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

Yuchen Qi

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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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Name:	Yuchen Qi
Student Number:	5695392
Thesis Committee:	Dr. Shadi Sharif Azadeh
	Dr. Yousef Maknoon
	Dr. ir. Gonçalo Homem de Almeida Correia

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Delft
University of
Technology

Abstract

This work presents a comprehensive framework to assist on-demand food 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 food 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

[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

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 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 work 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

[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

insights derived, and a case study of Amsterdam City. Finally, Chapter 7 concludes the report with a summary of findings and directions for future work.

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).

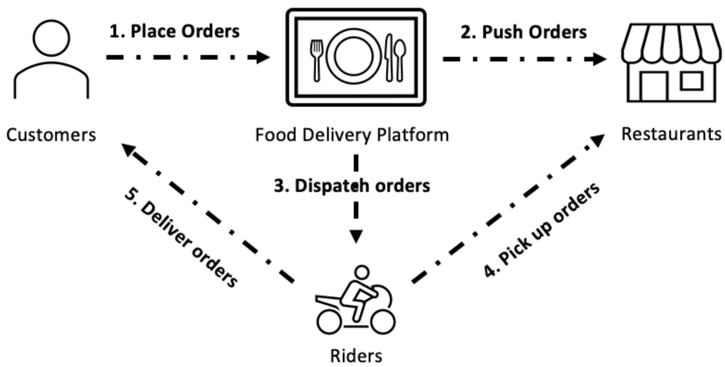


Figure 2.1. A typical process of on-demand meal delivery

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 report, 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 $\mathcal{T}$ represent a typical operation day in our planning horizon. This horizon is discretized into equal time intervals, where $\mathcal{T} = \{\tau_0, \tau_1, \dots, \tau_n, \dots, \tau_N\}$ 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.

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:

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

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.

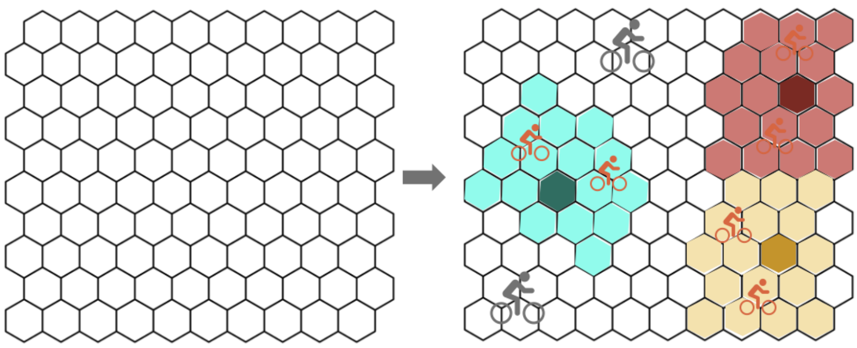


Figure 4.1. Illustration of key decisions

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).

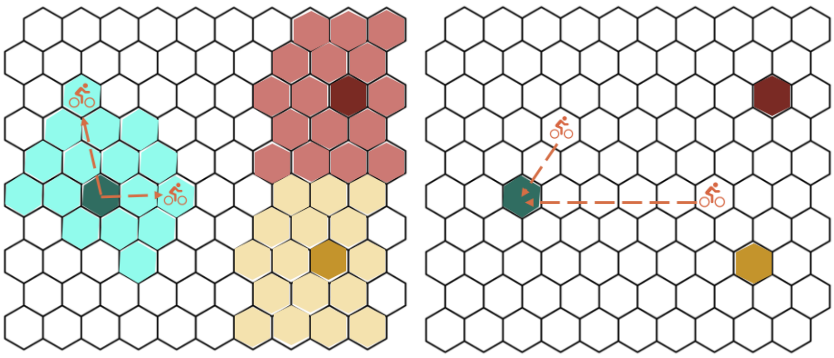
5

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

Continued on next page

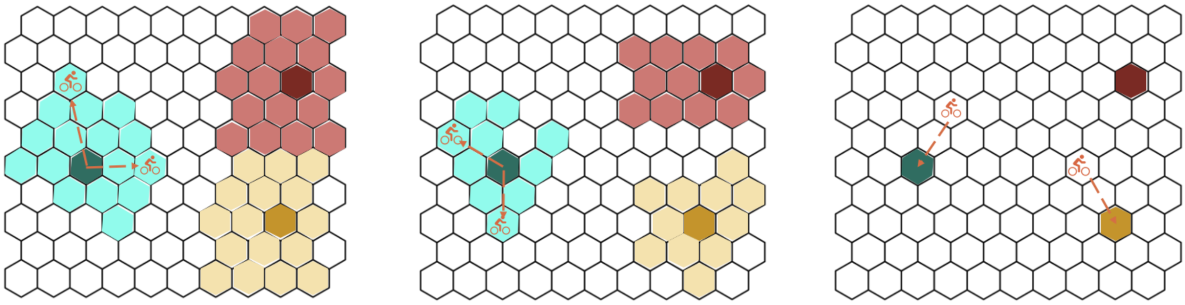
Table 5.1 – Continued from previous page

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	$A = \{(i,j) \mid i, j \in I$, and i is adjacent to $j\}$;
P	Set of candidate center and its coverage;
$\mathscr{T}$	set of time steps during operation period, and $\mathscr{T} = \{\tau_0, \tau_1, \dots, \tau_n, \dots, \tau_N\}$;
$G = \{I, A\}$	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 de-



(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

livery 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 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 Independent Contractor (IC) 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.

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

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

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

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

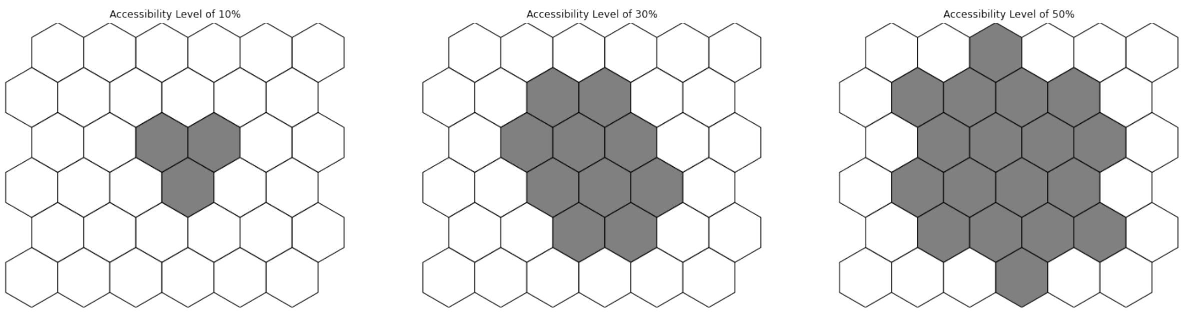
6
Results

In this Chapter, Section 6.1 details the process used to generate the experimental instances. Section 6.2 presents the computational performance of the proposed models. In Section 6.3, we examine the economic feasibility of micro-logistics centers under various urban conditions. This analysis focuses on key factors such as service density, urban spatial patterns, and relevant economic factors. Additionally, we investigate the impact of different operational policies and city accessibility levels, as well as vehicle configurations, when optimizing the planning of viable centers. We also apply our approach to a food delivery system in Amsterdam, to further illustrate the decisions on the dimensions of centers suggested by our models e.g., their locations and coverage areas, and conduct a discussion on the tradeoff between accessibility and costs in a city with well-developed public transportation in Section 6.4.

6.1 Instance Description

We assume all delivery activities occur within a predefined service zone, described using hexagonal units of 0.737 km^2. Three scenarios are considered for the coverage area: (1) 36 hexagonal units representing small urban areas (e.g., Delft), (2) 81 hexagonal units representing medium-sized cities, and (3) 144 hexagonal units representing metropolitan areas (e.g., The Hague).

For accessibility considerations of potential logistics center locations, we assume a typical urban structure where areas closer to the city center tend to have better public transport connections and thus higher accessibility scores. We define three accessibility levels - 10%, 30%, and 50% - representing the proportion of zones qualifying as candidate locations. Higher levels indicate cities with better infrastructure and more potential locations. This approach captures urban accessibility patterns without requiring detailed transport data. Figure 6.1 illustrates the eligible candidates (shown in grey) under these 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

Figure 6.1. Visualization of Different Urban Accessibility Levels

Courier Operations. The platform operates from 08:30 AM to 10:00 PM, divided into 1.5-hour intervals, resulting in 10 segments. Courier shifts are most frequent during peak hours-lunch (11:00 AM - 2:00 PM) and dinner (5:00 PM - 8:00 PM)-and less frequent during the off-peak afternoon period (2:00 PM - 5:00 PM). Courier density reflects these fluctuations, e.g., with 0.3 couriers/km^2 during peak hours and 0.075 couriers/km^2 during off-peak hours. By correlating courier density with the network area across these time segments, the number of couriers starting at any given time is determined.

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 $km^2 \approx 8$ 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 throughout the day.

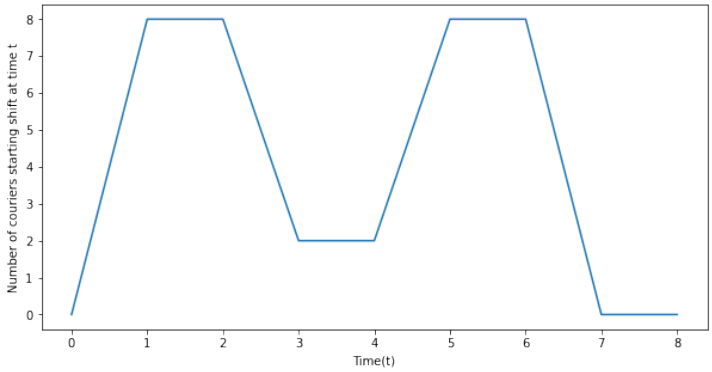


Figure 6.2. Number of couriers starting at different times on the 6x6 network instance

These total number of active couriers at each time segment is distributed across zones based on starting probability distributions to determine $\tilde{S}_i^\tau$. We consider three starting distributions: random, uniform, and centralized. Random distribution refers to randomly generated probabilities for couriers to start in each zone, while uniform distribution assigns equal probability across all zones. In the centralized distribution, 80% of active couriers at each time segment start within the central area, defined as the top 50% of zones closest to the city center. We also consider a service level of 0.7 to further determine potential CV courier needs S_i^τ and the remaining IC ones $\overline{S}_i^\tau$.

Probability matrix $n_{ij}^{\tau\tau'}$, describes the spatial-temporal distribution of courier movements, accounting for both shift duration and ending locations for each starting record. In the following instances, courier shifts are assumed to follow a truncated normal distribution with $\mu = 3$ hours and $\sigma = 1.5$ hours, truncated between 1.5 and 4.5 hours. The transition from starting zone i to ending zone j is randomly determined.

Example 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 that couriers use e-bikes with an average speed of 15-16 km/h within urban areas. The distance between the centers of two adjacent zones is 0.92 km, resulting in a travel time of 0.06 hours. Additional parameters used in the instances are listed in Table 6.3.

Table 6.3. Parameters of the Test Instances.

Parameters	**Value**	**Remark**
C_i^F	60 (€/day)	Costs of locating a center in any zone per day
C_b^F	1 (€/e-bike/day)	Depreciation costs for each e-bike per day
C_h^O	15 (€/hour)	Couriers' basic hourly salary
C_a^O	8 (€/person)	Allowance for IC couriers
TT_{ij}	0.06 (hour)	For traveling between adjacent zones $(i, j) \in A$
TT_{ij}	Shortest path	For non-adjacent zones i and j
$\lvert P\rvert$	3	Maximum centers allowed

In the following discussion, we employ a concise notation to represent the various settings of instances. The numbers 6, 9, and 12 denote 36, 81, and 144 hexagonal grids, respectively; R, U, and C represent random, uniform, and centralized courier starting distributions; and A1, A2, and A3 indicate 10%, 30%, and 50% accessibility levels. For example, '6-R-A1' represents a 36-hexagonal grid network with random courier starting distribution and 10% accessibility. To account for randomness in courier allocation, multiple instances with the same distribution pattern are generated, differentiated by appending numerical identifiers (e.g., 'R1', 'R2', 'R3').

6.2 Computational Performance

We tested both Model I and Model II on the generated instances with a time limit of 8 hours (28,800 seconds). Table 6.4 summarizes the computational results, including, in order: model type, instance name, execution time (in seconds), initial integer solution, initial relaxation bound, best integer solution, best bound, number of branched nodes, and integrity gap (in percentage).

Table 6.4. Computation Process of the Test Instances

Model	Ins. Name	Time(s)	In. Sol.	In. Bound	Best Sol.	Best Bound	# Node	Gap(%)
I	6-R-A1	0.1	288.0	135.0	264.4	264.3	1	0.0
	6-U-A1	0.1	288.0	130.6	261.2	261.2	1	0.0
	6-C-A1	0.1	288.0	118.7	242.8	242.8	1	0.0
	Avg.	**0.1**	**288.0**	**128.1**	**256.1**	**256.1**	**1.0**	**0.0**
	6-R-A2	0.6	288.0	135.0	264.3	264.3	64	0.0
	6-U-A2	1.2	288.0	130.2	261.2	261.2	21	0.0
	6-C-A2	0.5	288.0	118.7	242.8	242.8	72	0.0
	Avg.	**0.8**	**288.0**	**128.0**	**256.1**	**256.1**	**52.3**	**0.0**
	6-R-A3	1.8	288.0	135.0	264.3	264.3	467	0.0
	6-U-A3	2.1	288.0	130.1	261.2	261.2	342	0.0
	6-C-A3	0.9	288.0	118.7	242.8	242.8	343	0.0
	Avg.	**1.6**	**288.0**	**127.9**	**256.1**	**256.1**	**384.0**	**0.0**
II	6-R-A1	0.3	288.0	167.3	263.9	263.9	12	0.0
	6-U-A1	0.3	288.0	157.1	261.2	261.2	13	0.0
	6-C-A1	0.2	288.0	151.7	242.8	242.8	13	0.0
	Avg.	**0.3**	**288.0**	**158.7**	**256.0**	**256.0**	**12.7**	**0.0**
	6-R-A2	1.8	288.0	167.3	263.9	263.9	111	0.0
	6-U-A2	1.3	288.0	157.1	261.2	261.2	111	0.0
	6-C-A2	1.7	288.0	151.7	242.8	242.8	76	0.0
	Avg.	**1.6**	**288.0**	**158.7**	**256.0**	**256.0**	**99.3**	**0.0**
	6-R-A3	4.2	288.0	167.3	263.9	263.9	291	0.0
	6-U-A3	3.2	288.0	157.1	261.2	261.2	259	0.0
	6-C-A3	3.2	288.0	151.7	242.8	242.8	216	0.0
	Avg.	**3.5**	**288.0**	**158.7**	**256.0**	**256.0**	**255.3**	**0.0**
I	9-R-A1	1.9	640.0	271.4	630.8	630.8	146	0.0
	9-U-A1	3.1	640.0	268.8	622.8	622.8	129	0.0
	9-C-A1	2.9	640.0	269.6	587.2	587.2	171	0.0
	Avg.	**2.6**	**640.0**	**269.9**	**613.6**	**613.6**	**148.7**	**0.0**
	9-R-A2	208.4	640.0	271.4	628.7	628.7	33859	0.0
	9-U-A2	114.0	640.0	268.8	622.8	622.8	33169	0.0
	9-C-A2	28.6	640.0	269.6	587.2	587.2	4648	0.0
	Avg.	**117.0**	**640.0**	**269.9**	**612.9**	**612.9**	**23892.0**	**0.0**
	9-R-A3	96.2	640.0	271.3	628.7	628.7	2350	0.0
	9-U-A3	241.9	640.0	268.8	622.8	622.7	2470	0.0
	9-C-A3	127.1	640.0	269.6	587.2	587.1	1757	0.0
	Avg.	**155.1**	**640.0**	**269.9**	**612.9**	**612.8**	**2192.3**	**0.0**
II	9-R-A1	9.0	640.0	306.5	630.8	630.8	186	0.0
	9-U-A1	11.7	640.0	299.3	621.1	621.1	189	0.0
	9-C-A1	12.4	640.0	306.1	586.9	586.9	188	0.0
	Avg.	**11.0**	**640.0**	**304.0**	**612.9**	**612.9**	**187.7**	**0.0**
	9-R-A2	56.0	640.0	306.5	614.7	614.7	2903	0.0
	9-U-A2	59.9	640.0	299.3	601.4	601.4	3334	0.0
	9-C-A2	92.5	640.0	306.1	583.4	583.4	4379	0.0
	Avg.	**69.5**	**640.0**	**304.0**	**599.8**	**599.8**	**3538.7**	**0.0**
	9-R-A3	465.9	640.0	306.5	614.3	614.3	4036	0.0
	9-U-A3	644.5	640.0	299.3	594.7	594.7	10311	0.0
	9-C-A3	377.6	640.0	306.1	583.4	583.4	22424	0.0
	Avg.	**496.0**	**640.0**	**304.0**	**597.5**	**597.5**	**12257.0**	**0.0**
I	12-R-A1	14.5	1152.0	449.4	1152.0	1152.0	937	0.0
	12-U-A1	21.5	1152.0	430.2	1152.0	1152.0	937	0.0
	12-C-A1	19.0	1152.0	448.3	1143.7	1143.7	939	0.0
	Avg.	**18.3**	**1152.0**	**442.6**	**1149.2**	**1149.2**	**937.7**	**0.0**
	12-R-A2	1001.6	1152.0	449.4	1152.0	1152.0	56010	0.0

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Table 6.4 – Continued from previous page

Model	Ins. Name	Time(s)	In. Sol.	In. Bound	Best Sol.	Best Bound	# Node	Gap(%)
	12-U-A2	886.6	1152.0	430.2	1152.0	1152.0	56035	0.0
	12-C-A2	747.7	1152.0	448.2	1143.7	1143.7	58367	0.0
	Avg.	**878.6**	**1152.0**	**442.6**	**1149.2**	**1149.2**	**56804.0**	**0.0**
	12-R-A3	4614.9	1152.0	485.7	1152.0	1152.0	684204	0.0
	12-U-A3	3738.5	1152.0	462.0	1152.0	1152.0	245510	0.0
	12-C-A3	10402.5	1152.0	484.6	1143.7	1143.7	1386715	0.0
	Avg.	**6252.0**	**1152.0**	**477.4**	**1149.2**	**1149.2**	**772143.0**	**0.0**
II	12-R-A1	41.2	1152.0	477.9	1142.8	1142.8	945	0.0
	12-U-A1	66.0	1152.0	461.2	1147.9	1147.9	942	0.0
	12-C-A1	49.6	1152.0	483.8	1105.5	1105.5	948	0.0
	Avg.	**52.3**	**1152.0**	**474.3**	**1132.1**	**1132.1**	**945.0**	**0.0**
	12-R-A2	1501.5	1152.0	477.9	1083.4	1083.4	6365	0.0
	12-U-A2	1882.7	1152.0	461.2	1084.7	1084.7	7945	0.0
	12-C-A2	1336.8	1152.0	483.8	1041.1	1041.1	8823	0.0
	Avg.	**1573.7**	**1152.0**	**474.3**	**1069.7**	**1069.7**	**7711.0**	**0.0**
	12-R-A3	7134.2	1152.0	477.9	1062.5	1062.5	47522	0.0
	12-U-A3	4833.6	1152.0	461.2	1078.3	1078.3	39456	0.0
	12-C-A3	5652.1	1152.0	483.8	1041.1	1041.1	41646	0.0
	Avg.	**5873.3**	**1152.0**	**474.3**	**1060.6**	**1060.6**	**42874.7**	**0.0**
I	15-R-A1	44.0	1792.0	647.4	1792.0	1792.0	3586	0.0
	15-U-A1	36.4	1792.0	700.3	1792.0	1792.0	3583	0.0
	15-C-A1	63.8	1792.0	647.8	1792.0	1792.0	3567	0.0
	Avg.	**48.1**	**1792.0**	**665.2**	**1792.0**	**1792.0**	**3578.7**	**0.0**
	15-R-A2	2942.7	1792.0	681.1	1792.0	1792.0	123625	0.0
	15-U-A2	9339.5	1792.0	732.7	1792.0	1792.0	156656	0.0
	15-C-A2	13777.0	1792.0	719.0	1783.6	1783.6	527601	0.0
	Avg.	**8686.4**	**1792.0**	**710.9**	**1789.2**	**1789.2**	**269294.0**	**0.0**
	15-R-A3	28820.1	1792.0	680.7	1792.0	801.0	352282	55.3
	15-U-A3	28813.4	1792.0	732.4	1792.0	851.8	97599	52.5
	15-C-A3	28802.6	1792.0	679.7	1792.0	740.3	21060	58.7
	Avg.	**28812.0**	**1792.0**	**697.6**	**1792.0**	**797.7**	**156980.3**	**55.5**
II	15-R-A1	360.2	1792.0	680.2	1792.0	1792.0	3587	0.0
	15-U-A1	316.3	1792.0	717.0	1792.0	1792.0	3587	0.0
	15-C-A1	386.0	1792.0	679.1	1783.2	1783.2	3621	0.0
	Avg.	**354.2**	**1792.0**	**692.1**	**1789.1**	**1789.1**	**3598.3**	**0.0**
	15-R-A2	28808.3	1792.0	680.2	1759.3	1073.0	2942	39.0
	15-U-A2	28802.5	1792.0	717.0	1757.7	1056.6	3054	39.9
	15-C-A2	28814.6	1792.0	679.1	1706.0	1213.0	5325	28.9
	Avg.	**28808.5**	**1792.0**	**692.1**	**1741.0**	**1114.2**	**3773.7**	**35.9**
	15-R-A3	28800.8	1792.0	680.2	1743.3	1343.6	51705	22.9
	15-U-A3	28803.1	1792.0	717.0	1759.4	1095.3	2736	37.7
	15-C-A3	28806.7	1792.0	679.1	1700.0	1157.0	3093	31.9
	Avg.	**28803.5**	**1792.0**	**692.1**	**1734.2**	**1198.6**	**19178.0**	**30.8**

As shown in Table 6.4, most small instances are solved within minutes, with solution time increasing as the problem size grows. Computation time also generally correlates with the number of potential candidates linked to the accessibility level, with higher accessibility levels (A2, A3) typically requiring more time than lower levels (A1). The largest instances (15x15 grid) present significant computational challenges. For Model I with A3 accessibility, the average gap after 8 hours is 55.5%, while Model II shows a 30.8% gap for the same scenario. These large gaps highlight the problem's increasing complexity with instance size, especially at higher accessibility levels. For very large urban areas, heuristic approaches or decomposition methods may be necessary to obtain good solutions in reasonable computation times.

Model II requires more time to find a solution compared to Model I. This difference is negligible for small instances but increases with the number of zones and accessible locations. Our results also indicate that as the service area expands, the dynamic model has the potential to achieve lower total costs. In the 12x12 grid with A2 accessibility, Model II reduces the average total cost from 1149.2 (Model I) to 1069.7, a 6.9% improvement.

In conclusion, while both models can solve small to medium-sized instances efficiently, Model II offers potential cost savings at the expense of increased computation time. The trade-off between solution quality and computation time becomes more critical as the problem size and complexity increase.

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 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).

6.3.1 Market Maturity Analysis

The choice of delivery model strategy for a meal delivery platform should be tailored to the market maturity level. Specifically, we seek to determine the conditions under which the use of independent contractors (IC), company-vehicle (CV) couriers, or a combination of both would be most effective. These strategies are influenced by courier density, reflecting the market maturity of the service area.

In this section, we explore three distinct market scenarios with a 12x12 network. The details of these scenarios are outlined in Table 6.5. For each service area size, Scenario M0 represents emerging markets with low courier density, typically in new or low-density residential areas. Scenario M1 reflects established markets with moderate courier density. Scenario M2 corresponds to high-demand metropolitan areas with dense courier networks.

Table 6.5. Scenario Settings with Different Courier Density

Network	**Scenario**	**# Couriers**	**Density (couriers/km^2)**
12x12	M0	48	Peak: 0.1 Normal: 0.025
	M1	144	Peak: 0.3 Normal: 0.075
	M2	190	Peak: 0.4 Normal: 0.1

The detailed results of a total of 54 instances in our tests (18 for each scenario) are presented in 6.6 and we calculate the average result to summarize in Table 6.7 and Table 6.8. These tables include the following columns: Scenario (Scen.), Instance Name, Model Type (Mod., i.e. I, II), the total number of required micro-logistics centers (#C), the number of needed resources (#R), and the total number of couriers, which is further divided into the number of CV couriers and IC couriers. The CSR (Courier Supply Ratio) column represents the ratio of CV couriers in the optimized plan to the total potential CV demand across all zones and times ($\sum_{\tau\in\mathcal{T}}\sum_{i\in I} S_i^\tau$), based on the desired service level. The CSR reflects the extent to which the model chooses to utilize CV couriers versus IC ones (coverage of CV demands), with a higher ratio indicating greater CV coverage and a lower ratio suggesting more reliance on IC couriers. This metric provides a quantitative alternative to geographic illustrations of coverage of the whole system. The tables also include columns for Total Costs, CV Costs (which are further broken down into center construction costs (σ_b^F), resource purchasing costs (γ_b^F), and operational costs for non-productive legs (ζ_b^O), and IC service costs (θ_a^O). These indicators are calculated based on one operational day. The notation '12-R1-A1/2/3' in the table indicates identical results for all accessibility levels A1, A2 and A3.

Table 6.6. Comparison of Scenarios for 12x12 Network

Scen.	**Name**	**Mod.**	**#C**	**#Bikes**	# Couriers			Total	CV Costs			IC Costs
					CV	IC	CSR	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
M0	12-R1-A1/2/3	I	0	0	0	48	0.0	384	0	0	0	384
	12-R1-A1/2/3	II	0	0	0	48	0.0	384	0	0	0	384
	12-R2-A1/2/3	I	0	0	0	48	0.0	384	0	0	0	384
	12-R2-A1/2/3	II	0	0	0	48	0.0	384	0	0	0	384
	12-R3-A1/2/3	I	0	0	0	48	0.0	384	0	0	0	384
	12-R3-A1/2/3	II	0	0	0	48	0.0	384	0	0	0	384
M1	12-R1-A1/2/3	I	0	0	0	144	0.0	1152	0	0	0	1152
	12-R1-A1	II	0	0	0	144	0.0	1152	0	0	0	1152
	12-R1-A2	II	3	41	89	55	89%	1097	180	41	436	440
	12-R1-A3	II	3	42	89	55	89%	1089	180	42	427	440
	12-R2-A1/2/3	I	0	0	0	144	0.0	1152	0	0	0	1152
	12-R2-A1	II	2	33	73	71	73%	1146	120	33	425	568
	12-R2-A2	II	3	45	98	46	98%	1080	180	45	487	368
	12-R2-A3	II	3	43	97	47	97%	1064	180	43	465	376
	12-R3-A1/2/3	I	0	0	0	144	0.0	1152	0	0	0	1152
	12-R3-A1	II	0	0	0	144	0.0	1152	0	0	0	1152
	12-R3-A2	II	3	41	95	49	95%	1107	180	41	494	392
	12-R3-A3	II	3	40	92	52	92%	1088	180	40	452	416
M2	12-R1-A1/2/3	I	1	21	47	143	35.6%	1508	60	21	283	1144
	12-R1-A1	II	3	45	104	86	78.8%	1464	180	45	551	688
	12-R1-A2	II	3	50	111	79	84.1%	1379	180	50	517	632
	12-R1-A3	II	3	47	108	82	81.8%	1376	180	47	493	656
	12-R2-A1/2/3	I	0	0	0	190	0.0	1520	0	0	0	1520
	12-R2-A1	II	2	39	89	101	67.4%	1492	120	39	525	808
	12-R2-A2	II	3	54	124	66	93.9%	1386	180	54	624	528
	12-R2-A3	II	3	54	120	70	90.9%	1370	180	54	576	560
	12-R3-A1/2/3	I	0	0	0	190	0.0	1520	0	0	0	1520
	12-R3-A1	II	2	39	88	102	66.7%	1480	120	39	505	816
	12-R3-A2	II	3	53	124	66	93.9%	1360	180	53	599	528
	12-R3-A3	II	3	52	123	67	93.2%	1337	180	52	569	536

Table 6.7. Comparison of Scenarios for 12x12 Network (Model I and Model II)

Scen.	**Name**	**Mod.**	**#C**	**#Bikes**	**# Couriers**			**Total**	**CV Costs**			**IC Costs**
					CV	**IC**	**CSR**	**Costs**	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
M0	Avg.	I	0	0	0	48	0.0	384	0	0	0	384
		II	0	0	0	48	0.0	384	0	0	0	384
M1	Avg.	I	0	0	0	144	0.0	1152	0	0	0	1152
		II	2.2	31.7	70.3	73.7	70.3%	1108.3	133.3	31.7	354.0	589.3
M2	Avg.	I	0.3	7.0	15.7	174.3	11.9%	1516.0	20.0	7.0	94.3	1394.7
		II	2.8	48.1	110.1	79.9	83.4%	1404.9	166.7	48.1	551.0	639.1

The results presented in Tables 6.7 highlight how courier density and market maturity influence the optimal delivery model. In smaller markets with low courier density (Scenario M0), the IC model proves to be the most cost-effective, as all instances require no micro-logistics centers and almost all couriers are hired as independent contractors. As the market size and courier density increase (Scenarios M1 and M2), a shift towards a hybrid model becomes more advantageous. This is reflected in the nonzero values related to the CV service, e.g., # C, and # CV couriers.

Furthermore, Model II consistently leads to lower overall costs compared to Model I. For instance, in the 12×12 network under Scenario M1, Model II not only reduces costs but also suggests a strategic shift, with an average of 2.2 centers required, compared to a reliance solely on IC couriers in Model I. It also demonstrates the scalability of the model, allowing companies to expand operations smoothly as market demands grow, where the number of required resources increases significantly without a proportional rise in the number of centers.

Table 6.8. Comparison of Scenarios for 12x12 Network (Different Accessibility Levels)

Scen.	Name	Mod.	#C	#Bikes	# Couriers			Total	CV Costs			IC Costs
					CV	IC	CSR	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
M1	A1-Avg.	II	0.7	11.0	24.3	119.7	24.3%	1150.0	40.0	11.0	141.7	957.3
	A2-Avg.	II	3.0	42.3	94.0	50.0	94.0%	1094.7	180.0	42.3	472.3	400.0
	A3-Avg.	II	3.0	41.7	92.7	51.3	92.7%	1080.3	180.0	41.7	448.0	410.7
M2	A1-Avg.	II	2.3	41.0	93.7	96.3	71.0%	1478.7	140.0	41.0	527.0	770.7
	A2-Avg.	II	3.0	52.3	119.7	70.3	90.6%	1375.0	180.0	52.3	580.0	562.7
	A3-Avg.	II	3.0	51.0	117.0	73.0	88.6%	1361.0	180.0	51.0	546.0	584.0

A clear relationship is observed between accessibility levels and the optimal solution as shown in Table 6.8. As accessibility increases (from A1 to A3), total costs decrease significantly (e.g., from 1150 euros in A1 to 1080 euros in A3 under M1, and from 1478 euros in A1 to 1361 euros in A3 under M2). This outcome is expected, as higher accessibility levels expand the pool of candidate locations for logistics centers, enabling more cost-effective configurations. Furthermore, when accessibility levels are high (A2 and A3 compared to A1), the optimal delivery plan exhibits good stability during the transtion from M1 to M2. The key metrics such as the number of centers, resources, couriers, and total costs remain largely consistent, with only minor variations. These observations suggest that cities with a well-connected transportation system can often achieve more cost-effective meal delivery systems, while also demonstrating resilience and stability in their optimal delivery plans as market demand increases.

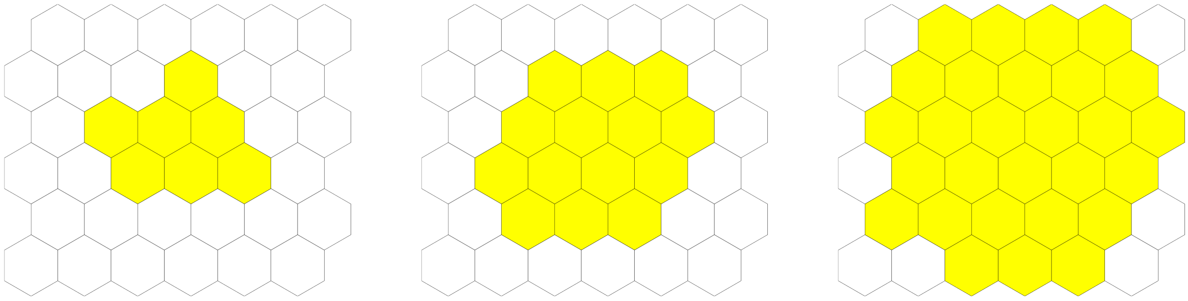
In conclusion, the analysis reveals that on-demand food delivery platforms should adapt their delivery models based on market maturity. In emerging markets with low courier density, the IC model proves most cost-effective. As markets mature and courier density increases, a hybrid model combining CV and IC couriers becomes advantageous. Cities with well-developed transportation infrastructure benefit from the increased use of CV couriers, as higher accessibility levels enable more cost-effective logistics center configurations. The model with flexible operational policy consistently outperforms the fixed model, especially in mature markets, by adapting to temporal demand fluctuations.

Furthermore, when considering scaling up operations, platforms should reassess their delivery strategies and findings suggest that they should plan for a gradual transition from purely IC-based models to optimized hybrid models. And in established markets, flexible operational policy, combined with a well-connected urban transportation system, provides greater resilience and adaptability for further market expansion.

6.3.2 Impact of Urban Spatial Patterns on Logistics Center Viability

Optimizing delivery models and logistics center placement for meal delivery platforms requires understanding the spatial distribution of courier activities, particularly their shift start and end locations. These locations, often near restaurant clusters and residential areas respectively, significantly affect the efficiency of delivery operations. We focus on two critical spatial factors: restaurant concentration, and the distance between restaurant and customer areas (it reflects overall courier movement patterns across the city, considering that work periods may involve multiple deliveries). Our aim is to provide insights for platforms to optimize logistics strategies based on a city's spatial characteristics.

To investigate the spatial distribution of starting locations, we developed three scenarios that represent varied restaurant distributions across the city. The first scenario models a highly concentrated distribution, where restaurants are located within the inner 20% of the city, simulating a dense urban core. The second scenario expands this concentration to the inner 40% of the city, representing a moderately dispersed distribution typical of mid-sized urban areas. The third scenario reflects a widely dispersed distribution, with restaurants spread across 80% of the city, capturing a sprawling urban environment or a platform with an extensive network of restaurant partnerships. In all scenarios, the delivery service is assumed to cover all zones, with customer locations randomly distributed across the city.



(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 Start Distributions

Table 6.9. Comparison of Scenarios for 12x12 Network under Different Starting Distributions

Scen.	Name	Mod.	#C	#Bikes	# Couriers		Total	CV Costs			IC Costs
					CV	IC	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
S1	12-R1-A2	I	1	23	51	43	693	60	23	266	344
	12-R1-A2	II	2	27	61	33	666	120	27	255	264
	12-R2-A2	I	1	26	61	33	708	60	26	358	264
	12-R2-A2	II	2	28	66	28	679	120	28	307	224
	12-R3-A2	I	1	25	59	35	726	60	25	361	280
	12-R3-A2	II	2	29	64	30	695	120	29	306	240
	Avg		**1.5**	**26.3**	**60.3**	**33.7**	**694.5**	**90**	**26.3**	**308.8**	**269.3**
S2	12-R1-A2	I	1	18	43	51	725	60	18	239	408
	12-R1-A2	II	3	29	66	28	699	180	29	266	224
	12-R2-A2	I	1	17	40	54	751	60	17	242	432
	12-R2-A2	II	2	28	65	29	693	120	28	313	232
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	3	29	67	27	716	180	29	291	216
	Avg		**1.7**	**20.2**	**46.8**	**47.2**	**722.7**	**100**	**20.2**	**225.2**	**377.3**
S3	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	2	23	54	40	742	120	23	279	230
	12-R2-A2	I	0	0	0	94	752	0	0	0	752
	12-R2-A2	II	3	29	65	29	738	180	29	297	232
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	0	0	0	94	752	0	0	0	752
	Avg		**0.8**	**8.7**	**19.8**	**74.2**	**748**	**50**	**8.7**	**96**	**578.3**

The results in Table 6.9 highlight the significant impact of restaurant distribution on the strategic placement and operational efficiency of logistics centers for on-demand food delivery platforms. As restaurants become more dispersed across the city, platforms should shift towards greater reliance on independent contractors (IC) rather than the company-vehicle model (CV).

In densely concentrated urban cores (S1), a balanced mix of CV and IC couriers is most cost-effective. However, as restaurant locations spread out (S2 and S3), the optimal strategy increasingly favors IC ones, with the average number of IC couriers rising from 33.7 in S1 to 47.2 in S2, and further to 74.3 in S3. This shift suggests it is challenging to manage CV resources with a widely dispersed restaurant network and the IC model offers more flexibility to cover a wider geographic area efficiently. The results also show that the decentralization of restaurants leads to higher operational costs - from 694.5 euros in the concentrated scenario to 748 euros in the dispersed scenario. This cost increase stems from the reduced efficiency in serving a widespread network.

These findings indicate platforms should assess their specific urban environment and restaurant distribution when determining the optimal logistics strategy. It suggests that in compact cities with centralized dining districts, investing in company vehicles and logistics centers can be beneficial. However, in cities with widely distributed restaurants, prioritizing a flexible IC workforce is likely to be more cost-effective.

To examine how the spatial relationship between restaurant-dense and customer-dense areas impacts logistics center viability, we designed scenarios simulating various distances between them. These areas represent zones where couriers are likely to start and end their deliveries, respectively, reflecting overall movement patterns across a city during work periods. In these scenarios, restaurants are consistently located within the inner 20% of the city center, while the distribution of residential areas varies to simulate different distances. Scenario D1 represents a compact city with short distances between restaurant and customer areas with residential areas situated 20-40% from the city center. In Scenario D2, they are located 40-60% from the center, and in Scenario D3, they are spread 80-100% from the center, to depict a moderately separated structure and a dispersed layout with significant distance between these zones respectively.

Table 6.10. Comparison of Scenarios for 12x12 Network under Different City Layouts

Scen.	**Name**	**Mod.**	**#C**	**#Bikes**	**# Couriers**		**Total**	**CV Costs**			**IC Costs**
					CV	**IC**	**Costs**	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
D1	12-R1-A2	I	1	28	62	32	659	60	28	315	256
	12-R1-A2	II	2	27	63	31	631	120	27	236	248
	12-R2-A2	I	1	28	68	26	646	60	28	346	208
	12-R2-A2	II	2	30	67	27	607	120	30	241	216
	12-R3-A2	I	1	25	56	38	672	60	25	283	304
	12-R3-A2	II	2	26	61	33	638	120	26	228	264
	Avg		**1.5**	**27.3**	**62.8**	**31.2**	**642.2**	**90**	**27.3**	**274.8**	**249.3**
D2	12-R1-A2	I	1	22	52	42	722	60	22	304	336
	12-R1-A2	II	2	24	55	39	695	120	24	239	312
	12-R2-A2	I	1	21	51	43	728	60	21	303	344
	12-R2-A2	II	2	26	60	34	689	120	26	271	272
	12-R3-A2	I	1	27	63	31	718	60	27	383	248
	12-R3-A2	II	3	30	67	27	693	180	30	267	216
	Avg		**1.7**	**25**	**58**	**36**	**707.5**	**100**	**25**	**294.5**	**288**
D3	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	0	0	0	94	752	0	0	0	752
	12-R2-A2	I	0	0	0	94	752	0	0	0	752
	12-R2-A2	II	0	0	0	94	752	0	0	0	752
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	0	0	0	94	752	0	0	0	752
	Avg		**0**	**0**	**0**	**0**	**94**	**752**	**0**	**0**	**752**

The results presented in Table 6.10 demonstrate that as the distance between couriers' starting points (restaurant clusters) and ending points (residential areas) increases from Scenario D1 to D3, the IC model becomes more cost-effective. This is evident in the decrease of CV couriers from an average of 62.8 in D1 to 0 in D3, with total costs correspondingly increasing from 642.2 euros to 752 euros. The shift towards IC couriers in dispersed urban layouts highlights the high costs of repositioning CV couriers and company vehicles over longer distances.

These findings have practical implications for meal delivery platforms to tailor their delivery strategies to the specific urban structure they operate. In compact cities, a hybrid model using both CV and IC couriers can optimize cost efficiency. However, in urban areas with distinct, widely separated commercial and residential zones, the flexibility of IC couriers becomes crucial.

6.3.3 Economic Impact on Delivery Strategies

The cost structure in urban delivery operations plays a crucial role in determining the optimal mix between CV and IC couriers, as well as the necessity of logistics centers. To evaluate this, we modeled five economic scenarios as shown in Table 6.11. Scenario C0 serves as our baseline, with facility costs of 60 €/day and IC compensation of 8 €/person. Scenarios C1 and C2 explore the effects of doubling (120 €/day) and halving (30 €/day) facility costs respectively, simulating high-rent urban centers versus more affordable areas with lower real estate prices. Scenarios C3 and C4 examine a 25% increase (10 €/person) and decrease (6 €/person) in IC compensation, representing markets with stronger gig worker bargaining power versus those with an excess supply of workers. These scenarios allow us to assess how changes in cost dynamics influence delivery strategies in different urban environments and economic conditions.

Table 6.11. Scenarios Settings with Different Costs.

Scenario	Facility Costs C_i^F (€/day)	%Change	IC Allowance C_a^O (€/day)	%Change
C0	60	–	8	–
C1	120	+100%	8	–
C2	30	-50%	8	–
C3	60	–	10	+25%
C4	60	–	6	-25%

Table 6.12. Comparison of Scenarios for 12x12 Network under Different Conditions

Scen.	Name	Mod.	#C	#Bikes	# Couriers		Total	CV Costs			IC Costs
					CV	IC	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
C0	12-R1-A2	I	1	23	51	43	693	60	23	266	344
	12-R1-A2	II	2	27	61	33	666	120	27	255	264
	12-R2-A2	I	1	26	61	33	708	60	26	358	264
	12-R2-A2	II	2	28	66	28	679	120	28	307	224
	12-R3-A2	I	1	25	59	35	726	60	25	361	280
	12-R3-A2	II	2	29	64	30	695	120	29	306	240
	Avg		**1.5**	**26.3**	**60.3**	**33.7**	**694.5**	**90**	**26.3**	**308.8**	**269.3**
C1	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	1	26	59	35	745	120	26	319	208
	12-R2-A2	I	0	0	0	94	752	0	0	0	752
	12-R2-A2	II	0	0	0	94	752	0	0	0	752
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	0	0	0	94	752	0	0	0	752
	Avg		**0.2**	**4.3**	**9.8**	**84.2**	**750.8**	**20.0**	**4.3**	**53.2**	**661.3**
C2	12-R1-A2	I	2	26	55	39	662	60	26	264	312
	12-R1-A2	II	3	27	60	34	603	90	27	214	272
	12-R2-A2	I	1	26	61	33	678	30	26	358	264
	12-R2-A2	II	3	30	67	27	610	90	30	274	216
	12-R3-A2	I	1	25	64	35	699	30	25	326	248
	12-R3-A2	II	3	30	65	29	616	90	30	264	232
	Avg		**2.2**	**27.3**	**62.0**	**32.8**	**644.7**	**65**	**27.3**	**283.3**	**257.3**
C3	12-R1-A2	I	1	26	57	37	773	60	26	317	370
	12-R1-A2	II	2	27	61	33	732	120	27	255	330
	12-R2-A2	I	1	29	66	28	767	60	29	398	280
	12-R2-A2	II	2	30	67	27	738	120	30	318	270
	12-R3-A2	I	1	28	62	32	797	60	28	389	320
	12-R3-A2	II	2	30	65	29	755	120	30	315	290
	Avg		**1.5**	**28.3**	**63.0**	**31.0**	**760.3**	**90**	**28.3**	**332.0**	**310.0**
C4	12-R1-A2	I	0	0	0	94	564	0	0	0	564
	12-R1-A2	II	0	0	0	94	564	0	0	0	564
	12-R2-A2	I	0	0	0	94	564	0	0	0	564
	12-R2-A2	II	0	0	0	94	564	0	0	0	564
	12-R3-A2	I	0	0	0	94	564	0	0	0	564
	12-R3-A2	II	0	0	0	94	564	0	0	0	564
	Avg		**0**	**0**	**0**	**94**	**564**	**0**	**0**	**0**	**564**

The results in Table 6.12 demonstrate how varying economic conditions influence delivery strategies. In scenarios with high infrastructure costs (C1) or low IC compensation (C4), the model suggests a shift towards greater reliance on IC couriers. For instance, in C1, where facility costs double, the average number of IC couriers increases from 34 in C0 to 84, and the CV model becomes economically unfeasible. Similarly, in C4, where IC compensation decreases, the model exclusively employs IC couriers and the need for CV couriers drops entirely. Conversely, low facility costs (C2) favor more use of company resources, with the average number of centers increasing from 1.5 to 2.2, accompanied by a small rise in CV couriers from 60 to 62. Also, higher IC compensation (C3) leans towards CV model, increasing CV couriers from 60 in C0 to 63. These patterns demonstrate the platform's ability to optimize resource allocation between CVs and ICs in response to varying economic conditions.

6.3.4 Evaluation of Vehicle Type Influence on Delivery Model Efficiency

To evaluate the impact of vehicle types on delivery model efficiency, we tested five scenarios, each representing a different transportation mode, as detailed in Table 6.13. Scenario T0 uses e-bikes as the baseline, with a speed of 15-16 km/h, serving as a reference point for both speed and cost. Scenario T1 introduces standard bicycles, which are slower at 12-13 km/h but more economical. Scenario T2 examines even slower bicycles at around 10 km/h, suitable for congested areas. Scenarios T3 and T4 involve faster scooters, offering higher speeds of 21-22 km/h at increased costs. Unit travel time reflects travel duration between adjacent zones, varying with vehicle speed. This results in an increase to 0.072 hours for T1, 0.09 (h) for T2, and a decrease to 0.042 (h) for both T3 and T4, compared to the baseline of 0.06 hours in T0. Purchasing costs (C_b^F) represent daily vehicle depreciation. These scenarios help identify how vehicle choice affects delivery strategy, particularly in optimizing costs and efficiency.

Table 6.13. Scenarios Settings with Different Modes.

Scenario	**Unit Travel Time (h)**	**%Changes**	**Purchasing Costs C_b^F (€/day)**	**%Changes**
T0	0.06	–	1	–
T1	0.072	+ 20%	0.5	- 50%
T2	0.09	+ 50%	0.5	- 50%
T3	0.042	- 30%	4	+ 300%
T4	0.042	- 30%	8	+ 700%

Table 6.14. Comparison of Scenarios for 12x12 Network under Different Transport Modes

Scen.	**Name**	**Mod.**	**#C**	**# Bikes**	**# Couriers CV**	**IC**	**Total Costs**	**CV Costs σ_b^F**	**γ_b^F**	**ζ_b^O**	**IC Costs θ_a^O**
T0	12-R1-A2	I	1	23	51	43	693	60	23	266	344
	12-R1-A2	II	2	27	61	33	666	120	27	255	264
	12-R2-A2	I	1	26	61	33	708	60	26	358	264
	12-R2-A2	II	2	28	66	28	679	120	28	307	224
	12-R3-A2	I	1	25	59	35	726	60	25	361	280
	12-R3-A2	II	2	29	64	30	695	120	29	306	240
	Avg		**1.5**	**26.3**	**60.3**	**33.7**	**694.5**	**90**	**26.3**	**308.8**	**269.3**
T1	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	2	27	61	33	702.5	120	13.5	305	264
	12-R2-A2	I	1	19	38	56	749.5	60	9.5	232	448
	12-R2-A2	II	2	26	61	33	732	120	13	335	264
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	2	24	51	43	737	120	12	261	344
	Avg		**1.2**	**16.0**	**35.2**	**58.8**	**737.5**	**70.0**	**8.0**	**188.8**	**470.7**
T2	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	0	0	0	94	752	0	0	0	752
	12-R2-A2	I	0	0	0	94	752	0	0	0	752
	12-R2-A2	II	0	0	0	94	752	0	0	0	752
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	0	0	0	94	752	0	0	0	752
	Avg		**0**	**0**	**0**	**94**	**752**	**0**	**0**	**0**	**752**
T3	12-R1-A2	I	1	24	54	40	682	60	96	206	320
	12-R1-A2	II	1	26	61	33	665	60	104	237	264
	12-R2-A2	I	1	28	64	30	680	60	112	268	240
	12-R2-A2	II	2	28	66	28	673	120	112	217	224
	12-R3-A2	I	1	26	63	31	689	60	104	277	248
	12-R3-A2	II	2	28	64	30	689	120	112	217	240

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Table 6.14 – continued from previous page

Scen.	Name	Mod.	#C	#	# Couriers		Total	CV Costs			IC Costs
				Bikes	CV	IC	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
	Avg		**1.3**	**26.7**	**62.0**	**32.0**	**679.7**	**80.0**	**106.7**	**237.0**	**256.0**
T4	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	0	0	0	94	752	0	0	0	752
	12-R2-A2	I	0	0	0	94	752	0	0	0	752
	12-R2-A2	II	0	0	0	94	752	0	0	0	752
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	0	0	0	94	752	0	0	0	752
	Avg		**0**	**0**	**0**	**94**	**752**	**0**	**0**	**0**	**752**

Table 6.14 demonstrates the impact of vehicle speed and cost on the efficiency and cost-effectiveness of delivery models. Scenario T0 (e-bikes) serves as the baseline with an average total cost of 694.5 euros, using a balanced mix of 60.3 CV couriers and 33.7 IC couriers. In contrast, switching to slower vehicles like standard bicycles in Scenario T1 increases costs to 737.5 euros, and Scenario T2 further raises costs to 752 euros, reflecting inefficiencies from reduced speed and a shift toward IC couriers over CV models.

In Scenario T3, the use of faster scooters reduces the average total cost to 679.7 euros, demonstrating that increased speed can offset higher vehicle costs and enhance efficiency without increasing overall expenses. This balance suggests that the right choice of faster modes can improve service quality while maintaining cost-effectiveness. However, Scenario T4 reveals a tipping point where the benefits of speed are outweighed by vehicle costs. Despite their speed, the premium scooters in T4 lead to higher total costs (752 euros), driving a shift towards IC couriers over company-owned fleets. This outcome indicates that while faster vehicles can improve operational efficiency, there's a critical threshold beyond which expensive equipment becomes less cost-effective.

The analysis indicates that there is a critical balance between speed and cost, and the choice of vehicle type must be carefully considered to optimize delivery strategies, particularly in high labor cost markets.

6.4 Case Study: Amsterdam City

This case study applies the proposed models to optimize the planning of logistics centers in Amsterdam, using historical data from an ODFD operator. We aim to explore center planning in a mature market with well-developed public transportation, investigating the trade-off between zone accessibility and costs. Also, by visualizing results on an Amsterdam map, we demonstrate our model's applicability to complex urban environments and examine the impact of different operational policies on delivery choices and center placement.

The study focuses on the meal delivery period from 10:00 AM to 11:00 PM, aligning with the main operational hours in Amsterdam. Initial courier locations are weighted by demand in high-order zones, while delivery destinations reflect historical trends of customer clusters. By analyzing courier start times, shift patterns, and destination distributions, we determined the number of couriers operating in each zone and time slot, as well as their expected shift duration and destinations.

The city of Amsterdam is spatially divided into 415 hexagonal zones using the h3 spatial index, allowing for detailed analysis. Accessibility scores for each zone are calculated based on the public transportation network, which includes 15 tram lines (139 stations), 5 metro lines (11 stations), 81 bus lines (893 stations, counting bidirectional stops separately), and 4 train lines (13 stations). Data for the public transportation network were sourced from the Amsterdam municipality website and OpenStreetMap API. These scores were computed using Equation (4.3), and Figure 6.4 illustrates the resulting accessibility scores across Amsterdam.

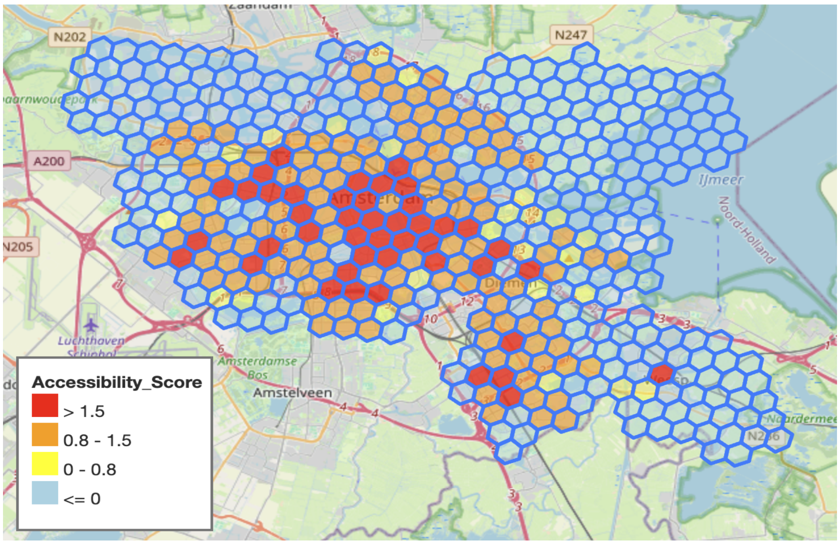


Figure 6.4. Accessibility Score of Amsterdam City

Table 6.15 presents the number of potential logistics center locations that meet the accessibility criteria under varying threshold levels. As the threshold decreases, more zones qualify as candidate locations, indicating a broader range of accessible areas suitable for establishing logistics centers.

Table 6.15. Different accessibility thresholds and the corresponding candidate locations

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

We consider a planning horizon of 5 years (1825 days). For all locations, we estimate the construction or leasing cost of a company-owned center at 25,000 euros per year, resulting in a daily cost of approximately 69 euros (C_i^F). We also consider the purchasing cost for company-owned e-bikes (C_b^F) at 1 euro per day, based on a total of 900 euros for purchasing and maintaining a bicycle over 5 years. The hourly wage for both types of couriers (C_h^O) is assumed to be 15 euros[1], with an additional bicycle allowance (C_a^O) of 13 euros per day for independent contractors (IC). The estimated parameters are summarized in Table 6.16.

Table 6.16. Value of the parameters for Amsterdam Case.

Parameters	**Value**	**Remark**
C_i^F	69 (€/day)	Costs of locating a center in any zone per day
C_b^F	1 (€/e-bike/day)	Depreciation costs for each e-bike per day
C_h^O	15 (€/hour)	Couriers' basic hourly salary
C_a^O	13 (€/person)	Allowance for IC couriers
TT_{ij}	0.06 (hour)	For traveling between adjacent zones $(i, j) \in A$
TT_{ij}	Shortest path	For non-adjacent zones i and j
$\|P\|$	3	Maximum centers allowed

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

Table 6.17 compares the performance of Model I and Model II in determining the optimal logistics center locations in Amsterdam under various accessibility thresholds. Both models indicate the necessity of establishing multiple logistics centers within the city, given the scale and distribution of demand. However, Model II consistently outperforms Model I, achieving a 15% reduction (indicated in 'Cost Red.' column) in total operational costs across all accessibility thresholds tested. For example, under an accessibility threshold of 2.8, Model II reduces total costs from 2474 euros (Model I) to 2104 euros while maintaining the same level of service (100% CSR with 222 CV couriers and 49 IC couriers). This cost reduction is primarily driven by the ability of Model II to adjust service coverage in response to temporal fluctuations in courier start and end locations, optimizing the use of CV and IC couriers.

Table 6.17. Results of Amsterdam Case Using Model I and II

Access. Threshold	**Mod.**	**#C**	**#Bikes**	**# Couriers CV**	**IC**	**CSR**	**Total Costs**	**Cost Red.**
1.3	I	3	119	222	49	100%	2458	–
	II	3	119	222	49	100%	2096	15%
2.2	I	3	119	222	49	100%	2458	–
	II	3	119	222	49	100%	2096	15%
2.8	I	3	119	222	49	100%	2474	–
	II	3	119	222	49	100%	2104	15%

Figures 6.5 and 6.6 depict the optimized logistics center placements and coverage areas for Model I and Model II respectively. The coverage refers to zones where CV couriers start their first deliveries, reflecting CV courier demand distribution. Different colors represent various centers and their service areas, with darker shades marking center locations and lighter shades showing coverage. Zone labels display CV courier numbers versus total couriers starting there. Figure 6.5 illustrates Model I's fixed coverage, where zone-to-center allocation remains constant. Labels show aggregate CV and total courier numbers over the entire period. Figure 6.6 demonstrates Model II's time-variant coverage at three times (11:00 AM, 16:00 PM, 17:00 PM), showing how coverage adapts to dynamic demands. Labels indicate the CV to total courier ratio ($S_i^\tau / \tilde{S}_i^\tau$) at each specific time. Furthermore, the time-variant nature of Model II is evident in the highlighted zone with a black dash circle. At Time 7, it's within the coverage of the red center on the left and CV couriers starting their shifts in this zone at this time will use vehicles from the red center. While at Time 8, the same zone is now covered by the blue center in the middle. This illustrates how Model II adjusts coverage dynamically to optimize resource allocation based on temporal demand changes.

The results presented in Table 6.18 demonstrate how varying accessibility thresholds impact operational costs in the Amsterdam case study. As the accessibility threshold increases from 0.2 to 2.8, there is a gradual rise in total costs, from 2440 euros at the lowest threshold to 2474 euros at the highest threshold, reflecting a 1.4% increase, as indicated in the 'Cost Inc.' column. This is primarily driven by the increased operational costs associated with repositioning CV couriers and vehicles depending on center locations. The modest cost increase despite significant changes in accessibility thresholds is related to an alignment between high-accessibility areas and courier activity hotspots. Zones with high accessibility scores often result from public transportation hubs and multi-modal stations within them. These areas typically feature business districts and restaurant clusters, where couriers are more likely to start their delivery shifts. As a result, the optimal locations for logistics centers tend to concentrate within a limited set of highly accessible candidate locations, regardless of the specific threshold chosen.

Higher accessibility thresholds improve convenience for couriers by making it easier for a larger population to commute between their homes and the centers. Our results suggest that investing in more accessible center locations may enhance courier efficiency and satisfaction with a minimal impact on overall operational costs in a city with well-developed public transportation. The platform can choose the best options from an already optimized set of locations, allowing them to prioritize courier convenience by investing only marginally more in highly accessible areas.

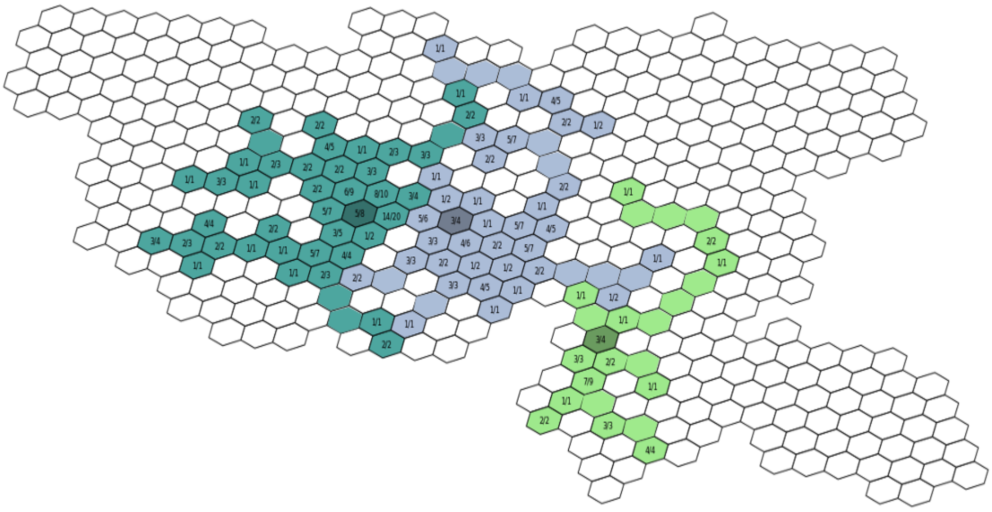
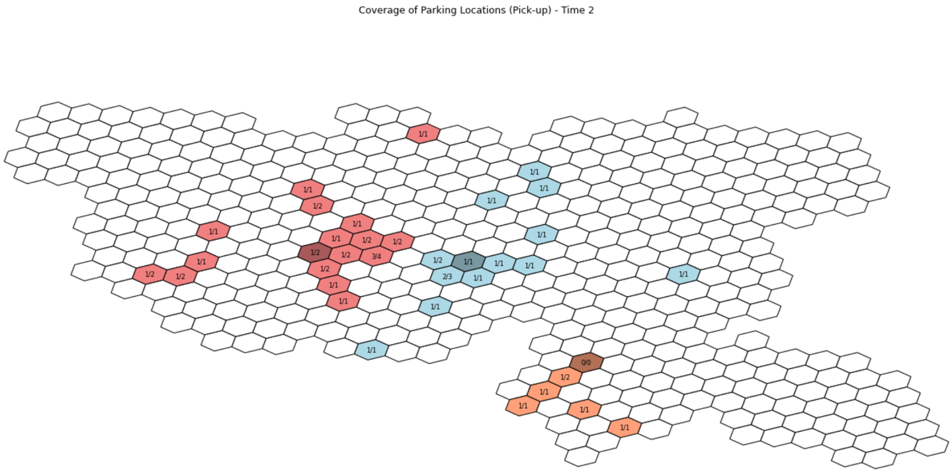


Figure 6.5. Illustration of Model I result on Amsterdam case

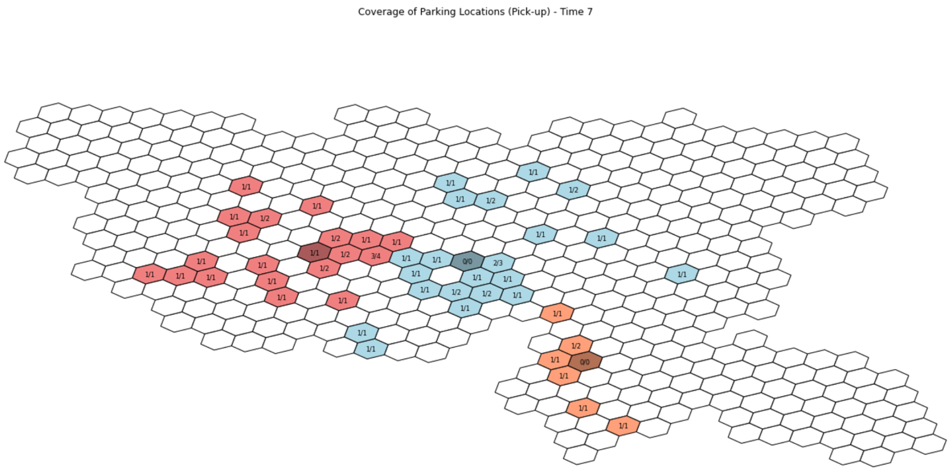
Table 6.18. Results of Amsterdam Case Under Different Accessibility Requirements

Access. Threshold	**Mod.**	**#C**	**#Bikes**	**# Couriers**		**Total Costs**	**Cost Inc.**
				CV	**IC**		
0.2	I	3	119	222	49	2440	–
1.08	I	3	119	222	49	2440	–
1.12	I	3	119	222	49	2440	–
1.2	I	3	119	222	49	2442	0.08%
1.3	I	3	119	222	49	2458	0.74%
1.7	I	3	119	222	49	2458	0.74%
2.2	I	3	119	222	49	2458	0.74%
2.8	I	3	119	222	49	2474	1.39%

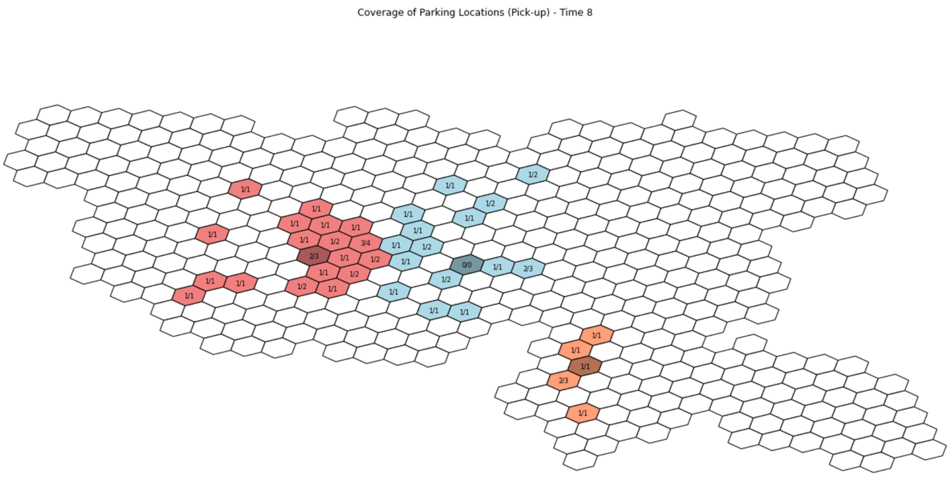
In this part, we illustrate the strategic advantage of adopting a more flexible approach (indicated by Model II) to logistics center management in terms of cost optimisation. Furthermore, highly accessible areas for logistics centers can provide a robust solution that balances operational efficiency with courier satisfaction. And while higher accessibility thresholds do lead to slightly increased costs, the benefits in terms of courier convenience and potential long-term operational efficiency likely outweigh these modest additional expenses.



(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 and cities with well-constructed public transport infrastructure. 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.

In established markets, multiple logistics centers may be beneficial. The optimal locations for these centers depend on courier activity patterns and desired accessibility levels. For cities with well-developed public transportation like Amsterdam, investing in highly accessible center locations can enhance courier efficiency and satisfaction with minimal impact on overall costs. When considering vehicle configuration for the company-vehicle model, platforms should balance speed and cost, as slower transport modes or expensive options are less economically viable, especially in markets with high labor costs. Moreover, in highly accessible cities, a more flexible operational policy (Model II) allows for only minor adjustments to infrastructure and resource plans in the optimal delivery strategy when scaling up operations.

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

Future research could consider the facility cost variations based on fleet size and explore buffer capacity implications in flexible return scenarios to have more nuanced decision-making regarding costs for space, charging infrastructure, and other facilities within centers. Additionally, relaxing the assumption of balance after each day's operations and exploring inter-center vehicle repositioning could lead to potential cost savings and more efficient resource utilization across the network in response to spatial-temporal imbalances in courier activity.

Currently, the model uses deterministic inputs and an additional important direction for future research would be to incorporate stochastic data into the model to handle real-world uncertainties in food delivery operations.

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A

Scientific Paper

The paper starts on the next page.

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

Yuchen Qi[a], Shadi Sharif Azadeh[b], G. Correia[b], Yousef Maknoon[a,*]

[a] *Engineering, Systems and Services Department, Delft University of Technology, Netherlands*
[b] *Transport and Planning Department, Delft University of Technology, Netherlands*

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 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 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.

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

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 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 (Zambetti et al. (2017); Furlan (2021); Scheiwe (2022)). The first involves platforms that match diners with restaurants but do not handle delivery logistics.

*Corresponding author

Email addresses: Y.Qi-5@student.tudelft.nl (Yuchen Qi), s.sharifazadeh@tudelft.nl (Shadi Sharif Azadeh), G.Correia@tudelft.nl (G. Correia), m.y.maknoon@tudelft.nl (Yousef Maknoon)

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 (JustEatTakeaway.com (2023)).

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 company-vehicle model or not. This paper addresses this challenge by focusing on a critical aspect of implementing 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 address 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 structured as follows: Section 2 reviews relevant literature. Section 3 describes the problem in detail and two mathematical models for micro-logistics are presented in Section 4. Section 5 reports scenario analyses for delivery strategy and center planning under different conditions, and presents a case study of Amsterdam. Finally, Section 6 concludes the paper and suggests future research directions.

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 operation of on-demand meal delivery is dynamic, capacitated, 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, committing to fulfil 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)).

Few studies addressing the delivery model choice and involved facility configuration for on-demand meal delivery service from the perspective of strategic planning. 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. 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. Ballare and Lin (2020) 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. Ai et al. (2021) 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 that organise 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 the 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 (Mahmutogullari and Kara (2016)), which is different from the logistics practices in on-demand food delivery industry, in terms of specific functions and operations.

2.3. 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 et al. (2013); Lin and Yang (2011)).

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 maximize 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 location.

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 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.

2.4. 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 (Liu and Lee (2003); Liu and Lin (2005); Hiassat et al. (2017)). 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 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 interpretation.

2.5. 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 (Zhong et al. (2007); Haugland 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.

3. 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 shift, indicating their first/last delivery locations, and their shift schedules. The delivery models and the historical data we considered are explained in Section 3.1.

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 detailed explanation in Section 3.2).
3. Coverage area and vehicle allocation: define the service zones allocated to each micro-logistics center for CV operations (coverage area is determined among the zones where couriers start their first delivery, indicating the vehicle pickup needs), 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.

In this study, we assume both type 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 CV model and additional payments for 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 $\mathcal{T} = \{\tau_0, \tau_1, \dots, \tau_n, \dots, \tau_N\}$ 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.

3.1. 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 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.

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

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

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 $0 \geq \alpha \leq 1$.

3.2. 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, including the availability and frequency of transport options within the zone 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:

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

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).

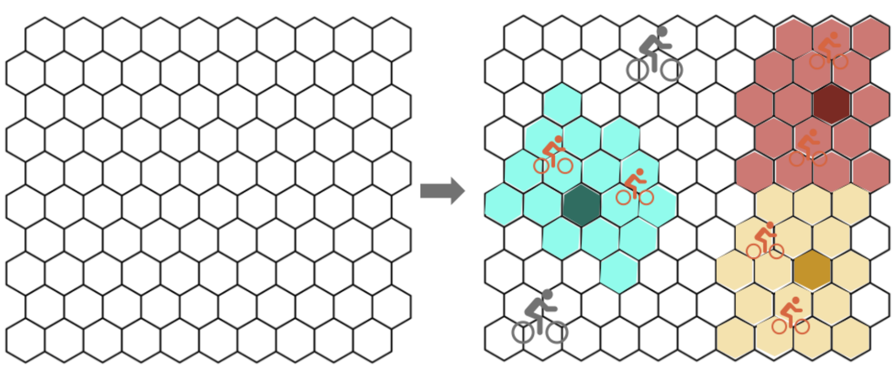


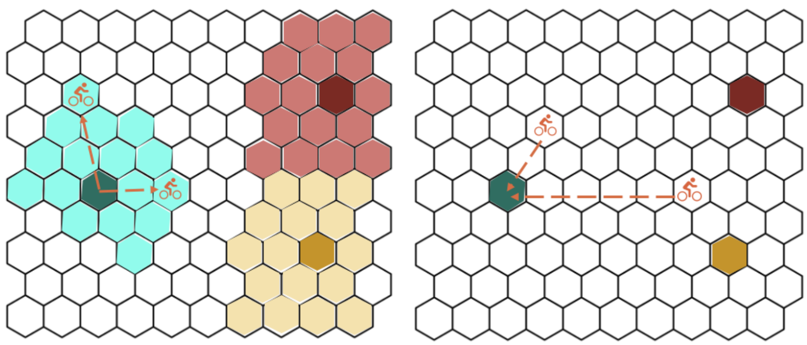
Figure 1: Illustration of Key Decisions

4. Mathematical Models

In this section, we will introduce two models: Model I considers a fixed-coverage problem with 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.

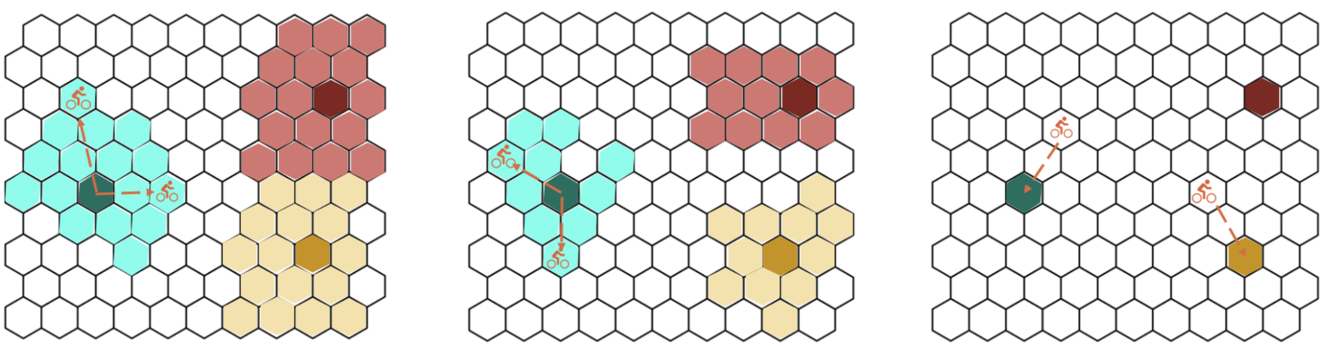
Model II addresses a problem with time-variant coverage and global redistribution optimisation to obtain more efficient resource allocation. It allows for flexible coverage areas of centers that can change with time τ. It also optimizes the returns for CV couriers based on overall cost trade-offs and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

Figure 2: Illustration of Model I



(a) Model II - Coverage at time 1 (b) Model II - Coverage at time 2 (c) Model II - Returns at certain time

Figure 3: Illustration of Model II

4.1. 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 definition of sets, parameters, and variables involved in the mathematical model can be found in Table 15 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 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)-(35). The following sections elaborate on each category of constraints.

4.1.1. 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 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.

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

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

4.1.2. Operation Costs

Costs for non-productive legs. CV couriers' shifts include time spent traveling 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 a 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 consists 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.

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

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

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

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

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

$$\tag{18}$$

$$z_{ij}^p \leq y_i^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{19}$$
$$z_{ij}^p \leq x_j^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{20}$$
$$1 + z_{ij}^p \geq x_j^p + y_i^p, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{21}$$
$$x_i^p \in \{0,1\}, \qquad \forall i \in I, \forall p \in P \tag{22}$$
$$y_i^p \in \{0,1\}, \qquad \forall i \in I_c, \forall p \in P \tag{23}$$
$$z_{ij}^p \in \{0,1\}, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P \tag{24}$$
$$v_i \in \{0,1\}, \qquad \forall i \in I \tag{25}$$
$$e_i^{p\tau} \in \mathbb{R}^+, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \tag{26}$$

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 (19) - (21) 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.

$$\sum_{j|(i,j)\in A} f_{ij}^p - \sum_{j|(j,i)\in A} f_{ij}^p \geq x_i^p - (|I|+1) * y_i^p, \quad \forall i \in I, \forall p \in P \tag{27}$$
$$\sum_{j|(j,i)\in A} f_{ij}^{pt} \leq |I| * x_i^p, \quad \forall i \in I, \forall p \in P \tag{28}$$
$$f_{ij}^p \geq 0, \qquad \forall (i,j) \in A, \forall p \in P \tag{29}$$

Continuity If a center is needed, the compactness and continuity of its 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 continuity requirement. Constraints (27) - (28) 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.

$$q^{p\tau_0} = q^{p\tau_N}, \qquad \forall p \in P \tag{30}$$
$$q^{p\tau} = q^{p(\tau-1)} - \sum_{i\in I} S_i^\tau * x_i^p + \sum_{i \in I} e_i^{p\tau}, \qquad \forall p \in P, \forall \tau \in \mathcal{T} \setminus \{\tau_0\} \tag{31}$$
$$q^{p(\tau_0)} \leq q_0^p \qquad \forall p \in P \tag{32}$$
$$q_0^p \leq U_0 * \sum_{i \in I_c} y_i^p, \qquad \forall p \in P \tag{33}$$
$$q^{p\tau} \in \mathbb{R}^+, \qquad \forall p \in P \tag{34}$$
$$q_0^p \in \mathbb{N} \tag{35}$$

Vehicle Inventory Constraints (30) - (31) 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 (32) determines the total stock of vehicles of each center p needed for CV couriers within its coverage. Constraint (33) 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.

4.2. 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 16 in Appendix.

The objective function in Model II includes updated operational costs:

$$\zeta_b^O = \sum_{\tau\in\mathcal{T}}\sum_{p\in P}\sum_{i\in I_c}\sum_{j\in I} C_h^O * t_{ij} * (z_{ij}^{(S)p\tau} + z_{ij}^{(E)p\tau}) \tag{36}$$

$$\theta_a^O = \sum_{i\in I}\sum_{\tau\in\mathcal{T}} C_a^O * \tilde{S}_i^\tau * v_i^t + C_a^O * \overline{S}_i^\tau * (1 - v_i^t) \tag{37}$$

Allocation constraints modified as follows, while Vehicle Inventory expressions remained the same as Model I. Particularly, constraint (39) ensures that vehicle returns are based on pickup demand, but without restrictions on specific centers.

$$v_i^\tau + \sum_{p\in P} x_i^{p\tau} = 1, \qquad \forall i \in I, \forall \tau \in \mathcal{T} \qquad (38)$$

$$\sum_{p\in P} e_i^{p\tau} = \sum_{p\in P}\sum_{j\in I}\sum_{\tau'\in\mathcal{T}} E_{ji}^{\tau'\tau} * x_j^{p\tau'}, \qquad \forall i \in I, \forall \tau \in \mathcal{T} \qquad (39)$$

$$\sum_{i\in I_c} y_i^p \leq 1, \qquad \forall p \in P \qquad (40)$$

$$\sum_{p\in P} y_i^p \leq 1, \qquad \forall i \in I_c \qquad (41)$$

$$x_j^{p\tau} \leq \sum_{i\in I_c} y_i^p, \qquad \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (42)$$

$$z_{ij}^{(S)p\tau} \leq M * y_i^p, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (43)$$

$$z_{ij}^{(S)p\tau} \leq S_j^\tau * x_j^{p\tau}, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (44)$$

$$z_{ij}^{(S)p\tau} \geq S_j^\tau * x_j^{p\tau} - M * (1 - y_i^p), \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (45)$$

$$z_{ij}^{(E)p\tau} \leq M * y_i^p, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (46)$$

$$z_{ij}^{(E)p\tau} \leq e_j^{p\tau}, \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (47)$$

$$z_{ij}^{(E)p\tau} \geq e_j^{p\tau} - M * (1 - y_i^p), \qquad \forall i \in I_c, \forall j \in J, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (48)$$

$$x_i^{p\tau} \in \{0, 1\}, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (49)$$

$$y_i^p \in \{0, 1\}, \qquad \forall i \in I_c, \forall p \in P \qquad (50)$$

$$z_{ij}^{(S)p\tau} \in \mathbb{N}, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (51)$$

$$z_{ij}^{(E)p\tau} \in \mathbb{R}^+, \qquad \forall i \in I_c, \forall j \in I, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (52)$$

$$v_i^\tau \in \{0, 1\}, \qquad \forall i \in I, \forall \tau \in \mathcal{T} \qquad (53)$$

$$e_i^{p\tau} \in \mathbb{R}^+, \qquad \forall i \in I, \forall p \in P, \forall \tau \in \mathcal{T} \qquad (54)$$

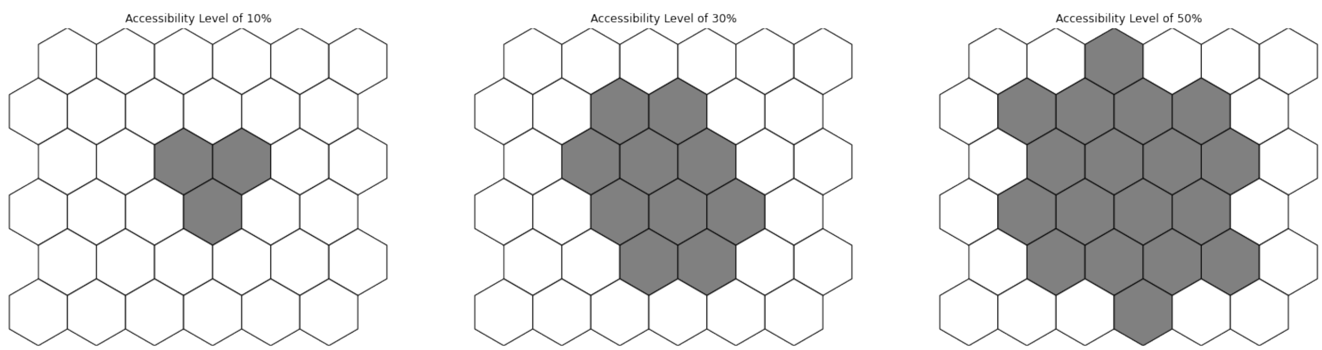
5. Results

We conducted our experiments using Python 3.9 and Gurobi Optimizer version 9.5.2. The experiments were performed on a machine with a 3.2 GHz CPU and 16 GB of RAM. Section 5.1 details the process used to generate the experimental instances. Section 5.2 presents the computational performance of the proposed models. In Section 5.3 - Section 5.6, we examine the economic feasibility of micro-logistics centers under various urban conditions. This analysis focuses on key factors such as service density, urban spatial patterns, and relevant economic factors. Additionally, we investigate the impact of different operational policies and city accessibility levels, as well as vehicle configurations, when optimizing the planning of viable centers. Finally, Section 5.7 applies our approach to a food delivery system in Amsterdam, to further illustrate the decisions on the dimensions of centers suggested by our models e.g., their locations and coverage areas, and conducts a discussion on the tradeoff between accessibility and costs in a city with well-developed public transportation.

5.1. Instance Description

We assume all delivery activities occur within a predefined service zone, described using hexagonal units of 0.737 km^2. Three scenarios are considered for the coverage area: (1) 36 hexagonal units representing small urban areas (e.g., Delft), (2) 81 hexagonal units representing medium-sized cities, and (3) 144 hexagonal units representing metropolitan areas (e.g., The Hague).

For accessibility considerations of potential logistics center locations, we assume a typical urban structure where areas closer to the city center tend to have better public transport connections and thus higher accessibility scores. We define three accessibility levels - 10%, 30%, and 50% - representing the proportion of zones qualifying as candidate locations. Higher levels indicate cities with better infrastructure and more potential locations. This approach captures urban accessibility patterns without requiring detailed transport data. Figure 4 illustrates the eligible candidates (shown in grey) under these 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

Figure 4: Visualization of Different Urban Accessibility Levels

Courier Operations. The platform operates from 08:30 AM to 10:00 PM, divided into 1.5-hour intervals, resulting in 10 segments. Courier shifts are most frequent during peak hours-lunch (11:00 AM - 2:00 PM) and dinner (5:00 PM - 8:00 PM)-and less frequent during the off-peak afternoon period (2:00 PM - 5:00 PM). Courier density reflects these fluctuations, e.g., with 0.3 couriers/km^2 during peak hours and 0.075 couriers/km^2 during off-peak hours. By correlating courier density with the network area across these time segments, the number of couriers starting at any given time is determined. For example, in a 6x6 network (36 zones, approximately 26 km^2) with the courier density mentioned earlier, around 8 couriers are active for each time segment during peak hours, while about 2 couriers are active during off-peak hours, leading to a total of 36 active couriers throughout the day.

These total number of active couriers at each time segment is distributed across zones based on starting probability distributions to determine $\tilde{S}_i^\tau$. We consider three starting distributions: random, uniform, and centralized. Random distribution refers to randomly generated probabilities for couriers to start in each zone, while uniform distribution assigns equal probability across all zones. In the centralized distribution, 80% of active couriers start within the central area, defined as the top 50% of zones closest to the city center. We also consider a service level of 0.7 to further determine possible CV courier needs S_i^τ and the remaining IC ones $\overline{S}_i^\tau$.

Probability matrix $n_{ij}^{\tau\tau'}$, describes the spatial-temporal distribution of courier movements, accounting for both shift duration and ending locations for each starting record. In the following instances, courier shifts are assumed to follow a truncated normal distribution with $\mu = 3$ hours and $\sigma = 1.5$ hours, truncated between 1.5 and 4.5 hours. The transition from starting zone i to ending zone j is randomly determined.

We assume that couriers use e-bikes with an average speed of 15-16 km/h within urban areas. The distance between the centers of two adjacent zones is 0.92 km, resulting in a travel time of 0.06 hours. Additional parameters used in the instances are listed in Table 1.

Table 1: Parameters of the test instances.

Parameters	**Value**	**Remark**
C_i^F	60 (€/day)	Costs of locating a center in any zone per day
C_b^F	1 (€/e-bike/day)	Depreciation costs for each e-bike per day
C_h^O	15 (€/hour)	Couriers' basic hourly salary
C_a^O	8 (€/person)	Allowance for IC couriers
TT_{ij}	0.06 (hour)	For traveling between adjacent zones $(i, j) \in A$
TT_{ij}	Shortest path	For non-adjacent zones i and j
$\|P\|$	3	Maximum centers allowed

In the following discussion, we employ a concise notation to represent the various settings of instances. The numbers 6, 9, and 12 denote 36, 81, and 144 hexagonal grids, respectively; R, U, and C represent random, uniform, and centralized courier starting distributions; and A1, A2, and A3 indicate 10%, 30%, and 50% accessibility levels. For example, '6-R-A1' represents a 36-hexagonal grid network with random courier starting distribution and 10% accessibility. To account for randomness in courier allocation, multiple instances with the same distribution pattern are generated, differentiated by appending numerical identifiers (e.g., 'R1', 'R2', 'R3').

5.2. Computational Performance

We tested both Model I and Model II on the generated instances with a time limit of 8 hours (28,800 seconds). Table 17 in the Appendix summarizes the computational results, including, in order: model type, instance name, execution time (in seconds), initial integer solution, initial relaxation bound, best integer solution, best bound, number of branched nodes, and integrity gap (in percentage).

As shown in Table 17, most small instances are solved within minutes, with solution time increasing as the problem size grows. Computation time also generally correlates with the number of potential candidates linked to the accessibility level, with higher accessibility levels (A2, A3) typically requiring more time than lower levels (A1). The largest instances (15x15 grid) present significant computational challenges. For Model I with A3 accessibility, the average gap after 8 hours is 55.5%, while Model II shows a 30.8% gap for the same scenario. These large gaps highlight the problem's increasing complexity with instance size, especially at higher accessibility levels. For very large urban areas, heuristic approaches or decomposition methods may be necessary to obtain good solutions in reasonable computation times.

Model II requires more time to find a solution compared to Model I. This difference is negligible for small instances but increases with the number of zones and accessible locations. Our results also indicate that as the service area expands, the dynamic model has the potential to achieve lower total costs. In the 12x12 grid with A2 accessibility, Model II reduces the average total cost from 1149.2 (Model I) to 1069.7, a 6.9% improvement.

In conclusion, while both models can solve small to medium-sized instances efficiently, Model II offers potential cost savings at the expense of increased computation time. The trade-off between solution quality and computation time becomes more critical as the problem size and complexity increase.

5.3. Market Maturity Analysis

The choice of delivery model strategy for a meal delivery platform should be tailored to the market maturity level. Specifically, we seek to determine the conditions under which the use of independent contractors (IC), company-vehicle (CV) couriers, or a combination of both would be most effective. These strategies are influenced by courier density, reflecting the market maturity of the service area.

In this section, we explore three distinct market scenarios with a 12x12 network. The details of these scenarios are outlined in Table 2. For each service area size, Scenario M0 represents emerging markets with low courier density, typically in new or low-density residential areas. Scenario M1 reflects established markets with moderate courier density. Scenario M2 corresponds to high-demand metropolitan areas with dense courier networks.

Table 2: Scenario Settings with Different Courier Density

Network	**Scenario**	**# Couriers**	**Density (couriers/km^2)**
12x12	M0	48	Peak: 0.1 Normal: 0.025
	M1	144	Peak: 0.3 Normal: 0.075
	M2	190	Peak: 0.4 Normal: 0.1

The detailed results of a total of 54 instances in our tests (18 for each scenario) are presented in 18 in the Appendix and we calculate the average result to summarize in Table 3 and Table 4. These tables include the following columns: Scenario (Scen.), Instance Name, Model Type (Mod., i.e. I, II), the total number of required micro-logistics centers (#C), the number of needed resources (#R), and the total number of couriers, which is further divided into the number of

CV couriers and IC couriers. The CSR (Courier Supply Ratio) column represents the ratio of CV couriers in the optimized plan to the total potential CV demand across all zones and times ($\sum_{\tau \in \mathcal{T}} \sum_{i \in I} S_i^\tau$), based on the desired service level. The CSR reflects the extent to which the model chooses to utilize CV couriers versus IC ones (coverage of CV demands), with a higher ratio indicating greater CV coverage and a lower ratio suggesting more reliance on IC couriers. This metric provides a quantitative alternative to geographic illustrations of coverage of the whole system. The tables also include columns for Total Costs, CV Costs (which are further broken down into center construction costs (σ_b^F), resource purchasing costs (γ_b^F), and operational costs for non-productive legs (ζ_b^O), and IC service costs (θ_a^O). These indicators are calculated based on one operational day.

Table 3: Comparison of Scenarios for 12x12 Network (Model I and Model II)

Scen.	Name	Mod.	#C	#Bikes	# Couriers			Total	CV Costs			IC Costs
					CV	IC	CSR	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
M0	Avg.	I	0	0	0	48	0.0	384	0	0	0	384
		II	0	0	0	48	0.0	384	0	0	0	384
M1	Avg.	I	0	0	0	144	0.0	1152	0	0	0	1152
		II	2.2	31.7	70.3	73.7	70.3%	1108.3	133.3	31.7	354.0	589.3
M2	Avg.	I	0.3	7.0	15.7	174.3	11.9%	1516.0	20.0	7.0	94.3	1394.7
		II	2.8	48.1	110.1	79.9	83.4%	1404.9	166.7	48.1	551.0	639.1

The results presented in Tables 3 highlight how courier density and market maturity influence the optimal delivery model. In smaller markets with low courier density (Scenario M0), the IC model proves to be the most cost-effective, as all instances require no micro-logistics centers and almost all couriers are hired as independent contractors. As the market size and courier density increase (Scenarios M1 and M2), a shift towards a hybrid model becomes more advantageous. This is reflected in the nonzero values related to the CV service, e.g., # C, and # CV couriers.

Furthermore, Model II consistently leads to lower overall costs compared to Model I. For instance, in the 12×12 network under Scenario M1, Model II not only reduces costs but also suggests a strategic shift, with an average of 2.2 centers required, compared to a reliance solely on IC couriers in Model I. It also demonstrates the scalability of the model, allowing companies to expand operations smoothly as market demands grow, where the number of required resources increases significantly without a proportional rise in the number of centers.

Table 4: Comparison of Scenarios for 12x12 Network (Different Accessibility Levels)

Scen.	Name	Mod.	#C	#Bikes	# Couriers			Total	CV Costs			IC Costs
					CV	IC	CSR	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
M1	A1-Avg.	II	0.7	11.0	24.3	119.7	24.3%	1150.0	40.0	11.0	141.7	957.3
	A2-Avg.	II	3.0	42.3	94.0	50.0	94.0%	1094.7	180.0	42.3	472.3	400.0
	A3-Avg.	II	3.0	41.7	92.7	51.3	92.7%	1080.3	180.0	41.7	448.0	410.7
M2	A1-Avg.	II	2.3	41.0	93.7	96.3	71.0%	1478.7	140.0	41.0	527.0	770.7
	A2-Avg.	II	3.0	52.3	119.7	70.3	90.6%	1375.0	180.0	52.3	580.0	562.7
	A3-Avg.	II	3.0	51.0	117.0	73.0	88.6%	1361.0	180.0	51.0	546.0	584.0

A clear relationship is observed between accessibility levels and the optimal solution as shown in Table 4. As accessibility increases (from A1 to A3), total costs decrease significantly (e.g., from 1150 euros in A1 to 1080 euros in A3 under M1, and from 1478 euros in A1 to 1361 euros in A3 under M2). This outcome is expected, as higher accessibility levels expand the pool of candidate locations for logistics centers, enabling more cost-effective configurations. Furthermore, when accessibility levels are high (A2 and A3 compared to A1), the optimal delivery plan exhibits good stability during the transtion from M1 to M2. The key metrics such as the number of centers, resources, couriers, and total costs remain largely consistent, with only minor variations. These observations suggest that cities with a well-connected transportation system can often achieve more cost-effective meal delivery systems, while also demonstrating resilience and stability in their optimal delivery plans as market demand increases.

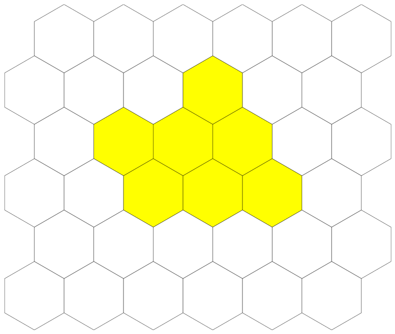
In conclusion, the analysis reveals that on-demand food delivery platforms should adapt their delivery models based on market maturity. In emerging markets with low courier density, the IC model proves most cost-effective. As markets mature and courier density increases, a hybrid model combining CV and IC couriers becomes advantageous. Cities with well-developed transportation infrastructure benefit from the increased use of CV couriers, as higher accessibility levels enable more cost-effective logistics center configurations. The model with flexible operational policy consistently outperforms the fixed model, especially in mature markets, by adapting to temporal demand fluctuations.

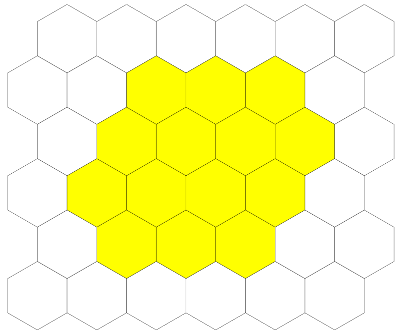
Furthermore, when considering scaling up operations, platforms should reassess their delivery strategies and findings suggest that they should plan for a gradual transition from purely IC-based models to optimized hybrid models. And in established markets, flexible operational policy, combined with a well-connected urban transportation system, provides greater resilience and adaptability for further market expansion.

5.4. Impact of Urban Spatial Patterns on Logistics Center Viability

Optimizing delivery models and logistics center placement for meal delivery platforms requires understanding the spatial distribution of courier activities, particularly their shift start and end locations. These locations, often near restaurant clusters and residential areas respectively, significantly affect the efficiency of delivery operations. We focus on two critical spatial factors: restaurant concentration, and the distance between restaurant and customer areas (it reflects overall courier movement patterns across the city, considering that work periods may involve multiple deliveries). Our aim is to provide insights for platforms to optimize logistics strategies based on a city's spatial characteristics.

To investigate the spatial distribution of starting locations, we developed three scenarios that represent varied restaurant distributions across the city. The first scenario models a highly concentrated distribution, where restaurants are located within the inner 20% of the city, simulating a dense urban core. The second scenario expands this concentration to the inner 40% of the city, representing a moderately dispersed distribution typical of mid-sized urban areas. The third scenario reflects a widely dispersed distribution, with restaurants spread across 80% of the city, capturing a sprawling urban environment or a platform with an extensive network of restaurant partnerships. In all scenarios, the delivery service is assumed to cover all zones, with customer locations randomly distributed across the city.


(a) S1: 0% - 20 % Areas from Center


(b) S2: 0% - 40 % Areas from Center

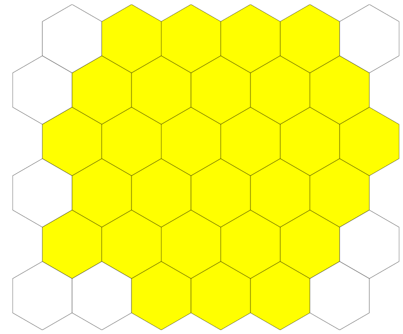

(c) S3: 0% - 80 % Areas from Center

Figure 5: Visualization of Different Start Distributions

Table 5: Comparison of Scenarios for 12x12 Network under Different Starting Distributions

Scen.	Name	Mod.	#C	#Bikes	# Couriers CV	# Couriers IC	Total Costs	CV Costs σ_b^F	CV Costs γ_b^F	CV Costs ζ_b^O	IC Costs θ_a^O
S1	12-R1-A2	I	1	23	51	43	693	60	23	266	344
	12-R1-A2	II	2	27	61	33	666	120	27	255	264
	12-R2-A2	I	1	26	61	33	708	60	26	358	264
	12-R2-A2	II	2	28	66	28	679	120	28	307	224
	12-R3-A2	I	1	25	59	35	726	60	25	361	280
	12-R3-A2	II	2	29	64	30	695	120	29	306	240
	Avg		**1.5**	**26.3**	**60.3**	**33.7**	**694.5**	**90**	**26.3**	**308.8**	**269.3**
S2	12-R1-A2	I	1	18	43	51	725	60	18	239	408
	12-R1-A2	II	3	29	66	28	699	180	29	266	224
	12-R2-A2	I	1	17	40	54	751	60	17	242	432
	12-R2-A2	II	2	28	65	29	693	120	28	313	232
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	3	29	67	27	716	180	29	291	216
	Avg		**1.7**	**20.2**	**46.8**	**47.2**	**722.7**	**100**	**20.2**	**225.2**	**377.3**
S3	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	2	23	54	40	742	120	23	279	230
	12-R2-A2	I	0	0	0	94	752	0	0	0	752
	12-R2-A2	II	3	29	65	29	738	180	29	297	232
	12-R3-A2	I/II	0	0	0	94	752	0	0	0	752
	Avg		**0.8**	**8.7**	**19.8**	**74.2**	**748**	**50**	**8.7**	**96**	**578.3**

Table 5 summarises the results. The notation 'I/II' in the table indicates identical results for both Model I and Model II. Similarly, '12-R1/2/3-A2' denotes identical results for instances R1, R2, and R3 with a 12x12 grid and accessibility level A2. This notation is used consistently throughout subsequent tables to concisely present results across multiple scenarios.

The results in Table 5 highlight the significant impact of restaurant distribution on the strategic placement and operational efficiency of logistics centers for on-demand food delivery platforms. As restaurants become more dispersed across the city, platforms should shift towards greater reliance on independent contractors (IC) rather than the company-vehicle model (CV).

In densely concentrated urban cores (S1), a balanced mix of CV and IC couriers is most cost-effective. However, as restaurant locations spread out (S2 and S3), the optimal strategy increasingly favors IC ones, with the average number of IC couriers rising from 33.7 in S1 to 47.2 in S2, and further to 74.3 in S3. This shift suggests it is challenging to manage CV resources with a widely dispersed restaurant network and the IC model offers more flexibility to cover a wider geographic area efficiently. The results also show that the decentralization of restaurants leads to higher operational costs - from 694.5 euros in the concentrated scenario to 748 euros in the dispersed scenario. This cost increase stems from the reduced efficiency in serving a widespread network.

These findings indicate platforms should assess their specific urban environment and restaurant distribution when determining the optimal logistics strategy. It suggests that in compact cities with centralized dining districts, investing in company vehicles and logistics centers can be beneficial. However, in cities with widely distributed restaurants, prioritizing a flexible IC workforce is likely to be more cost-effective.

To examine how the spatial relationship between restaurant-dense and customer-dense areas impacts logistics center viability, we designed scenarios simulating various distances between them. These areas represent zones where couriers are likely to start and end their deliveries, respectively, reflecting overall movement patterns across a city during work periods. In these scenarios, restaurants are consistently located within the inner 20% of the city center, while the distribution of residential areas varies to simulate different distances. Scenario D1 represents a compact city with short distances between restaurant and customer areas with residential areas situated 20-40% from the city center. In Scenario D2, they are located 40-60% from the center, and in Scenario D3, they are spread 80-100% from the center, to depict a moderately separated structure and a dispersed layout with significant distance between these zones respectively.

Table 6: Comparison of Scenarios for 12x12 Network under Different City Layouts

Scen.	Name	Mod.	#C	#Bikes	# Couriers		Total	CV Costs			IC Costs
					CV	IC	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
D1	12-R1-A2	I	1	28	62	32	659	60	28	315	256
	12-R1-A2	II	2	27	63	31	631	120	27	236	248
	12-R2-A2	I	1	28	68	26	646	60	28	346	208
	12-R2-A2	II	2	30	67	27	607	120	30	241	216
	12-R3-A2	I	1	25	56	38	672	60	25	283	304
	12-R3-A2	II	2	26	61	33	638	120	26	228	264
	Avg		**1.5**	**27.3**	**62.8**	**31.2**	**642.2**	**90**	**27.3**	**274.8**	**249.3**
D2	12-R1-A2	I	1	22	52	42	722	60	22	304	336
	12-R1-A2	II	2	24	55	39	695	120	24	239	312
	12-R2-A2	I	1	21	51	43	728	60	21	303	344
	12-R2-A2	II	2	26	60	34	689	120	26	271	272
	12-R3-A2	I	1	27	63	31	718	60	27	383	248
	12-R3-A2	II	3	30	67	27	693	180	30	267	216
	Avg		**1.7**	**25**	**58**	**36**	**707.5**	**100**	**25**	**294.5**	**288**
D3	12-R1/2/3-A2	I/II	0	0	0	94	752	0	0	0	752
	Avg		**0**	**0**	**0**	**0**	**94**	**752**	**0**	**0**	**752**

The results presented in Table 6 demonstrate that as the distance between couriers' starting points (restaurant clusters) and ending points (residential areas) increases from Scenario D1 to D3, the IC model becomes more cost-effective. This is evident in the decrease of CV couriers from an average of 62.8 in D1 to 0 in D3, with total costs correspondingly increasing from 642.2 euros to 752 euros. The shift towards IC couriers in dispersed urban layouts highlights the high costs of repositioning CV couriers and company vehicles over longer distances.

These findings have practical implications for meal delivery platforms to tailor their delivery strategies to the specific urban structure they operate. In compact cities, a hybrid model using both CV and IC couriers can optimize cost efficiency. However, in urban areas with distinct, widely separated commercial and residential zones, the flexibility of IC couriers becomes crucial.

5.5. Economic Impact on Delivery Strategies

The cost structure in urban delivery operations plays a crucial role in determining the optimal mix between CV and IC couriers, as well as the necessity of logistics centers. To evaluate this, we modeled five economic scenarios as shown in Table 7. Scenario C0 serves as our baseline, with facility costs of 60 €/day and IC compensation of 8 €/person. Scenarios C1 and C2 explore the effects of doubling (120 €/day) and halving (30 €/day) facility costs respectively, simulating high-rent urban centers versus more affordable areas with lower real estate prices. Scenarios C3 and C4 examine a 25% increase (10 €/person) and decrease (6 €/person) in IC compensation, representing markets with stronger gig worker bargaining power versus those with an excess supply of workers. These scenarios allow us to assess how changes in cost dynamics influence delivery strategies in different urban environments and economic conditions.

Table 7: Scenarios Settings with Different Costs.

Scenario	Facility Costs C_i^F (€/day)	%Change	IC Allowance C_a^O (€/day)	%Change
C0	60	–	8	–
C1	120	+100%	8	–
C2	30	-50%	8	–
C3	60	–	10	+25%
C4	60	–	6	-25%

The results in Table 8 demonstrate how varying economic conditions influence delivery strategies. In scenarios with high infrastructure costs (C1) or low IC compensation (C4), the model suggests a shift towards greater reliance on IC couriers. For instance, in C1, where facility costs double, the average number of IC couriers increases from 34 in C0 to 84, and the CV model becomes economically unfeasible. Similarly, in C4, where IC compensation decreases, the model exclusively employs IC couriers and the need for CV couriers drops entirely. Conversely, low facility costs (C2) favor more use of company resources, with the average number of centers increasing from 1.5 to 2.2, accompanied by a small rise in CV couriers from 60 to 62. Also, higher IC compensation (C3) leans towards CV model, increasing CV couriers from 60 in C0 to 63. These patterns demonstrate the platform's ability to optimize resource allocation between CVs and ICs in response to varying economic conditions.

Table 8: Comparison of Scenarios for 12x12 Network under Different Conditions

Scen.	Name	Mod.	#C	#Bikes	# Couriers		Total	CV Costs			IC Costs
					CV	IC	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
C0	12-R1-A2	I	1	23	51	43	693	60	23	266	344
	12-R1-A2	II	2	27	61	33	666	120	27	255	264
	12-R2-A2	I	1	26	61	33	708	60	26	358	264
	12-R2-A2	II	2	28	66	28	679	120	28	307	224
	12-R3-A2	I	1	25	59	35	726	60	25	361	280
	12-R3-A2	II	2	29	64	30	695	120	29	306	240
	Avg		**1.5**	**26.3**	**60.3**	**33.7**	**694.5**	**90**	**26.3**	**308.8**	**269.3**
C1	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	1	26	59	35	745	120	26	319	208
	12-R2/3-A2	I/II	0	0	0	94	752	0	0	0	752
	Avg		**0.2**	**4.3**	**9.8**	**84.2**	**750.8**	**20.0**	**4.3**	**53.2**	**661.3**
C2	12-R1-A2	I	2	26	55	39	662	60	26	264	312
	12-R1-A2	II	3	27	60	34	603	90	27	214	272
	12-R2-A2	I	1	26	61	33	678	30	26	358	264
	12-R2-A2	II	3	30	67	27	610	90	30	274	216
	12-R3-A2	I	1	25	64	35	699	30	25	326	248
	12-R3-A2	II	3	30	65	29	616	90	30	264	232
	Avg		**2.2**	**27.3**	**62.0**	**32.8**	**644.7**	**65**	**27.3**	**283.3**	**257.3**
C3	12-R1-A2	I	1	26	57	37	773	60	26	317	370
	12-R1-A2	II	2	27	61	33	732	120	27	255	330
	12-R2-A2	I	1	29	66	28	767	60	29	398	280
	12-R2-A2	II	2	30	67	27	738	120	30	318	270
	12-R3-A2	I	1	28	62	32	797	60	28	389	320
	12-R3-A2	II	2	30	65	29	755	120	30	315	290
	Avg		**1.5**	**28.3**	**63.0**	**31.0**	**760.3**	**90**	**28.3**	**332.0**	**310.0**
C4	12-R1/2/3-A2	I/II	0	0	0	94	564	0	0	0	564
	Avg		**0**	**0**	**0**	**94**	**564**	**0**	**0**	**0**	**564**

5.6. Evaluation of Vehicle Type Influence on Delivery Model Efficiency

To evaluate the impact of vehicle types on delivery model efficiency, we tested five scenarios, each representing a different transportation mode, as detailed in Table 9. Scenario T0 uses e-bikes as the baseline, with a speed of 15-16 km/h, serving as a reference point for both speed and cost. Scenario T1 introduces standard bicycles, which are slower at 12-13 km/h but more economical. Scenario T2 examines even slower bicycles at around 10 km/h, suitable for congested areas. Scenarios T3 and T4 involve faster scooters, offering higher speeds of 21-22 km/h at increased costs. Unit travel time reflects travel duration between adjacent zones, varying with vehicle speed. This results in an increase to 0.072 hours for T1, 0.09 (h) for T2, and a decrease to 0.042 (h) for both T3 and T4, compared to the baseline of 0.06 hours in T0. Purchasing costs (C_b^F) represent daily vehicle depreciation. These scenarios help identify how vehicle choice affects delivery strategy, particularly in optimizing costs and efficiency.

Table 9: Scenarios Settings with Different Modes.

Scenario	Unit Travel Time (h)	%Changes	Purchasing Costs C_b^F (€/day)	%Changes
T0	0.06	–	1	–
T1	0.072	+ 20%	0.5	- 50%
T2	0.09	+ 50%	0.5	- 50%
T3	0.042	- 30%	4	+ 300%
T4	0.042	- 30%	8	+ 700%

Table 10 demonstrates the impact of vehicle speed and cost on the efficiency and cost-effectiveness

Table 10: Comparison of Scenarios for 12x12 Network under Different Transport Modes

Scen.	Name	Mod.	#C	# Bikes	# Couriers CV	# Couriers IC	Total Costs	CV Costs σ_b^F	CV Costs γ_b^F	CV Costs ζ_b^O	IC Costs θ_a^O
T0	12-R1-A2	I	1	23	51	43	693	60	23	266	344
	12-R1-A2	II	2	27	61	33	666	120	27	255	264
	12-R2-A2	I	1	26	61	33	708	60	26	358	264
	12-R2-A2	II	2	28	66	28	679	120	28	307	224
	12-R3-A2	I	1	25	59	35	726	60	25	361	280
	12-R3-A2	II	2	29	64	30	695	120	29	306	240
	Avg		**1.5**	**26.3**	**60.3**	**33.7**	**694.5**	**90**	**26.3**	**308.8**	**269.3**
T1	12-R1-A2	I	0	0	0	94	752	0	0	0	752
	12-R1-A2	II	2	27	61	33	702.5	120	13.5	305	264
	12-R2-A2	I	1	19	38	56	749.5	60	9.5	232	448
	12-R2-A2	II	2	26	61	33	732	120	13	335	264
	12-R3-A2	I	0	0	0	94	752	0	0	0	752
	12-R3-A2	II	2	24	51	43	737	120	12	261	344
	Avg		**1.2**	**16.0**	**35.2**	**58.8**	**737.5**	**70.0**	**8.0**	**188.8**	**470.7**
T2	12-R1/2/3-A2	I/II	0	0	0	94	752	0	0	0	752
	Avg		**0**	**0**	**0**	**94**	**752**	**0**	**0**	**0**	**752**
T3	12-R1-A2	I	1	24	54	40	682	60	96	206	320
	12-R1-A2	II	1	26	61	33	665	60	104	237	264
	12-R2-A2	I	1	28	64	30	680	60	112	268	240
	12-R2-A2	II	2	28	66	28	673	120	112	217	224
	12-R3-A2	I	1	26	63	31	689	60	104	277	248
	12-R3-A2	II	2	28	64	30	689	120	112	217	240
	Avg		**1.3**	**26.7**	**62.0**	**32.0**	**679.7**	**80.0**	**106.7**	**237.0**	**256.0**
T4	12-R1/2/3-A2	I/II	0	0	0	94	752	0	0	0	752
	Avg		**0**	**0**	**0**	**94**	**752**	**0**	**0**	**0**	**752**

of delivery models. Scenario T0 (e-bikes) serves as the baseline with an average total cost of 694.5 euros, using a balanced mix of 60.3 CV couriers and 33.7 IC couriers. In contrast, switching to slower vehicles like standard bicycles in Scenario T1 increases costs to 737.5 euros, and Scenario T2 further raises costs to 752 euros, reflecting inefficiencies from reduced speed and a shift toward IC couriers over CV models.

In Scenario T3, the use of faster scooters reduces the average total cost to 679.7 euros, demonstrating that increased speed can offset higher vehicle costs and enhance efficiency without increasing overall expenses. This balance suggests that the right choice of faster modes can improve service quality while maintaining cost-effectiveness. However, Scenario T4 reveals a tipping point where the benefits of speed are outweighed by vehicle costs. Despite their speed, the premium scooters in T4 lead to higher total costs (752 euros), driving a shift towards IC couriers over company-owned fleets. This outcome indicates that while faster vehicles can improve operational efficiency, there's a critical threshold beyond which expensive equipment becomes less cost-effective.

The analysis indicates that there is a critical balance between speed and cost, and the choice of vehicle type must be carefully considered to optimize delivery strategies, particularly in high labor cost markets.

5.7. Case Study: Amsterdam City

This case study applies the proposed models to optimize the planning of logistics centers in Amsterdam, using historical data from an ODFD operator. We aim to explore center planning in a mature market with well-developed public transportation, investigating the trade-off between zone accessibility and costs. Also, by visualizing results on an Amsterdam map, we demonstrate our model's applicability to complex urban environments and examine the impact of different operational policies on delivery choices and center placement.

The study focuses on the meal delivery period from 10:00 AM to 11:00 PM, aligning with the main operational hours in Amsterdam. Initial courier locations are weighted by demand in high-order zones, while delivery destinations reflect historical trends of customer clusters. By analyzing courier start times, shift patterns, and destination distributions, we determined the number of couriers operating in each zone and time slot, as well as their expected shift duration and destinations.

The city of Amsterdam is spatially divided into 415 hexagonal zones using the h3 spatial index, allowing for detailed analysis. Accessibility scores for each zone are calculated based on the public transportation network, which includes 15 tram lines (139 stations), 5 metro lines (11 stations), 81 bus lines (893 stations, counting bidirectional stops separately), and 4 train lines (13 stations). Data for the public transportation network were sourced from the Amsterdam municipality website and OpenStreetMap API. These scores were computed using Equation (3), and Figure 6 illustrates the resulting accessibility scores across Amsterdam.

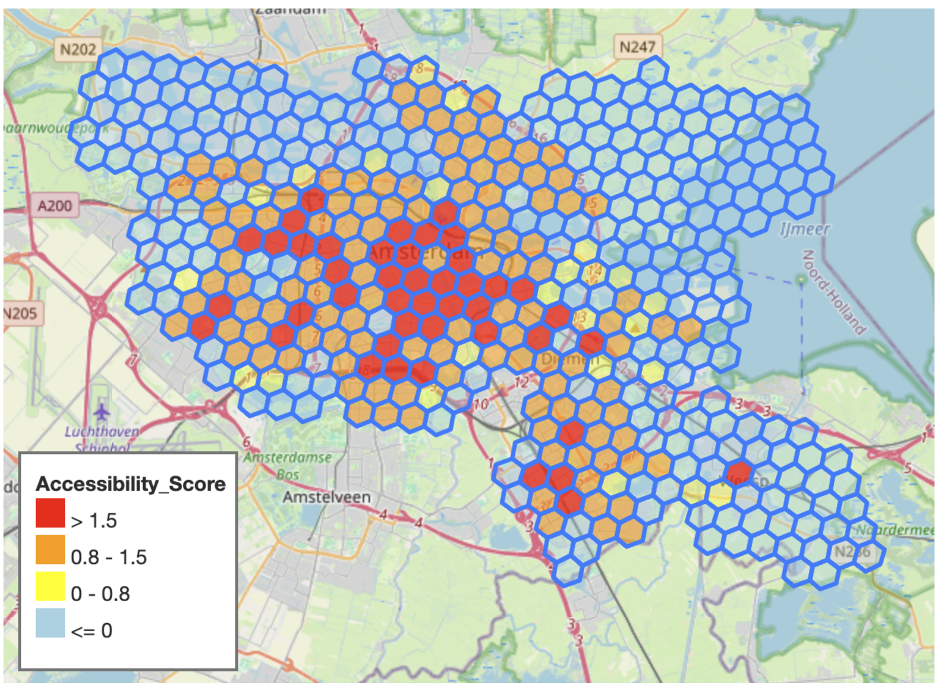


Figure 6: Accessibility Score of Amsterdam City

Table 11 presents the number of potential logistics center locations that meet the accessibility criteria under varying threshold levels. As the threshold decreases, more zones qualify as candidate locations, indicating a broader range of accessible areas suitable for establishing logistics centers.

Table 11: Different accessibility thresholds and the corresponding candidate locations

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

We consider a planning horizon of 5 years (1825 days). For all locations, we estimate the construction or leasing cost of a company-owned center at 25,000 euros per year, resulting in a daily cost of approximately 69 euros (C_i^F). We also consider the purchasing cost for company-owned e-bikes (C_b^F) at 1 euro per day, based on a total of 900 euros for purchasing and maintaining a bicycle over 5 years. The hourly wage for both types of couriers (C_h^O) is assumed to be 15 euros[1], with an additional bicycle allowance (C_a^O) of 13 euros per day for independent contractors (IC). The estimated parameters are summarized in Table 12.

Table 12: Value of the parameters for Amsterdam Case.

Parameters	Value	Remark
C_i^F	69 (€/day)	Costs of locating a center in any zone per day
C_b^F	1 (€/e-bike/day)	Depreciation costs for each e-bike per day
C_h^O	15 (€/hour)	Couriers' basic hourly salary
C_a^O	13 (€/person)	Allowance for IC couriers
TT_{ij}	0.06 (hour)	For traveling between adjacent zones $(i, j) \in A$
TT_{ij}	Shortest path	For non-adjacent zones i and j
$\|P\|$	3	Maximum centers allowed

Table 13 compares the performance of Model I and Model II in determining the optimal logistics center locations in Amsterdam under various accessibility thresholds. Both models indicate the necessity of establishing multiple logistics centers within the city, given the scale and distribution of demand. However, Model II consistently outperforms Model I, achieving a 15% reduction (indicated in 'Cost Red.' column) in total operational costs across all accessibility thresholds tested. For example, under an accessibility threshold of 2.8, Model II reduces total costs from 2474 euros (Model I) to 2104 euros while maintaining the same level of service (100% CSR with 222 CV couriers and 49 IC couriers). This cost reduction is primarily driven by the ability of Model II to adjust service coverage in response to temporal fluctuations in courier start and end locations, optimizing the use of CV and IC couriers.

Table 13: Results of Amsterdam Case Using Model I and II

Access.	Mod.	#C	#Bikes	# Couriers			Total	Cost
Threshold				CV	IC	CSR	Costs	Red.
1.3	I	3	119	222	49	100%	2458	–
	II	3	119	222	49	100%	2096	15%
2.2	I	3	119	222	49	100%	2458	–
	II	3	119	222	49	100%	2096	15%
2.8	I	3	119	222	49	100%	2474	–
	II	3	119	222	49	100%	2104	15%

Figures 7 and 8 depict the optimized logistics center placements and coverage areas for Model I and Model II respectively. The coverage refers to zones where CV couriers start their first

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

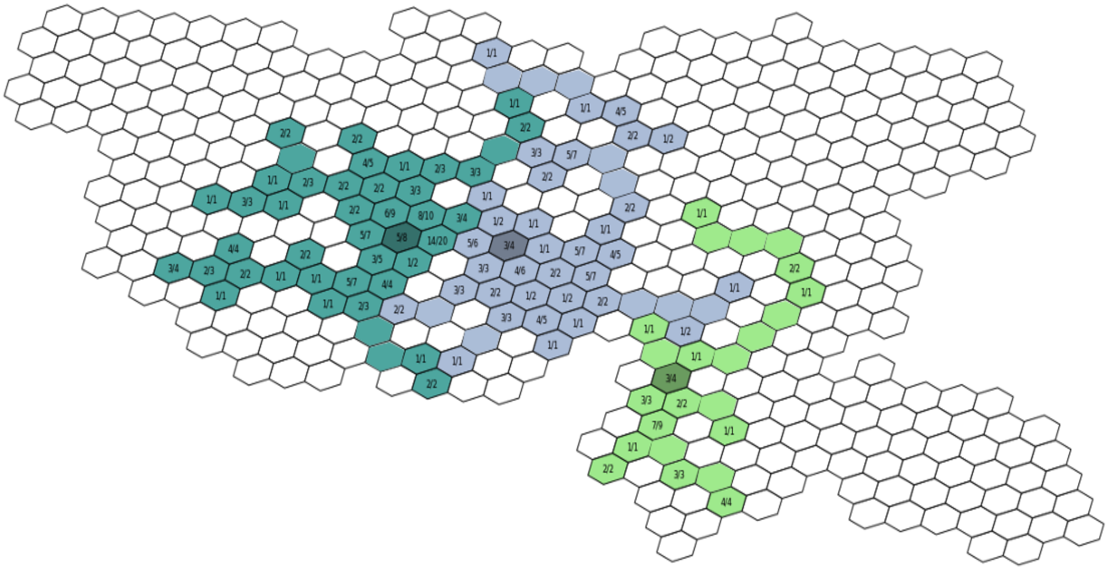
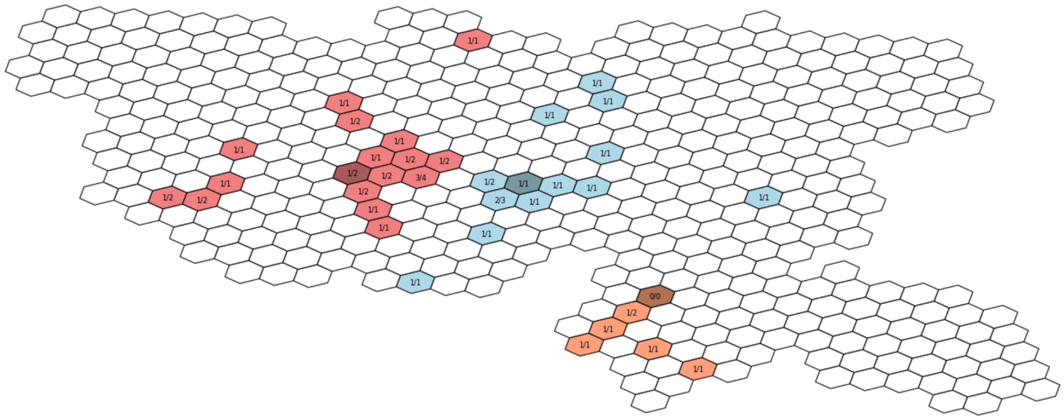


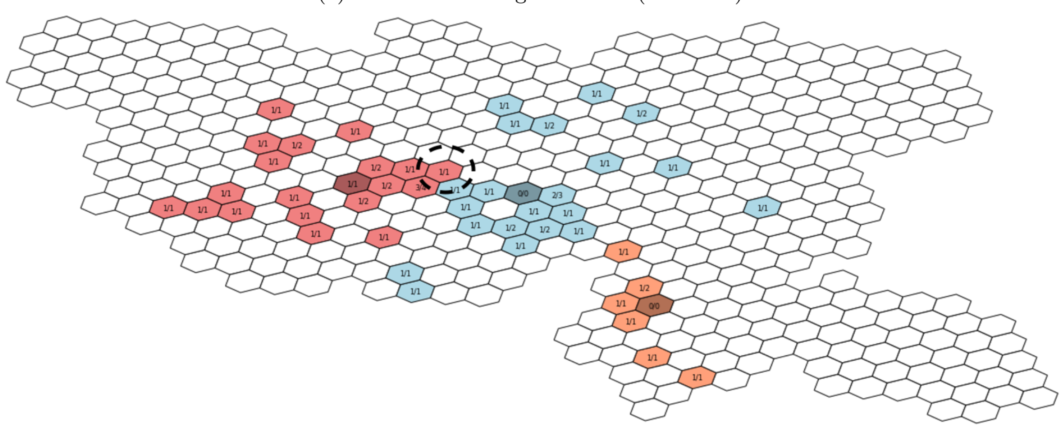
Figure 7: Illustration of Model I result on Amsterdam case

deliveries, reflecting CV courier demand distribution. Different colors represent various centers and their service areas, with darker shades marking center locations and lighter shades showing coverage. Zone labels display CV courier numbers versus total couriers starting there. Figure 7 illustrates Model I's fixed coverage, where zone-to-center allocation remains constant. Labels show aggregate CV and total courier numbers over the entire period. Figure 8 demonstrates Model II's time-variant coverage at three times (11:00 AM, 16:00 PM, 17:00 PM), showing how coverage adapts to dynamic demands. Labels indicate the CV to total courier ratio ($S_i^\tau/\tilde{S}_i^\tau$) at each specific time. Furthermore, the time-variant nature of Model II is evident in the highlighted zone with a black dash circle. At Time 7, it's within the coverage of the red center on the left and CV couriers starting their shifts in this zone at this time will use vehicles from the red center. While at Time 8, the same zone is now covered by the blue center in the middle. This illustrates how Model II adjusts coverage dynamically to optimize resource allocation based on temporal demand changes.

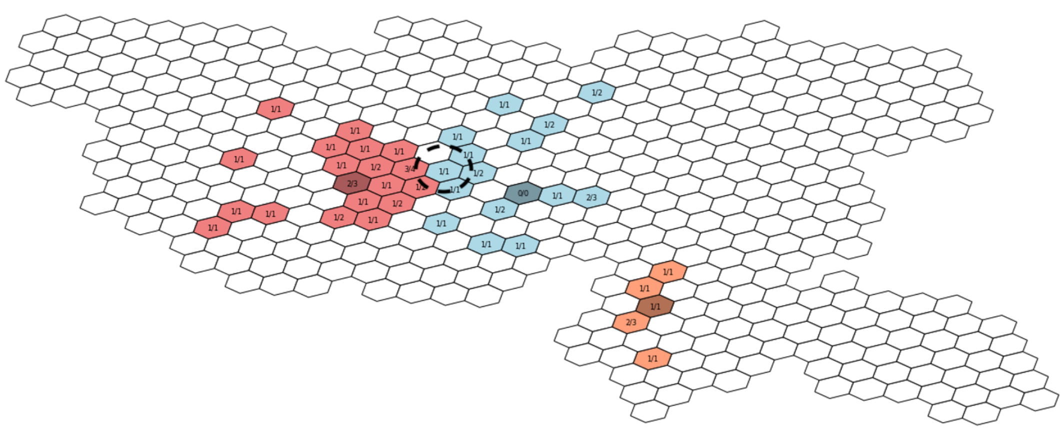
The results presented in Table 14 demonstrate how varying accessibility thresholds impact operational costs in the Amsterdam case study. As the accessibility threshold increases from 0.2 to 2.8, there is a gradual rise in total costs, from 2440 euros at the lowest threshold to 2474 euros at the highest threshold, reflecting a 1.4% increase, as indicated in the 'Cost Inc.' column. This is primarily driven by the increased operational costs associated with repositioning CV couriers and vehicles depending on center locations. The modest cost increase despite significant changes in accessibility thresholds is related to an alignment between high-accessibility areas and courier activity hotspots. Zones with high accessibility scores often result from public transportation hubs and multi-modal stations within them. These areas typically feature business districts and



(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 8: Model II results at different times of Amsterdam case

restaurant clusters, where couriers are more likely to start their delivery shifts. As a result, the optimal locations for logistics centers tend to concentrate within a limited set of highly accessible candidate locations, regardless of the specific threshold chosen.

Higher accessibility thresholds improve convenience for couriers by making it easier for a larger population to commute between their homes and the centers. Our results suggest that investing in more accessible center locations may enhance courier efficiency and satisfaction with a minimal impact on overall operational costs in a city with well-developed public transportation. The platform can choose the best options from an already optimized set of locations, allowing them to prioritize courier convenience by investing only marginally more in highly accessible areas.

Table 14: Results of Amsterdam Case Under Different Accessibility Requirements

Access. Threshold	**Mod.**	**#C**	**#Bikes**	**# Couriers**		**Total Costs**	**Cost Inc.**
				CV	**IC**		
0.2	I	3	119	222	49	2440	–
1.08	I	3	119	222	49	2440	–
1.12	I	3	119	222	49	2440	–
1.2	I	3	119	222	49	2442	0.08%
1.3	I	3	119	222	49	2458	0.74%
1.7	I	3	119	222	49	2458	0.74%
2.2	I	3	119	222	49	2458	0.74%
2.8	I	3	119	222	49	2474	1.39%

In this part, we illustrate the strategic advantage of adopting a more flexible approach (indicated by Model II) to logistics center management in terms of cost optimisation. Furthermore, highly accessible areas for logistics centers can provide a robust solution that balances operational efficiency with courier satisfaction. And while higher accessibility thresholds do lead to slightly increased costs, the benefits in terms of courier convenience and potential long-term operational efficiency likely outweigh these modest additional expenses.

6. Conclusion

This study develops a framework for optimizing micro-logistics centers in on-demand meal delivery services, offering insights into the strategic planning of delivery models and center locations. Independent contractor (IC) model are shown to be cost-effective in scenarios with sparse markets, low IC allowances, high real estate costs, and widely dispersed restaurant or residential areas. In contrast, dense urban environments benefit from a hybrid delivery model that combines company-owned vehicles (CV) with strategically located logistics centers for optimal cost efficiency.

The choice of logistics center locations depends on courier activity patterns and accessibility requirements. Operational strategies should align with the geographic and temporal characteristics of the market. Model I with strict geographic continuity is suitable for stable markets, while Model II with a flexible operational policy that adapts to fluctuating courier distributions can reduce operational costs in more variable environments.

Future research could consider the facility cost variations based on fleet size and explore buffer capacity implications in flexible return scenarios to have more nuanced decision-making regarding costs for space, charging infrastructure, and other facilities within centers. Additionally, relaxing the assumption of balance after each day's operations and exploring inter-center vehicle repositioning could lead to potential cost savings and more efficient resource utilization across the network in response to spatial-temporal imbalances in courier activity. Currently, the model uses deterministic inputs and an additional important direction for future research would be to incorporate stochastic data into the model to handle real-world uncertainties in food delivery operations.

Appendix

Table 15: 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	$A = \{(i,j) \mid i,j \in I$, 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 16: 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 17: Computation Process of the test instances

Model	Ins. Name	Time(s)	In. Sol.	In. Bound	Best Sol.	Best Bound	# Node	Gap(%)
I	6-R-A1	0.1	288.0	135.0	264.4	264.3	1	0.0
	6-U-A1	0.1	288.0	130.6	261.2	261.2	1	0.0
	6-C-A1	0.1	288.0	118.7	242.8	242.8	1	0.0
	Avg.	**0.1**	**288.0**	**128.1**	**256.1**	**256.1**	**1.0**	**0.0**
	6-R-A2	0.6	288.0	135.0	264.3	264.3	64	0.0
	6-U-A2	1.2	288.0	130.2	261.2	261.2	21	0.0
	6-C-A2	0.5	288.0	118.7	242.8	242.8	72	0.0
	Avg.	**0.8**	**288.0**	**128.0**	**256.1**	**256.1**	**52.3**	**0.0**
	6-R-A3	1.8	288.0	135.0	264.3	264.3	467	0.0
	6-U-A3	2.1	288.0	130.1	261.2	261.2	342	0.0
	6-C-A3	0.9	288.0	118.7	242.8	242.8	343	0.0
	Avg.	**1.6**	**288.0**	**127.9**	**256.1**	**256.1**	**384.0**	**0.0**
II	6-R-A1	0.3	288.0	167.3	263.9	263.9	12	0.0
	6-U-A1	0.3	288.0	157.1	261.2	261.2	13	0.0
	6-C-A1	0.2	288.0	151.7	242.8	242.8	13	0.0
	Avg.	**0.3**	**288.0**	**158.7**	**256.0**	**256.0**	**12.7**	**0.0**
	6-R-A2	1.8	288.0	167.3	263.9	263.9	111	0.0
	6-U-A2	1.3	288.0	157.1	261.2	261.2	111	0.0
	6-C-A2	1.7	288.0	151.7	242.8	242.8	76	0.0
	Avg.	**1.6**	**288.0**	**158.7**	**256.0**	**256.0**	**99.3**	**0.0**
	6-R-A3	4.2	288.0	167.3	263.9	263.9	291	0.0
	6-U-A3	3.2	288.0	157.1	261.2	261.2	259	0.0
	6-C-A3	3.2	288.0	151.7	242.8	242.8	216	0.0
	Avg.	**3.5**	**288.0**	**158.7**	**256.0**	**256.0**	**255.3**	**0.0**
I	9-R-A1	1.9	640.0	271.4	630.8	630.8	146	0.0
	9-U-A1	3.1	640.0	268.8	622.8	622.8	129	0.0
	9-C-A1	2.9	640.0	269.6	587.2	587.2	171	0.0
	Avg.	**2.6**	**640.0**	**269.9**	**613.6**	**613.6**	**148.7**	**0.0**
	9-R-A2	208.4	640.0	271.4	628.7	628.7	33859	0.0
	9-U-A2	114.0	640.0	268.8	622.8	622.8	33169	0.0
	9-C-A2	28.6	640.0	269.6	587.2	587.2	4648	0.0
	Avg.	**117.0**	**640.0**	**269.9**	**612.9**	**612.9**	**23892.0**	**0.0**
	9-R-A3	96.2	640.0	271.3	628.7	628.7	2350	0.0
	9-U-A3	241.9	640.0	268.8	622.8	622.7	2470	0.0
	9-C-A3	127.1	640.0	269.6	587.2	587.1	1757	0.0
	Avg.	**155.1**	**640.0**	**269.9**	**612.9**	**612.8**	**2192.3**	**0.0**
II	9-R-A1	9.0	640.0	306.5	630.8	630.8	186	0.0
	9-U-A1	11.7	640.0	299.3	621.1	621.1	189	0.0
	9-C-A1	12.4	640.0	306.1	586.9	586.9	188	0.0
	Avg.	**11.0**	**640.0**	**304.0**	**612.9**	**612.9**	**187.7**	**0.0**
	9-R-A2	56.0	640.0	306.5	614.7	614.7	2903	0.0
	9-U-A2	59.9	640.0	299.3	601.4	601.4	3334	0.0
	9-C-A2	92.5	640.0	306.1	583.4	583.4	4379	0.0
	Avg.	**69.5**	**640.0**	**304.0**	**599.8**	**599.8**	**3538.7**	**0.0**
	9-R-A3	465.9	640.0	306.5	614.3	614.3	4036	0.0
	9-U-A3	644.5	640.0	299.3	594.7	594.7	10311	0.0
	9-C-A3	377.6	640.0	306.1	583.4	583.4	22424	0.0
	Avg.	**496.0**	**640.0**	**304.0**	**597.5**	**597.5**	**12257.0**	**0.0**
I	12-R-A1	14.5	1152.0	449.4	1152.0	1152.0	937	0.0
	12-U-A1	21.5	1152.0	430.2	1152.0	1152.0	937	0.0
	12-C-A1	19.0	1152.0	448.3	1143.7	1143.7	939	0.0
	Avg.	**18.3**	**1152.0**	**442.6**	**1149.2**	**1149.2**	**937.7**	**0.0**
	12-R-A2	1001.6	1152.0	449.4	1152.0	1152.0	56010	0.0
	12-U-A2	886.6	1152.0	430.2	1152.0	1152.0	56035	0.0
	12-C-A2	747.7	1152.0	448.2	1143.7	1143.7	58367	0.0
	Avg.	**878.6**	**1152.0**	**442.6**	**1149.2**	**1149.2**	**56804.0**	**0.0**

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Table 17 – *Continued from previous page*

Model	Ins. Name	Time(s)	In. Sol.	In. Bound	Best Sol.	Best Bound	# Node	Gap(%)
	12-R-A3	4614.9	1152.0	485.7	1152.0	1152.0	684204	0.0
	12-U-A3	3738.5	1152.0	462.0	1152.0	1152.0	245510	0.0
	12-C-A3	10402.5	1152.0	484.6	1143.7	1143.7	1386715	0.0
	Avg.	**6252.0**	**1152.0**	**477.4**	**1149.2**	**1149.2**	**772143.0**	**0.0**
II	12-R-A1	41.2	1152.0	477.9	1142.8	1142.8	945	0.0
	12-U-A1	66.0	1152.0	461.2	1147.9	1147.9	942	0.0
	12-C-A1	49.6	1152.0	483.8	1105.5	1105.5	948	0.0
	Avg.	**52.3**	**1152.0**	**474.3**	**1132.1**	**1132.1**	**945.0**	**0.0**
	12-R-A2	1501.5	1152.0	477.9	1083.4	1083.4	6365	0.0
	12-U-A2	1882.7	1152.0	461.2	1084.7	1084.7	7945	0.0
	12-C-A2	1336.8	1152.0	483.8	1041.1	1041.1	8823	0.0
	Avg.	**1573.7**	**1152.0**	**474.3**	**1069.7**	**1069.7**	**7711.0**	**0.0**
	12-R-A3	7134.2	1152.0	477.9	1062.5	1062.5	47522	0.0
	12-U-A3	4833.6	1152.0	461.2	1078.3	1078.3	39456	0.0
	12-C-A3	5652.1	1152.0	483.8	1041.1	1041.1	41646	0.0
	Avg.	**5873.3**	**1152.0**	**474.3**	**1060.6**	**1060.6**	**42874.7**	**0.0**
I	15-R-A1	44.0	1792.0	647.4	1792.0	1792.0	3586	0.0
	15-U-A1	36.4	1792.0	700.3	1792.0	1792.0	3583	0.0
	15-C-A1	63.8	1792.0	647.8	1792.0	1792.0	3567	0.0
	Avg.	**48.1**	**1792.0**	**665.2**	**1792.0**	**1792.0**	**3578.7**	**0.0**
	15-R-A2	2942.7	1792.0	681.1	1792.0	1792.0	123625	0.0
	15-U-A2	9339.5	1792.0	732.7	1792.0	1792.0	156656	0.0
	15-C-A2	13777.0	1792.0	719.0	1783.6	1783.6	527601	0.0
	Avg.	**8686.4**	**1792.0**	**710.9**	**1789.2**	**1789.2**	**269294.0**	**0.0**
	15-R-A3	28820.1	1792.0	680.7	1792.0	801.0	352282	55.3
	15-U-A3	28813.4	1792.0	732.4	1792.0	851.8	97599	52.5
	15-C-A3	28802.6	1792.0	679.7	1792.0	740.3	21060	58.7
	Avg.	**28812.0**	**1792.0**	**697.6**	**1792.0**	**797.7**	**156980.3**	**55.5**
II	15-R-A1	360.2	1792.0	680.2	1792.0	1792.0	3587	0.0
	15-U-A1	316.3	1792.0	717.0	1792.0	1792.0	3587	0.0
	15-C-A1	386.0	1792.0	679.1	1783.2	1783.2	3621	0.0
	Avg.	**354.2**	**1792.0**	**692.1**	**1789.1**	**1789.1**	**3598.3**	**0.0**
	15-R-A2	28808.3	1792.0	680.2	1759.3	1073.0	2942	39.0
	15-U-A2	28802.5	1792.0	717.0	1757.7	1056.6	3054	39.9
	15-C-A2	28814.6	1792.0	679.1	1706.0	1213.0	5325	28.9
	Avg.	**28808.5**	**1792.0**	**692.1**	**1741.0**	**1114.2**	**3773.7**	**35.9**
	15-R-A3	28800.8	1792.0	680.2	1743.3	1343.6	51705	22.9
	15-U-A3	28803.1	1792.0	717.0	1759.4	1095.3	2736	37.7
	15-C-A3	28806.7	1792.0	679.1	1700.0	1157.0	3093	31.9
	Avg.	**28803.5**	**1792.0**	**692.1**	**1734.2**	**1198.6**	**19178.0**	**30.8**

Table 18: Comparison of Scenarios for 12x12 Network (Model I and Model II)

Scen.	**Name**	**Mod.**	**#C**	**#Bikes**	# Couriers			Total	CV Costs			IC Costs
					CV	IC	CSR	Costs	σ_b^F	γ_b^F	ζ_b^O	θ_a^O
M0	12-R1-A1/2/3	I	0	0	0	48	0.0	384	0	0	0	384
	12-R1-A1/2/3	II	0	0	0	48	0.0	384	0	0	0	384
	12-R2-A1/2/3	I	0	0	0	48	0.0	384	0	0	0	384
	12-R2-A1/2/3	II	0	0	0	48	0.0	384	0	0	0	384
	12-R3-A1/2/3	I	0	0	0	48	0.0	384	0	0	0	384
	12-R3-A1/2/3	II	0	0	0	48	0.0	384	0	0	0	384
M1	12-R1-A1/2/3	I	0	0	0	144	0.0	1152	0	0	0	1152
	12-R1-A1	II	0	0	0	144	0.0	1152	0	0	0	1152
	12-R1-A2	II	3	41	89	55	89%	1097	180	41	436	440
	12-R1-A3	II	3	42	89	55	89%	1089	180	42	427	440
	12-R2-A1/2/3	I	0	0	0	144	0.0	1152	0	0	0	1152
	12-R2-A1	II	2	33	73	71	73%	1146	120	33	425	568
	12-R2-A2	II	3	45	98	46	98%	1080	180	45	487	368
	12-R2-A3	II	3	43	97	47	97%	1064	180	43	465	376
	12-R3-A1/2/3	I	0	0	0	144	0.0	1152	0	0	0	1152
	12-R3-A1	II	0	0	0	144	0.0	1152	0	0	0	1152
	12-R3-A2	II	3	41	95	49	95%	1107	180	41	494	392
	12-R3-A3	II	3	40	92	52	92%	1088	180	40	452	416
M2	12-R1-A1/2/3	I	1	21	47	143	35.6%	1508	60	21	283	1144
	12-R1-A1	II	3	45	104	86	78.8%	1464	180	45	551	688
	12-R1-A2	II	3	50	111	79	84.1%	1379	180	50	517	632
	12-R1-A3	II	3	47	108	82	81.8%	1376	180	47	493	656
	12-R2-A1/2/3	I	0	0	0	190	0.0	1520	0	0	0	1520
	12-R2-A1	II	2	39	89	101	67.4%	1492	120	39	525	808
	12-R2-A2	II	3	54	124	66	93.9%	1386	180	54	624	528
	12-R2-A3	II	3	54	120	70	90.9%	1370	180	54	576	560
	12-R3-A1/2/3	I	0	0	0	190	0.0	1520	0	0	0	1520
	12-R3-A1	II	2	39	88	102	66.7%	1480	120	39	505	816
	12-R3-A2	II	3	53	124	66	93.9%	1360	180	53	599	528
	12-R3-A3	II	3	52	123	67	93.2%	1337	180	52	569	536

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