists. Based on the historical data, we can obtain observations of courier activities, particularly their starting and ending times and locations, which indicate their historical first and last delivery zones. We define $\tilde{S_i^\tau}$ as the number of couriers starting their shift at zone i at time τ and $n_{ij}^{\tau\tau'}$ as the probability for a courier starting at zone i at time τ to end their shift at zone j at time τ'.

For a hybrid delivery model, to introduce micro-logistics centers and provide CV service in such an area, we assume that the platform considers a service level, denoted by α. The service level represents the percentage of time that a given number of couriers can adequately cover the observed courier activity patterns in a specific zone based on historical data. We use S_i^τ to denote the number of couriers at certain service level desired by the platform. And S_i^τ can be determined at a given service level (α) by equation 1. For zone i at time τ, for example, we have 400 days of historical data on couriers' starting records where 200 days with 0 couriers, 100 with 1, and 100 with 2. Thus, 0 couriers cover 50% of demand, 1 covers 75% and 2 for 100%. And if the platform's desired service level α is 75%, then S_i^τ would be 1.

When determining the possible CV service needs of zone i in terms of the number of couriers, S_i^τ is considered and the remaining required number of couriers will be assigned as IC couriers, denoted by $\overline{S}_i^\tau$. The historical starting and ending records of these S_i^τ couriers are treated as their first and last delivery locations, which will result in 'non-productive legs' - the trips from potential centers to these delivery points.

Furthermore, in the context of the CV model, the starting and ending shift activities of CV couriers impact vehicles' inventory at centers through pickup and drop-off activities. To maintain system balance, all vehicles that are picked up must be returned to designated centers.

$$S_i^\tau = \min \xi_i^\tau : F_i^\tau(\xi_i^\tau) \geq \alpha, \qquad \forall i \in I, \tau \in \mathcal{T} \qquad (1)$$

$$\xi_i^\tau \in \mathbb{N}, \qquad \forall i \in I, \tau \in \mathcal{T} \qquad (2)$$

where F_i^τ is the cumulative distribution function of courier counts for zone i at time τ; α is the desired service level and $0 \geq \alpha \leq 1$.

B. Accessibility Measure

We introduce the **accessibility score** for each zone, A_i, as a quantitative measure to evaluate public transport conditions for each zone in a network, reflecting the convenience for couriers to access the zone. We assume that couriers use public transportation for their commutes. And a higher accessibility score suggests that a zone is well-connected to public transport networks, implying a lower effort for couriers to reach these locations. While the exact commute costs are challenging to quantify due to the privacy concerns and variability of

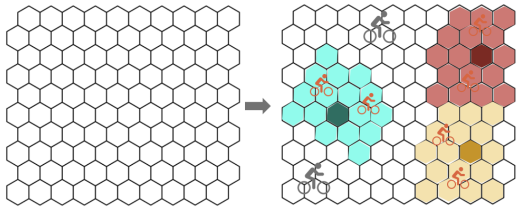


Fig. 1: Illustration of Key Decisions

couriers' residences, the accessibility score serves as a practical alternative to assess a zone's potential for easy access. By considering this score when selecting center locations, companies can provide convenience for couriers who commute to these centers using company vehicles, potentially improving job satisfaction and employee retention, as well as the attractiveness of their company-vehicle model to potentially increase its adoption among couriers.

A_i is calculated based on the public transportation condition within zone i, including the availability and frequency of transport options within it and the zone's connectivity to others. Specifically, the accessibility score A_i consists of three components, the number of public transport modes available within a certain walking distance from the center of the zone, the number of lines of the corresponding mode, and the number of zones it can connect to represent each zone's accessibility and make sure the chosen location of center meets the requirement of accessibility. Let $\Omega = \{1, 2, 3, 4\}$ be the set of different modes, with 1,2,3 and 4 denoting bus, metro, tram, and train, respectively. Particularly, since each mode contributes to the overall accessibility by offering different options for commuters, the number of public transport modes available within 350m walking distance from the centroid of zone i is counted with the denotation of PT_i^1. The number of lines in the corresponding mode is denoted by $PT_i^{2m}, m \in \Omega$, respectively. To some extent, it represents the frequency of service for each mode of public transport, and higher frequencies generally mean shorter waiting times, improving accessibility. Also, the number of zones connected via public transport $PT_i^{3m}, m \in \Omega$ reveals the coverage of key destinations that can be reached from zone i. It is important for the candidate zone for the location of center to be accessible by couriers living in different zones.

The overall accessibility score A_i of zone i can be interpreted in terms of the weighted sum of these critical factors:

$$A_i = u_1 * PT_i^1 + u_2 * \sum_{m\in\Omega} u_{2m} * PT_i^{2m} + u_3 * \sum_{m\in\Omega} u_{3m} * PT_i^{3m} \tag{3}$$

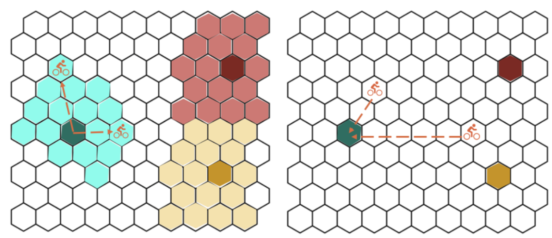
Figure 1 illustrates our decisions to divide a uniform hexagonal grid according to the delivery model choice. Colored zones represent different coverage areas for centers with CV couriers (in orange), with darker ones indicating potential center placements. The white areas suggest they are assigned to be served by IC couriers (in grey).

IV. Mathematical Models

In this section, we will introduce two models: Model I considers a fixed-coverage problem with the return-to-origin operational policy, in hybrid delivery operations where centers, if needed, have fixed coverage areas for CV service. These areas remain constant over time, considering geographic connectivity constraints imposed by physical or administrative requirements. Also, CV couriers need to return company-owned vehicles to their original centers at the end of their shifts, regardless of their final locations.

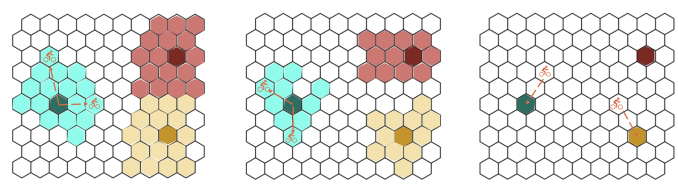
Model II addresses a problem with time-variant coverage and global redistribution optimisation to obtain more efficient resource allocation. It allows for flexible coverage areas of centers that can change with time τ. It also optimizes the returns for CV couriers based on overall cost trade-offs and maintains a system-wide balance in company-owned vehicles' inventory.

Figure 2 and Figure 3 show the illustration of the requirements and decisions included in Model I and II respectively.



(a) Model I - Coverage & Vehicles' Supply (b) Model I - Returns

Fig. 2: Illustration of Model I



(a) Model II - Coverage & Vehicles' Supply at time 1 (b) Model II - Coverage & Vehicles' Supply at time 2 (c) Model II - Returns at certain time

Fig. 3: Illustration of Model II

A. Model I

This section provides a complete description of Model I, where the centers, if needed, have fixed coverage over periods during the operation with geographic continuity constraints. The definition of sets, parameters, and variables involved in the mathematical model can be found in Table X in Appendix.

Model I with the objective of cost minimisation is formulated as follows:

$$\min \quad \sigma_b^F + \gamma_b^F + \zeta_b^O + \theta_a^O \tag{4}$$

The objective function (4) aims to minimize the total investment and operation costs of the delivery model adopted for one typical business day. Specifically, the investment refers to the construction (σ_b^F) and vehicle-depreciation costs (γ_b^F) for centers to provide CV service. The operation cost includes the cost of non-productive legs for CV couriers (ζ_b^O) that they are required to travel between the center and their starting and ending delivery locations, and the labour costs for IC couriers (θ_a^O). The same part of labor cost calculated on the basic hourly salary for couriers in both IC and CV plans is omitted.

The model also seeks the optimal number of centers needed. We explain each item of objectives separately in (5)-(11). Constraints on districting and capacity of centers are presented by (13)-(34). The following sections elaborate on each category of constraints.

1) Investment Cost: **Facility-related cost.** Let $p \in P$ be the set of centers. Each center has a coverage area in which CV service is provided. We introduce the binary variable y_i^p, and it equals 1 when the center p is located at the zone i. Also, the center locations can only be selected from the candidate zones in set $I_c, I_c \subseteq I$, whose accessibility score meets the minimum threshold. If center p is required and it is selected to be placed in zone i, the associated facility cost is determined by dividing the total cost of setting up a center in zone i over the duration of planning to estimate the daily cost (C_i^F). We define σ_b^F as the fractional variable to represent the facility-related cost.

$$\sigma_b^F = \sum_{p \in P} \sum_{i \in I_c} C_i^F * y_i^p \tag{5}$$

$$\sigma_b^F \in \mathbb{R} \tag{6}$$

Vehicle depreciation costs. To provide CV couriers with company-owned vehicles, there are costs for purchasing these vehicles. C_b^F is introduced to reflect this term of cost, which is also broken down across the planning time horizon into one-day cost. q_0^p denotes the initial inventory (which also is the total vehicles needed for the CV couriers within the coverage areas) at center p. Fractional variable γ_b^F is calculated to purchase all vehicles needed.

$$\gamma_b^F = \sum_{p \in P} C_b^F * q_0^p \tag{7}$$

$$\gamma_b^F \in \mathbb{R} \tag{8}$$

2) Operation Costs: **Costs for non-productive legs.** CV couriers' shifts include time spent travelling between the centers and zones where they have the first and last delivery. We use z_{ij}^p to denote the non-productive legs and it equals 1 if zone j is covered by center p located at zone i. C_h^O represents the hourly salary paid to couriers, and fractional variable ζ_b^O calculates the costs for these non-productive trips when repositioning couriers between the centers and their starting (or ending) point over an operational day.

$$\zeta_b^O = \sum_{p \in P} \sum_{\tau \in \mathcal{T}} \sum_{i \in I_c} \sum_{j \in I} C_h^O * z_{ij}^p * (t_{ij} * S_j^\tau + \sum_{k \in I} \sum_{\tau' \in \mathcal{T}} t_{ik} * E_{jk}^{\tau'\tau}) \tag{9}$$

$$\zeta_b^O \in \mathbb{R} \tag{10}$$

Costs for Owner-operator Couriers IC couriers will also receive an extra allowance C_a^O for using their own vehicles. Thus, the labor cost for an IC courier is C_a^O. v_i indicates whether zone i is served by IC couriers or not, and the fractional variable θ_a^O calculates the labor costs for zones included in the owner-operator plan for daily operation.

$$\theta_a^O = \sum_{i \in I} \sum_{\tau \in \mathcal{T}} C_a^O * \tilde{S}_i^\tau * v_i + C_a^O * \overline{S}_i^\tau * (1 - v_i) \tag{11}$$

$$\theta_a^O \in \mathbb{R} \tag{12}$$

The constraints consist of two interdependent parts: Allocation and Vehicle Inventory. Allocation determines center numbers, locations, and coverage, with an additional Continuity constraint in Model I. Vehicle Inventory optimizes fleet size and initial center inventories.

$$v_i + \sum_{p \in P} x_i^p = 1, \qquad \forall i \in I \tag{13}$$

$$e_i^{p\tau} = \sum_{j \in I} \sum_{\tau' \in \mathcal{T}} E_{ji}^{\tau'\tau} * x_j^p, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{14}$$

$$\sum_{i \in I_c} y_i^p \leq 1, \qquad \forall p \in P \tag{15}$$

$$y_i^p = 0, \qquad \forall i \in I \setminus I_c, \forall p \in P \tag{16}$$

$$\sum_{p \in P} y_i^p \leq 1, \qquad \forall i \in I_c \tag{17}$$

$$z_{ij}^p \leq y_i^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{18}$$

$$z_{ij}^p \leq x_j^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{19}$$

$$1 + z_{ij}^p \geq x_j^p + y_i^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{20}$$

$$x_i^p \in \{0, 1\}, \qquad \forall i \in I, \forall p \in P \tag{21}$$

$$y_i^p \in \{0, 1\}, \qquad \forall i \in I_c, \forall p \in P \tag{22}$$

$$z_{ij}^p \in \{0, 1\}, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{23}$$

$$v_i \in \{0, 1\}, \qquad \forall i \in I \tag{24}$$

$$e_i^{p\tau} \in \mathbb{R}^+, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{25}$$

Allocation Constraint (13) determines whether a zone is included in CV service or not. Constraint (14) determines the value of the vehicles' return $e_i^{p\tau}$. It depends on $E_{ji}^{\tau'\tau}$, the number of CV couriers for center p ending their shift in this zone time τ, where $E_{ji}^{\tau'\tau} = S_j^{\tau'} * n_{ji}^{\tau'\tau}$. Constraints (15) - (16) ensure that if center p is needed, exactly one location is assigned to it, and this location must meet the accessibility requirement. Constraints (17) guarantees that each potential candidate location can be used for at most one center. Constraints (18) - (20) ensure z_{ij}^p equal 1 only when zone j is within the coverage of center p and meanwhile zone i serves as its location.

$$\sum_{j|(i,j) \in A} f_{ij}^p - \sum_{j|(j,i) \in A} f_{ij}^p \geq x_i^p - (|I| + 1) * y_i^p, \quad \forall i \in I, \forall p \in P \tag{26}$$

$$\sum_{j|(j,i) \in A} f_{ij}^{pt} \leq |I| * x_i^p, \quad \forall i \in I, \forall p \in P \tag{27}$$

$$f_{ij}^p \geq 0, \qquad \forall (i, j) \in A, \forall p \in P \tag{28}$$

Continuity If a center is needed, the compactness and continuity of its coverage area are incorporated into the construction of the network and the minimising objective of the distance-based travel time. The following constraints provide an enhanced version of the continuity requirement. Constraints (26) - (27) ensure the overall continuity within the coverage area of center p, where variable f_{ij}^p representing continuity on arc $(i,j) \in A$ within the coverage area of center p.

$$q^{p\tau 0} = q^{p\tau N}, \quad \forall p \in P \tag{29}$$

$$q^{p\tau} = q^{p(\tau-1)} - \sum_{i \in I} S_i^{\tau} * x_i^p + \sum_{i \in I} e_i^{p\tau}, \quad \forall p \in P, \forall \tau \in \mathcal{T} \setminus \{\tau_0\} \tag{30}$$

$$q^{p(\tau_0)} \leq q_0^p \quad \forall p \in P \tag{31}$$

$$q_0^p \leq U_0 * \sum_{i \in I_c} y_i^p, \quad \forall p \in P \tag{32}$$

$$q^{p\tau} \in \mathbb{R}^+, \quad \forall p \in P \tag{33}$$

$$q_0^p \in \mathbb{N} \tag{34}$$

Vehicle Inventory Constraints (29) - (30) determine the inventory level of vehicles in each center at time τ ($q^{p\tau}$) and ensure its balance after one-day operation. Particularly, the inventory of each center varies with the pick-up needs and returns at time τ. Constraint (31) determines the total stock of vehicles of each center p needed for CV couriers within its coverage. Constraint (32) also ensures that if the CV service is needed, there must be a center to accommodate the vehicles required, with maximum capacity restriction considering the center limitation U_0.

B. Model II

Model II considers the starting distribution of couriers changing throughout the day, their possible ending locations varying based on starting point and time (reflecting different customer clusters for various restaurants and times), and their impact on the non-productive costs related to the travel times spent on vehicles pickup and return trips, as well as vehicle inventory determined based on vehicles' demands and turnover. Allocation decisions in the Model II adapt over time. Moreover, vehicles are not required to return to their original centers. Instead, return locations are optimized based on the distance to available centers and overall system balance.

Model II considers the spatial-temporal distribution of courier shifts changing with time τ as well as the balance of vehicles in the whole network and each center. And the allocation-related variables are updated to x_i^{pt} and v_i^t, compared with Model I (the location of centers remains unchanged over time in both models, as indicated by y_i^p). In addition, Model II introduces variables $z_{ij}^{(S)p\tau}$ and $z_{ij}^{(E)p\tau}$ to denote the non-productive legs of distribution and collection, respectively. Detailed variable description of Model II can be found in Table XI in Appendix.

The objective function in Model II includes updated operational costs:

$$\zeta_b^O = \sum_{\tau \in \mathcal{T}} \sum_{p \in P} \sum_{i \in I_c} \sum_{j \in I} C_h^O * t_{ij} * (z_{ij}^{(S)p\tau} + z_{ij}^{(E)p\tau}) \tag{35}$$

$$\theta_a^O = \sum_{i \in I} \sum_{\tau \in \mathcal{T}} C_a^O * \tilde{S}_i^{\tau} * v_i^t + C_a^O * \overline{S}_i^{\tau} * (1 - v_i^t) \tag{36}$$

Allocation constraints were modified as follows, while Vehicle Inventory expressions remained the same as Model I. Particularly, constraint (38) ensures that vehicle returns are based on pickup demand, but without restrictions on specific centers.

$$v_i^{\tau} + \sum_{p \in P} x_i^{p\tau} = 1, \quad \forall i \in I, \forall \tau \in \mathcal{T} \tag{37}$$

$$\sum_{p \in P} e_i^{p\tau} = \sum_{p \in P} \sum_{j \in I} \sum_{\tau' \in \mathcal{T}} E_{ji}^{\tau' \tau} * x_j^{p\tau'}, \quad \forall i \in I, \forall \tau \in \mathcal{T} \tag{38}$$

$$\sum_{i \in I_c} y_i^p \leq 1, \quad \forall p \in P \tag{39}$$

$$\sum_{p \in P} y_i^p \leq 1, \quad \forall i \in I_c \tag{40}$$

$$x_j^{p\tau} \leq \sum_{i \in I_c} y_i^p, \quad \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{41}$$

$$z_{ij}^{(S)p\tau} \leq M * y_i^p, \quad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{42}$$

$$z_{ij}^{(S)p\tau} \leq S_j^{\tau} * x_j^{p\tau}, \quad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{43}$$

$$z_{ij}^{(S)p\tau} \geq S_j^{\tau} * x_j^{p\tau} - M * (1 - y_i^p), \quad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{44}$$

$$z_{ij}^{(E)p\tau} \leq M * y_i^p, \quad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{45}$$

$$z_{ij}^{(E)p\tau} \leq e_j^{p\tau}, \quad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{46}$$

$$z_{ij}^{(E)p\tau} \geq e_j^{p\tau} - M * (1 - y_i^p), \quad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \tag{47}$$

$$x_i^{p\tau} \in \{0,1\}, \quad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{48}$$

$$y_i^p \in \{0,1\}, \quad \forall i \in I_c, \forall p \in P \tag{49}$$

$$z_{ij}^{(S)p\tau} \in \mathbb{N}, \quad \forall i \in I_c, \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{50}$$

$$z_{ij}^{(E)p\tau} \in \mathbb{R}^+, \quad \forall i \in I_c, \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{51}$$

$$v_i^{\tau} \in \{0,1\}, \quad \forall i \in I, \forall \tau \in \mathcal{T} \tag{52}$$

$$e_i^{p\tau} \in \mathbb{R}^+, \quad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{53}$$

V. Results

In the following sections, we describe the instances and case study on Amsterdam and investigate the managerial insights that can be provided by our model.

A. Instance Description

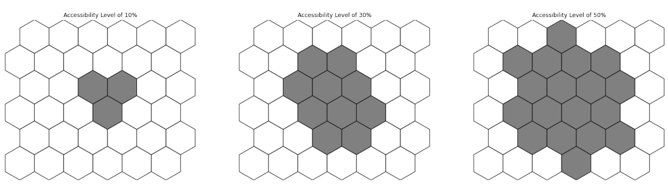
Network Settings Three network configurations are considered to simulate either entire cities of varying sizes or core operational areas within larger metropolitan regions, depending on the specific characteristics of the on-demand platform's service region and the concentration of courier activities. Furthermore, we employ a hexagonal network generated using the H3 spatial indexing system with a resolution of 8 to these areas. Each hexagon covers an average area of 0.737 km^2[1], offering a granular representation of urban landscapes and uniform adjacency among zones in the network.

- 6x6 network (36 zones): Representing smaller urban areas (e.g., Delft, Netherlands) or compact business districts;
- 9x9 network (81 zones): Representing medium-sized cities or expanded central business areas;

[1] https://h3geo.org/docs/core-library/restable/

- 12x12 network (144 zones): Representing large cities (e.g., Den Haag, Netherlands) or extensive business areas of major metropolitan cities.

Accessibility Levels We introduce three accessibility levels: 10%, 30%, and 50%. These percentages represent the proportion of zones within the network whose accessibility scores exceed a defined threshold, making them eligible as candidate locations for centers. This can reflect cities with different rates of transportation infrastructure connectivity. In the following instances, we assume accessibility decreases with distance from the city center, reflecting typical urban patterns where central areas have more diverse and frequent public transportation options, and the proportion, e.g, 10%, means the top 10% zones closest to the city center. Figure 4 shows the eligible candidates (indicated in grey) under these three different accessibility levels on a 6x6 network.



(a) 10% Accessibility Level: Top 10% of zones closest to city center (b) 30% Accessibility Level: Top 30% of zones closest to city center (c) 50% Accessibility Level: Top 50% of zones closest to city center

Fig. 4: Visualization of Different Urban Accessibility Levels

Temporal Distribution of Couriers We consider a one-day operation period spanning from 08:30 AM to 22:00 PM. We segment this period into 1.5-hour intervals, each represented by a time stamp in the set $T = \{0, 1, 2, 3, ..., 7, 8, 9\}$, where each number indicates the start of an interval. We suppose that couriers start their shift between 11:00 AM and 20:00 PM and this period is further categorized into operational periods that reflect typical meal delivery patterns:

- Lunch peak period [1, 2]: from 11:00 AM to 14:00 PM;
- Normal period [3, 4]: from 14:00 PM to 17:00 PM;
- Dinner peak period [5, 6]: from 17:00 PM to 20:00 PM.

The number of active couriers fluctuates throughout the day. We use courier density, measured in 'couriers/km^2', to describe the number of available couriers relative to the size of the market or service area. Based on industry observations, we have the following assumption to represent a higher courier density during meal times to handle increased order volume, which is a pattern commonly observed in food delivery operations.

- Peak hours (lunch and dinner): 0.3 couriers/km^2;
- Normal period: 0.075 couriers/km^2.

To illustrate, consider a 6x6 network (36 zones, covering approximately 26 km^2) as shown in Figure 5, during peak hours (time stamp 1, 2, 5 or 6) is 0.3 couriers/km^2 * 26 km^2 $\approx$ 8 couriers start their shift; and during off-peak hours (times 3 or 4) 0.075 * 26 $\approx$ 2 courier starts their shift. This results in a total of 36 active couriers over a full day.

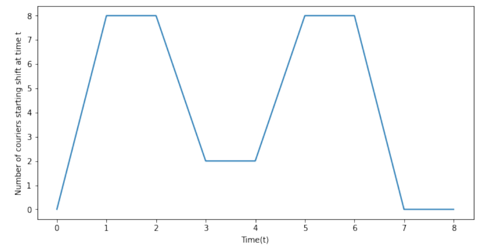


Fig. 5: Number of couriers starting at different times on the 6x6 network instance

Courier shift lengths are modeled using a normal distribution with a mean of 2 time units (3 hours) and a standard deviation of 1 unit (1.5 hours), with a maximum of 3 units (4.5 hours) and a minimum of 1 unit (1.5 hours).

Spatial Distribution of Couriers We assume a uniform random spatial distribution for both the starting and ending locations of couriers in the following instances.

Examples We use this example to illustrate the data we consider: couriers' starting records and the couriers' movement matrix $n_{ij}^{\tau\tau'}$. For instance, the total number of couriers starting at Zone 2 at time 5 is 2 and $\tilde{S}_2^5 = 2$. And $S_2^5 = 1$ indicating the CV couriers needed at service level 0.7, and thus, $\overline{S}_2^5 = 1$ as the number of IC couriers required if CV service is provided for Zone 2 at time 5. Moreover, for couriers starting at Zone 2 at time 5, they have 0.2 chance of ending their shift at Zone 5 at time 6, 0.14 chance to end at Zone 7 at time 6, and 0.66 to end at Zone 4 at time 7, where $n_{25}^{56} = 0.2, n_{27}^{56} = 0.14, n_{24}^{57} = 0.66$.

We assume the vehicles couriers are using are e-bikes with a speed of 15-16 km/h within urban areas. The distance between centers of two adjacent zones is 0.92 km and then the travel time is 0.06 h. And other parameters we used in the instances are listed in I.

TABLE I: Parameters of the test instances.

Parameters	Value	Remark
C_i^F	60 (€/day)	for all locations
C_b^F	1 (€/e-bike)	
C_h^O	15 (€/hour)	
C_a^O	8 (€/person)	
TT_{ij}	0.06 (hour)	for adjacent zones $(i, j) \in A$
TT_{ij}	shortest path	for non-adjacent zones i and j
$\|P\|$	3	Maximum centers allowed

B. Computational Results

We conduct our experiments using Python 3.9 and Gurobi Optimizer version 9.5.2 build v9.5.2rc0 (mac64[arm]). Computational time mainly depends on two factors: network size and the number of candidate locations, which are determined by the accessibility level. Table II and Table XII show the settings and results for instances with varying network sizes and accessibility levels.

The largest case '12-R-A3-Model II' requires 11755.7(s) to solve and it indicates our model can solve a real-world size case with an exact solution within a reasonable time. Moreover, computation time increases exponentially with both network size and accessibility levels. This is due to the growing number of nodes and candidate locations, respectively. Instances for Model II generally require more computation time than Model I ones.

TABLE II: Settings of computational tests.

Instance Name / Network Size \ Accessibility Level	10%	30%	50%
6x6	6-R-A1	6-R-A2	6-R-A3
9x9	9-R-A1	9-R-A2	9-R-A3
12x12	12-R-A1	12-R-A2	12-R-A3

C. *Topics Based on Insights*

Our experimental design aims to provide insights for on-demand meal delivery platforms optimizing logistics strategies across diverse urban environments and market conditions.

We begin by examining market size and maturity, reflecting different stages of market development and levels of demands (see Section V-C1).

We also assess the impact of diverse urban structures on optimal delivery strategies and micro-logistics center planning. Combining the the logistics dynamics for on-demand meal delivery, our scenarios assume that couriers typically start near restaurant clusters for their first delivery and end their shifts/last delivery closer to customer areas. In Section V-C2, we investigate how varying restaurant distributions and distances between commercial and residential zones influence platform decisions.

Our study also compares decisions under different economic conditions, including infrastructure costs and courier compensations (see Section V-C3).

Lastly, we evaluate various transport options to gain insights into optimal vehicle fleet configuration (see Section V-C4).

For each scenario, we generate 3 random sets of initial distributions (R1, R2, R3) due to the random distribution assumption introduced earlier. We test each setting across three accessibility levels (A1, A2, A3) as shown in Table I. If the results are identical for different accessibility levels, we use a compact format to illustrate, e.g., '6-R1-A1/2/3-Model I'.

1) Market: As shown in Table III, Scenario M0 simulates emerging markets with low courier density, reflecting areas new to food delivery services. Scenario M1 represents established markets with moderate courier density, typical of stable urban areas. Scenario M2 depicts high-demand metropolitan environments with dense courier networks. The variations are tested on both 6x6 and 12x12 networks. By varying courier density from low to high across these scenarios, we aim to examine how market size and maturity influence optimal delivery strategies. The model results are presented in Table XIII.

TABLE III: Scenarios Settings with Different Markets.

Network	Scenarios	Number of Total Couriers	Courier Density
6x6	Scenario M0	22	Peak Hours: 0.2 Normal Hours: 0.05
	Scenario M1	36	Peak Hours: 0.3 Normal Hours: 0.075
	Scenario M2	50	Peak Hours: 0.4 Normal Hours: 0.1
12x12	Scenario M0	94	Peak Hours: 0.2 Normal Hours: 0.05
	Scenario M1	144	Peak Hours: 0.3 Normal Hours: 0.075
	Scenario M2	190	Peak Hours: 0.4 Normal Hours: 0.1

We use indicators: the number of micro-logistics centers needed ($\#C$), the number of e-bikes needed ($\#Bikes$), the number of CV couriers included to provide CV service and IC couriers needed, and the costs of CV (particularly, the center construction costs σ_b^F, the bicycle purchasing costs γ_b^F, and the operational costs for non-productive legs ζ_b^O) and IC service (θ_a^O) respectively to evaluate different scenarios. We also use the indicator, CV Courier Supply Ratio (CSR), to denote the ratio of the optimal number of CV couriers, as determined by the cost-minimization delivery plan model, divided by the maximum potential CV courier demand based on the desired service level across all zones.

Table XIII shows the results for each instance and Table XIV calculates the average results of the three random cases under different accessibility levels and the models.

When the courier density is quite low, which indicates the market size is small (Scenario M0), the IC model is optimal (there are approximated 0 or 0 centers needed for both 6*6 and 12*12 networks and almost all the couriers are hired as independent contractors).

As markets grow and courier density increases, a hybrid model becomes preferable (the average values of CSR increase from 0 to approximated 1). For smaller areas, a single center is sufficient, while larger networks with expanded operations benefit from multiple centers (some average values of '#C' are greater than 1 for the 12x12 network in both M1 and M2 scenarios). The model also demonstrates good scalability, allowing companies' transition from medium market M1 to larger market M2 to maintain their existing infrastructure while simply increasing the number of e-bikes to meet growing demand (with maintaining the optimal number of centers as 1, the average number of e-bikes needed grows from 11.3 to 14.2 on 6x6 network).

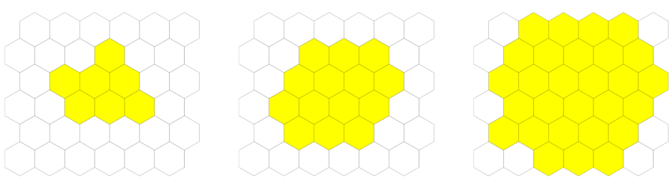
Moreover, Model II generally leads to lower costs compared to Model I. Also, as compared to adopting all IC couriers with the operational strategy as Model I for the 12x12 network in M1, Model II implies an average of 2.2 centers needed, suggesting a varied delivery model choice and center plan under different operating strategies.

Also, as accessibility levels increase (from A1 to A3), the changes in the optimal solution (in M1 the average value of total costs under A1 1151 euro as indicated in 'Avg-12-A1' decreases to 1116.2 euro under A3 level, also it drops from 1497.3 euro of A1 to 1438.5 euro of A3 in M2) suggests that sometimes a wider range of center options offers more opportunities to optimize operations.

2) Urban Structures: **A.** We developed three scenarios representing varied restaurant distributions, as shown in Table IV and Figure 6. These scenarios range from highly concentrated (inner 20% of the city) to widely dispersed, reflecting diverse city layouts or the scope of platform-partnered restaurants. It also reflects how couriers might begin their shifts in different areas of the city. Moreover, we assume random ending locations across all scenarios, simulating a typical situation with more deterministic restaurant placements and stochastic customer distributions.

TABLE IV: Scenarios Settings with Different Starting Distribution.

Scenarios	Starting Areas
Scenario S1	0% - 20 %
Scenario S2	0% - 40 %
Scenario S3	0% - 80 %



(a) S1: 0% - 20 % Areas from Center (b) S2: 0% - 40 % Areas from Center (c) S3: 0% - 80 % Areas from Center

Fig. 6: Visualization of different starting/restaurant areas

As illustrated in Table XV, as restaurants' distribution becomes more decentralized (moving from S1 to S3), the IC model becomes more cost-effective (the average number of IC couriers needed increases from the 5.8 in S1, 11.5 in S2 to 22 in S3). Moreover, total costs generally rise from S1 to S3 (from 162.5 euro to 176 euro), indicating higher operational costs for spread-out distributions. This suggests that urban structure and its restaurants' distribution will influence the choice of delivery model.

B. We designed scenarios to simulate diverse urban layouts with varying distances between central business districts and residential areas to investigate their impact on the decisions. As shown in Table V, we assume restaurants are clustered within the inner 20% of the city center. We then vary the distributions of residential areas from 20-40% from the center (D1) to 80-100% from center (D3), which also indicates the couriers' shift-ending locations.

TABLE V: Scenarios Settings with Different City Layouts.

Scenarios	Ending Areas
Scenario D1	20-40%
Scenario D2	40-60%
Scenario D3	80-100%

Table XVI shows, generally, as the distance between couriers' starting points (restaurant clusters) and ending points (residential areas) increases, the IC model becomes more economically advantageous (the average number of IC couriers needed rises from 9.3 in D1, 8.2 in D2, to 19.2 in D3 while the average number of centers needed decreases from 0.8 to 0.2). It suggests that, in practice, more concise decisions should be made on company-specific historical data related to geographic distribution of restaurants and customers.

3) Costs: Table VI outlines three economic scenarios designed to test delivery model adaptability under varying cost structures. Scenario C0 serves as our baseline (M1 from Table XIII). C1 simulates higher facility costs, particularly common in dense urban areas or strict regulations on commercial spaces. C2 introduces lower independent contractor (IC) compensation, representing markets with abundant gig workers. By testing these key economic variables, we aim to understand how cost dynamics influence the optimal choice between company-owned vehicles (CV) and IC couriers, and the necessity of centers across different urban economic landscapes. And the results of different indicators under these scenarios are listed in Table XVII.

TABLE VI: Scenarios Settings with Different Costs.

Scenarios \ Costs	C_i^F (€/day)	C_b^F (€/bike)	C_h^O (€/hour)	C_a^O (€/person)
Scenario C0	60	1	15	8
Scenario C1	100	1	15	8
Scenario C2	60	1	15	6

It shows when facility costs are substantially higher (C1), it becomes economically unfavorable to adopt a CV delivery model with centers (the average number of IC couriers needed increases from 11 to 36). When the compensation for IC couriers is relatively lower in C2, companies can optimize costs by increasing their reliance on IC couriers (compared to the hybrid one in market condition C0 with an average of 25 CV couriers and 11 for IC, it shows in C2 that the platform should better hire all 36 couriers as IC one).

The results suggest that companies need to adapt their strategies - favoring IC models in high-facility-cost urban areas and leveraging lower IC rates when available.

4) Couriers' Transport Mode: To assess how vehicle types impact the trade-off between delivery models, we tested 5 scenarios, as shown in Table VII, to inform platforms' choices when equipping their company fleet.

- Scenario T0: Baseline - E-bikes;
- Scenario T1: Standard bicycles, slow but cheaper;

- Scenario T2: Slower regular bicycles, potentially in congested areas;
- Scenario T3: Fast scooters, increasing speed at a higher cost;
- Scenario T4: Premium Scooters, better quality but at a higher cost.

TABLE VII: Scenarios Settings with Different Modes.

Scenarios	Unit Travel Time	Purchasing Costs C_b^F
Scenario T0	0.06	1
Scenario T1	0.072	0.5
Scenario T2	0.09	0.5
Scenario T3	0.042	4
Scenario T4	0.042	7

Vehicle speed influences travel time and thus operational costs, especially in high labor cost markets, and a balance exists between vehicle speed and cost when considering the choice of vehicle type. As shown in Table XVIII, in scenarios with low-speed vehicles (T1, T2), despite a lower vehicle purchasing cost, we observe an increase in total costs (from an average of 265.3, 280.6 to 288 euro), as well as a trend toward more IC couriers rejecting CV models. In comparison, despite higher purchasing costs, faster modes (T3) show similar total costs to the baseline (T0) (267.8 euro in T3, compared to 265.3 euro in T0), suggesting that the speed gain offsets the higher vehicle cost. However, there's a tipping point where more costly vehicles should be excluded from company vehicle configuration options, indicated by the preference for IC models over owned fleets in T4 and higher overall total costs (288 euro).

D. Case Study: Amsterdam City

In this section, we look at the potential of using the models proposed above in practice by conducting a case study using historical data from one of the OMFD operators in Amsterdam.

We consider an operation period from 10:00 AM to 23:00 PM, covering the main meal delivery hours in Amsterdam. Starting locations are weighted towards high-order zones, while end locations reflect historical delivery zone distributions. By integrating data on courier start times, shift records, and derived location distributions, we obtained the number of couriers starting per zone and time slot, along with probable shift durations and destinations.

Using h3 spatial index and Amsterdam map[2], the city is divided into 415 hexagons. Regarding the accessibility scores for each zone, the public transportation network (including train, bus, metro, and tram) in Amsterdam is considered. Specifically, 15 tram lines with 139 tram stations, 5 metro lines with 11 metro stations, 81 bus lines (bidirectional) with 893 bus stations (those on different sides of the road are counted as 2), and 4 train lines with 13 train stations are considered. The relative data are obtained from the municipality of Amsterdam website[3] and via OpenStreetMap API[4]. Then, the accessibility score of each zone according to the equation (3) is calculated. Figure 7 shows the accessibility score calculation results of each zone in Amsterdam.

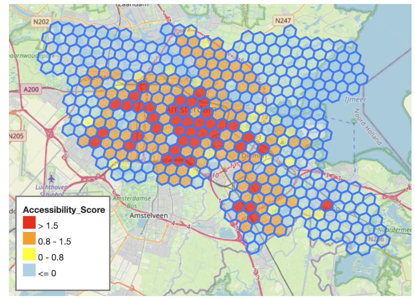


Fig. 7: Accessibility Score of Amsterdam City

Table VIII shows a different number of potential candidates for center locations that meet accessibility requirements under varying levels of threshold. When the threshold becomes lower, it means more zones can meet the requirement of accessibility to serve as center location candidates.

TABLE VIII: Different accessibility thresholds and the corresponding candidate locations

Accessibility Threshold	Number of Candidate Locations
2.8	8
2.2	33
1.7	41
1.3	53
1.2	63
1.12	95
1.08	123
0.2	163

Considering the planning horizon of 5 years (1825 days), for all places, the construction or leasing cost of a company-owned center is 25,000 euro per year and then C_i^F is around 69 euro per day. And the purchasing cost for company-owned e-bikes C_b^F is 1 euro (about 900 euro for purchasing and 900 euro for maintaining a bicycle for 5 years). Assume the hourly salary for both types of couriers C_h^O is 15 euro per hour[5], and the extra bicycle allowance C_a^O is 13 euro per day for an IC courier. The estimated parameters are listed in Table IX.

TABLE IX: Parameters of Amsterdam Case.

Parameters	Value	Remark
C_i^F	69 (€/day)	for all locations
C_b^F	1 (€/bicycle)	
C_h^O	15 (€/hour)	
C_a^O	13 (€/person)	
TT_{ij}	0.06 (hour)	for adjacent zones $(i, j) \in A$
$\|P\|$	3	Maximum centers allowed

[2]https://maps.amsterdam.nl/gebiedsindeling/

[3]https://maps.amsterdam.nl/trammetro/

[4]https://overpass-turbo.eu/

[5]https://www.thuisbezorgd.nl/en/courier

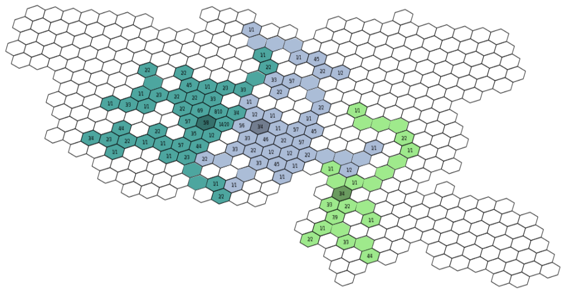
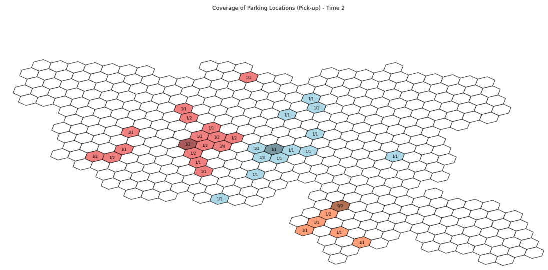


Fig. 8: Illustration of Model I result on Amsterdam case

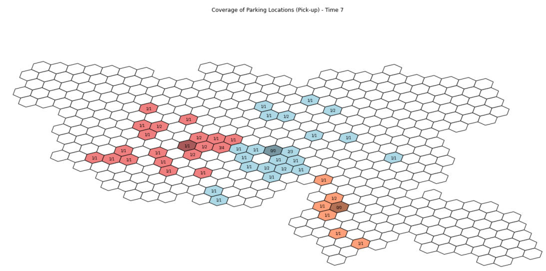
Table XIX presents the results of center location decisions using Model I and Model II considering various accessibility requirements in Amsterdam city. The data shows that multiple centers are necessary for cities of Amsterdam's scale, based on given historical data. Notably, Model II results in a significant 15% reduction in operational costs compared to Model I. It suggests that while both models fully satisfy courier vehicle (CV) needs in Amsterdam, the Model II approach offers additional benefits. It leads to the reduction in the average cost for couriers to access centers when picking up and returning e-bikes by adjusting service coverage based on temporal fluctuations in couriers' starting and ending distribution (varying by their starting location and starting time of the day) and flexible returning choices.

Figure 8 and Figure 9 show the final courier assignment decision and the coverage of each center according to Model I and Model II (at certain times) respectively. Different colors illustrate different centers and their coverage. The darker colored zones indicate the location of each center and the lighter color shows its coverage. The labels on each zone show the number of CV couriers and the total number of couriers starting at that zone. The white zones are the ones assigned to IC couriers.

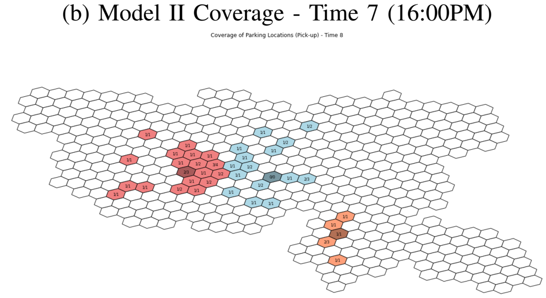
The results shown in Table XX illustrate the relationship between accessibility thresholds and operational costs in the Amsterdam case study. As the accessibility threshold increases from 0.2 to 2.8, there's a slight increase in total costs (from 2440 to 2474 euro, 14% increase), mainly due to increased operational costs related to the cost to pick up and drop off e-bikes at centers. Since higher accessibility thresholds mean greater convenience for a larger population to commute between their home and these centers, it suggests that, in this case, the company can consider investing a marginal amount to provide better courier convenience.



(a) Model II Coverage - Time 2 (11:00AM)



(b) Model II Coverage - Time 7 (16:00PM)



(c) Model II Coverage - Time 8 (17:00PM)

Fig. 9: Model II results at different times of Amsterdam case

VI. Conclusion

This study presents a comprehensive framework for planning and optimizing micro-logistics centers in on-demand meal delivery services. We offer some key insights for platforms on delivery model trade-off and center planning: Independent contractor (IC) models prove more cost-effective in specific scenarios, including sparse markets, areas with low IC allowances, regions with high real estate costs, and markets with dispersed restaurants or geographically distant business and residential areas. In established, dense markets, a hybrid delivery model incorporating company-vehicle (CV) service based on centers optimizes costs. The optimal locations for parking spaces, when necessary, are highly dependent on specific courier activity patterns and desired accessibility levels. Different operational strategies, such as ensuring stringent geographic continuity requirements and managing a fixed region, or dealing with varying courier distributions, may result in differences in costs, delivery model selection, and center site design.

Future research directions could address these limitations and expand the scope of our framework. Investigating the impact of partial zone allocations on overall system efficiency could reveal new optimization opportunities. Considering facility cost variations based on fleet size and exploring the implications of buffer capacity in flexible return scenarios would enhance the model's practicality.

Appendix

TABLE X: Sets, Variables, and Parameters in Model I

Set	
I	Set of zones;
I_c	$I_c \subseteq I$, Set of candidate zones for center location whose accessibility score meets the minimum threshold;
A	$A = \{(i,j) \| i,j \in I$, and i is adjacent to $j\}$;
P	Set of candidate center and its coverage;
$\mathcal{T}$	set of time steps during operation period, and $\mathcal{T} = \{\tau_0, \tau_1, \ldots, \tau_n, \ldots, \tau_N\}$;
$G = \{I, A\}$	Graph of the network;
Variable	
x_i^p	equals 1 if zone $i, i \in I$ is covered by center p, 0 otherwise;
y_i^p	equals 1 if the center p is located at zone i, 0 otherwise;
z_{ij}^p	equals 1 if zone j is covered by center p located at zone i, 0 otherwise;
v_i	equals 1 if zone i is assigned to be served by IC couriers, 0 otherwise;
$q^{p\tau}$	inventory in terms of the number of vehicles in center p at time τ;
q_0^p	stock of vehicles needed for the CV couriers within the coverage area of center p;
$e_i^{p\tau}$	number of CV couriers ending their shift at zone i at time τ that need to return to center p ;
f_{ij}^p	variable representing continuity on arc $(i,j) \in A$ within the coverage area of center p;
Parameter	
$n_{ij}^{\tau\tau'}$	the probability of couriers starting their shift at zone i at time τ and ending their shift at zone j at time τ'
$\tilde{S}_i^\tau$	the total number of couriers starting their shift at zone i at time τ, and $S_i^\tau = \overline{S}_i^\tau + S_i^\tau$
S_i^τ	the number of couriers needed as CV couriers for a certain service level α starting at zone i at time τ
$\overline{S}_i^\tau$	the remaining number of couriers hired as IC couriers to start at zone i at time τ if zone i is assigned to be served by CV service
$E_{ji}^{\tau'\tau}$	the number of CV couriers ending at zone i at time τ who start their shift at zone j at time τ', with $E_{ji}^{\tau'\tau} = S_j^{\tau'} * n_{ji}^{\tau'\tau}$
t_{ij}	travel time between zone i and j (h) by company vehicles assuming free flow speed;
C_i^F	fixed costs of locating a center in the center of zone i (expressed in euros per day);
C_h^O	couriers' basic hourly salary (expressed in euros per hour);
C_b^F	depreciation costs for each vehicle (expressed in euros per day);
C_a^O	the allowance paid for one IC courier using their personal vehicles (expressed in euro per person);
U_0	maximum number of vehicles that fit in each center;

TABLE XI: Additional Parameters and Variables for Model II

Parameter	
M	big number;
Variable	
$x_i^{p\tau}$	equals 1 if zone i is covered by center p at time τ, 0 otherwise;
y_i^p	equals 1 if the center p is located at zone $i, i \in I_c$, 0 otherwise;
$z_{ij}^{(S)p\tau}$	the number of CV couriers to travel from center p located at zone i to zone j within its coverage to start their shift at time τ;
$z_{ij}^{(E)p\tau}$	the number of CV couriers to travel from zone j to end their shift at time τ to center p located at zone i;
v_i^τ	equals 1 if zone i is assigned to be served by IC couriers at time τ;
$q^{p\tau}$	the inventory state in center p, in terms of the number of vehicles;
q_0^p	the total vehicles needed in center p to provide CV couriers;
$e_i^{p\tau}$	number of CV couriers ending their shift at zone i at time τ that need to return center p

TABLE XII: Computation Process of the test instances.

Instance Name	Time(s)	Initial Solution	Initial Bound	Best Solution	Best Bound	# Node Explore	Gap(%)
6-R-A1-Model I	0.17	400	167.16	342.7	342.7	1	0.0
6-R-A1-Model II	0.38	400	192.0	342.2	342.2	1	0.0
6-R-A2-Model I	0.74	400	166.93	342.7	342.7	99	0.0
6-R-A2-Model II	2.22	400	192.0	342.2	342.2	111	0.0
6-R-A3-Model I	2.12	400	166.93	342.7	342.7	365	0.0
6-R-A3-Model II	6.76	400	192.0	342.2	342.2	343	0.0
9-R-A1-Model I	3.3	864	371.5	812.4	812.4	75	0.0
9-R-A1-Model II	26.4	864	470	799	799	195	0.0
9-R-A2-Model I	3.49	864	371.5	812.4	812.4	403	0.0
9-R-A2-Model II	100.1	864	470	799	799	1636	0.0
9-R-A3-Model I	23.5	864	371.5	812.4	812.4	6275	0.0
9-R-A3-Model II	928.9	864	470	799	799	24189	0.0
12-R-A1-Model I	20.79	1520	659.5	1508	1508	940	0.0
12-R-A1-Model II	100.21	1520	680.1	1464	1464	960	0.0
12-R-A2-Model I	980.7	1520	659.5	1508	1508	56591	0.0
12-R-A2-Model II	3132	1520	583.5	1359	1359	44288	0.0
12-R-A3-Model I	1709.1	1520	694.3	1508	1508	175121	0.0
12-R-A3-Model II	11755.7	1520	583.5	1336.8	1336.8	54271	0.0

TABLE XIII: Results under different market scenarios.

Instance Name	#C	#Bikes	# Couriers			Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC	CSR		σ_b^F	γ_b^F	ζ_b^O	
Scenario M0										
6-R1-A1/2/3-Model I	1	8	18	4	100%	171.5	60	8	71.5	32
6-R1-A1/2/3-Model II	1	8	18	4	100%	171.5	60	8	71.5	32
6-R2-A1/2/3-Model I	0	0	0	22	0.0	176	0	0	0	176
6-R2-A1/2/3-Model II	0	0	0	22	0.0	176	0	0	0	176
6-R3-A1/2/3-Model I	0	0	0	22	0.0	176	0	0	0	176
6-R3-A1/2/3-Model II	0	0	0	22	0.0	176	0	0	0	176
12-R1-A1/2/3-Model I	0	0	0	94	0.0	752	0	0	0	752
12-R1-A1/2/3-Model II	0	0	0	94	0.0	752	0	0	0	752
12-R2-A1/2/3-Model I	0	0	0	94	0.0	752	0	0	0	752
12-R2-A1/2/3-Model II	0	0	0	94	0.0	752	0	0	0	752
12-R3-A1/2/3-Model I	0	0	0	94	0.0	752	0	0	0	752
12-R3-A1/2/3-Model II	0	0	0	94	0.0	752	0	0	0	752
Scenario M1										
6-R1-A1/2/3-Model I	1	12	26	10	100%	254	60	12	102	80
6-R1-A1/2/3-Model II	1	12	26	10	100%	254	60	12	102	80
6-R2-A1/2/3-Model I	1	11	25	11	96.2%	268	60	11	109	88
6-R2-A1/2/3-Model II	1	11	25	11	96.2%	268	60	11	109	88
6-R3-A1/2/3-Model I	1	11	24	12	96.2%	276	60	11	109	96
6-R3-A1/2/3-Model II	1	11	24	12	92.3%	272	60	11	105	96
12-R1-A1/2/3-Model I	0	0	0	144	0.0	1152	0	0	0	1152
12-R1-A1-Model II	0	0	0	144	0.0	1152	0	0	0	1152
12-R1-A2-Model II	3	41	89	55	89%	1097	180	41	436	440
12-R1-A3-Model II	3	42	89	55	89%	1089	180	42	427	440
12-R2-A1/2/3-Model I	0	0	0	144	0.0	1152	0	0	0	1152
12-R2-A1-Model II	2	33	73	71	73%	1146	120	33	425	568
12-R2-A2-Model II	3	45	98	46	98%	1080	180	45	487	368
12-R2-A3-Model II	3	43	97	47	97%	1064	180	43	465	376
12-R3-A1/2/3-Model I	0	0	0	144	0.0	1152	0	0	0	1152

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Table XIII continued

Instance Name	#C	# Bikes	# Couriers			Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC	CSR		σ_b^F	γ_b^F	ζ_b^O	
12-R3-A1-Model II	0	0	0	144	0.0	1152	0	0	0	1152
12-R3-A2-Model II	3	41	95	49	95%	1107	180	41	494	392
12-R3-A3-Model II	3	40	92	52	92%	1088	180	40	452	416
Scenario M2										
6-R1-A1/2/3-Model I	1	13	25	25	69.4%	378	60	13	105	200
6-R1-A1/2/3-Model II	1	13	28	22	77.8%	365	60	13	116	176
6-R2-A1/2/3-Model I	1	13	28	22	77.8%	355	60	13	106	176
6-R2-A1/2/3-Model II	1	14	30	20	83.3%	346	60	14	112	160
6-R3-A1/2/3-Model I	1	16	35	15	97.2%	342	60	16	146	120
6-R3-A1/2/3-Model II	1	16	35	15	97.2%	342	60	16	150	120
12-R1-A1/2/3-Model I	1	21	47	143	35.6%	1508	60	21	283	1144
12-R1-A1-Model II	3	45	104	86	78.8%	1464	180	45	551	688
12-R1-A2-Model II	3	50	111	79	84.1%	1379	180	50	517	632
12-R1-A3-Model II	3	47	108	82	81.8%	1376	180	47	493	656
12-R2-A1/2/3-Model I	0	0	0	190	0.0	1520	0	0	0	1520
12-R2-A1-Model II	2	39	89	101	67.4%	1492	120	39	525	808
12-R2-A2-Model II	3	54	124	66	93.9%	1386	180	54	624	528
12-R2-A3-Model II	3	54	120	70	90.9%	1370	180	54	576	560
12-R3-A1/2/3-Model I	0	0	0	190	0.0	1520	0	0	0	1520
12-R3-A1-Model II	2	39	88	102	66.7%	1480	120	39	505	816
12-R3-A2-Model II	3	53	124	66	93.9%	1360	180	53	599	528
12-R3-A3-Model II	3	52	123	67	93.2%	1337	180	52	569	536

TABLE XIV: Average results under different market scenarios.

Instance Name	#C	#Bikes	# Couriers			Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC	CSR		σ_b^F	γ_b^F	ζ_b^O	
Scenario M0										
Avg-6-A1	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-A2	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-A3	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-Model I	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-6-Model II	0.3	2.7	6	16	0.3	174.5	20	2.7	23.8	128
Avg-12-A1	0	0	0	94	0.0	752	0	0	0	752
Avg-12-A2	0	0	0	94	0.0	752	0	0	0	752
Avg-12-A3	0	0	0	94	0.0	752	0	0	0	752
Avg-12-Model I	0	0	0	94	0.0	752	0	0	0	752
Avg-12-Model II	0	0	0	94	0.0	752	0	0	0	752
Scenario M1										
Avg-6-A1	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-A2	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-A3	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-Model I	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-6-Model II	1	11.3	25	11	1	265.3	60	11.3	106	88
Avg-12-A1	0.3	5.5	12.2	131.8	0.1	1151	20	5.5	70.8	1054.7
Avg-12-A2	1.5	21.2	47	97	0.5	1123.3	90	21.2	236.2	776
Avg-12-A3	1.5	20.8	46.3	97.7	0.5	1116.2	90	20.8	224.0	781.3
Avg-12-Model I	0	0	0	144	0.0	1152	0	0	0	1152
Avg-12-Model II	2.2	31.7	70.3	73.7	0.7	1108.3	133.3	31.7	354	589.3
Scenario M2										
Avg-6-A1	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-A2	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-A3	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-Model I	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-6-Model II	1	14.2	30.2	19.8	0.8	354.7	60	14.2	122.5	158.7
Avg-12-A1	1.3	24	54.7	135.3	0.4	1497.3	80	24	310.7	1082.7
Avg-12-A2	1.7	29.7	67.7	122.3	0.5	1445.5	100	29.7	337.2	978.7
Avg-12-A3	1.7	29	66.3	123.7	0.5	1438.5	100	29	320.2	989.3
Avg-12-Model I	0.3	7	15.7	174.3	0.1	1516	20	7	94.3	1394.7
Avg-12-Model II	2.8	48.1	110.1	79.9	0.8	1404.9	166.7	48.1	551	639.1

TABLE XV: Results under different starting/restaurant areas.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
Scenario S1									
6-R1-A1/2/3-Model I	1	8	18	4	158	60	8	58	32
6-R1-A1/2/3-Model II	1	8	18	4	158	60	8	58	32
6-R2-A1/2/3-Model I	1	7	14	8	170	60	7	39	64
6-R2-A1/2/3-Model II	1	7	16	6	163	60	7	46	48
6-R3-A1/2/3-Model I	1	8	15	7	166	60	8	42	56
6-R3-A1/2/3-Model II	1	8	16	6	160	60	8	44	48
Avg	1	7.7	16.2	5.8	162.5	60	7.7	47.8	46.7
Scenario S2									
6-R1-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R1-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model I	1	6	14	8	169	60	6	39	64
6-R2-A1/2/3-Model II	1	8	16	6	163	60	8	47	48

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Table XV continued

Instance Name	#C	# Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
6-R3-A1/2/3-Model I	1	8	16	6	168	60	8	52	48
6-R3-A1/2/3-Model II	1	8	17	5	163	60	8	55	40
Avg	0.7	5	10.5	11.5	169.2	40	5	32.2	92
Scenario S3									
6-R1-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R1-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
Avg	0	0	0	22	176	0	0	0	176

TABLE XVI: Results under different ending/customer areas.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
Scenario D1									
6-R1-A1/2/3-Model I	1	6	10	12	184	60	6	22	96
6-R1-A1/2/3-Model II	1	7	16	6	152	60	7	37	48
6-R2-A1/2/3-Model I	1	8	18	4	142	60	8	42	32
6-R2-A1/2/3-Model II	1	8	18	4	142	60	8	42	32
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	1	8	14	8	165	60	8	33	64
Avg	0.8	6.2	12.7	9.3	160.2	50.0	6.2	29.3	74.7
Scenario D2									
6-R1-A1/2/3-Model I	1	7	16	6	161	60	7	46	48
6-R1-A1/2/3-Model II	1	8	17	5	158	60	8	50	40
6-R2-A1/2/3-Model I	1	8	18	4	151	60	8	51	32
6-R2-A1/2/3-Model II	1	8	18	4	151	60	8	51	32
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	1	7	14	8	169	60	7	38	64
Avg	0.8	6.3	13.8	8.2	161.0	50.0	6.3	39.3	65.3
Scenario D3									
6-R1-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R1-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R2-A1/2/3-Model II	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model I	0	0	0	22	176	0	0	0	176
6-R3-A1/2/3-Model II	1	8	17	5	176	60	8	68	40
Avg	0.2	1.3	2.8	19.2	176.0	10.0	1.3	11.3	153.3

TABLE XVII: Results under different cost scenarios.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs θ_a^O
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	
Scenario C0									
6-R1-A1/2/3-Model I	1	12	26	10	254	60	12	102	80
6-R1-A1/2/3-Model II	1	12	26	10	254	60	12	102	80
6-R2-A1/2/3-Model I	1	11	25	11	268	60	11	109	88
6-R2-A1/2/3-Model II	1	11	25	11	268	60	11	109	88
6-R3-A1/2/3-Model I	1	11	24	12	276	60	11	109	96
6-R3-A1/2/3-Model II	1	11	24	12	272	60	11	105	96
6-R3-A1/2/3-Model II	1	11	24	12	272	60	11	105	96
Avg	1	11.3	25	11	265.3	60	11.3	106	88.0
Scenario C1									
6-R1-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R1-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
Avg	0	0	0	36	288	0	0	0	288
Scenario C2									
6-R1-A1/2/3-Model I	0	0	0	36	216	0	0	0	216
6-R1-A1/2/3-Model II	0	0	0	36	216	0	0	0	216
6-R2-A1/2/3-Model I	0	0	0	36	216	0	0	0	216
6-R2-A1/2/3-Model II	0	0	0	36	216	0	0	0	216
6-R3-A1/2/3-Model I	0	0	0	36	216	0	0	0	216
6-R3-A1/2/3-Model II	0	0	0	36	216	0	0	0	216
Avg	0	0	0	36	216	0	0	0	216

TABLE XVIII: Results under different mode scenarios.

Instance Name	#C	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	θ_a^O
Scenario T0									
6-R1-A1/2/3-Model I	1	12	26	10	254	60	12	102	80
6-R1-A1/2/3-Model II	1	12	26	10	254	60	12	102	80
6-R2-A1/2/3-Model I	1	11	25	11	268	60	11	109	88
6-R2-A1/2/3-Model II	1	11	25	11	268	60	11	109	88
6-R3-A1/2/3-Model I	1	11	24	12	276	60	11	109	96
6-R3-A1/2/3-Model II	1	11	24	12	272	60	11	105	96
Avg	1	11.3	25	11	265.3	60	11.3	106	88.0
Scenario T1									
6-R1-A1/2/3-Model I	1	12	26	10	269	60	6	123	80
6-R1-A1/2/3-Model II	1	12	26	10	269	60	6	123	80
6-R2-A1/2/3-Model I	1	12	26	10	285	60	6	138	80
6-R2-A1/2/3-Model II	1	12	26	10	285	60	6	138	80
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	1	11	24	12	287.5	60	5.5	126	96
Avg	0.8	9.8	21.3	14.7	280.6	50	4.9	108	117.3
Scenario T2									
6-R1-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R1-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
Avg	0	0	0	36	288	0	0	0	288
Scenario T3									
6-R1-A1/2/3-Model I	1	12	26	10	260	60	48	72	80
6-R1-A1/2/3-Model II	1	12	26	10	260	60	48	72	80
6-R2-A1/2/3-Model I	1	11	25	11	270	60	44	78	88
6-R2-A1/2/3-Model II	1	11	25	11	268	60	44	76	88
6-R3-A1/2/3-Model I	1	11	24	12	276	60	44	76	96
6-R3-A1/2/3-Model II	1	11	24	12	273	60	44	73	96
Avg	1	11.3	25	11	267.8	60	45.3	74.5	88
Scenario T4									
6-R1-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R1-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R2-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model I	0	0	0	36	288	0	0	0	288
6-R3-A1/2/3-Model II	0	0	0	36	288	0	0	0	288
Avg	0	0	0	36	288	0	0	0	288

TABLE XIX: Results of Amsterdam case using Model I and II.

Accessibility Threshold	#PL	#Bikes	# Couriers			Total Costs	Reduction	CV Costs			IC Costs
			CV	IC	CSR			σ_b^F	γ_b^F	ζ_b^O	θ_a^O
2.8 (Model I)	3	119	222	49	100%	2474		207	119	1511	637
2.8 (Model II)	3	119	222	49	100%	2104	15%	207	119	1141	637
2.2 (Model I)	3	119	222	49	100%	2458		207	119	1495	637
2.2 (Model II)	3	119	222	49	100%	2096	15%	207	119	1133	637
1.3 (Model I)	3	119	222	49	100%	2458		207	119	1495	637
1.3 (Model II)	3	119	222	49	100%	2096	15%	207	119	1133	637

TABLE XX: Results of Amsterdam case under different accessibility requirement.

Accessibility Threshold	#PL	#Bikes	# Couriers		Total Costs	CV Costs			IC Costs
			CV	IC		σ_b^F	γ_b^F	ζ_b^O	θ_a^O
0.2 (Model I)	3	119	222	49	2440	207	119	1477	637
1.08 (Model I)	3	119	222	49	2440	207	119	1477	637
1.12 (Model I)	3	119	222	49	2440	207	119	1477	637
1.2 (Model I)	3	119	222	49	2442	207	119	1479	637
1.3 (Model I)	3	119	222	49	2458	207	119	1495	637
1.7 (Model I)	3	119	222	49	2458	207	119	1495	637
2.2 (Model I)	3	119	222	49	2458	207	119	1495	637
2.8 (Model I)	3	119	222	49	2474	207	119	1511	637

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