Mobile fleet inventory: An integrated approach to fleet management for an on-demand delivery system

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Short summary

On-demand delivery systems commonly rely on stationary facilities to organize operations and manage resources. While stationary facilities provide stability and structured coverage, they are inherently rigid and struggle to adapt to the spatial and temporal fluctuations of urban service demand. This study introduces an optimization framework for deploying Mobile Fleet Inventories (MFIs) to address operational inefficiencies in on-demand delivery systems. We formulate the problem as an MILP to optimize MFI deployment, where key decisions are the optimal number, placement of MFIs, and fleet size. We apply our model to a meal delivery platform in Amsterdam to demonstrate the applicability, stability and generalizability of the framework.
Keywords: Capacitated mobile facility location, Meal delivery problem; Mobile fleet inventory, Urban waterway logistics.

1 Introduction

A critical component of on-demand delivery systems is the micro-facility, which plays a vital role in maintaining operational efficiency. These facilities serve three key functions: housing and managing fleets, redistributing resources, and serving as pickup/drop-off points for riders. Despite their importance, stationary facilities often fall short of meeting the dynamic and scalable requirements of on-demand services. For example, business districts experience surges during the day, while residential neighborhoods see higher demand in the evening. This mismatch leads to resource imbalances, with shortages in high-demand areas and idle resources elsewhere. Platforms often address these inefficiencies with truck-based redistribution, which increases costs, congestion, and environmental impacts (Du et al., 2020; DeMaio, 2009; Schuijbroek et al., 2017).

To address these limitations, this research explores the use of electric waterborne vessels (EWVs) as Mobile Fleet Inventories (MFIs) — movable facilities that leverage urban waterways to overcome the rigidity of stationary facilities. MFIs address key urban logistics challenges by offering three distinct advantages: (i) freeing valuable urban space by eliminating the need for stationary facilities, (ii) replacing truck-based redistribution with environmentally friendly, vessel-driven fleet rebalancing, and (iii) reducing rider idle time, thereby improving operational efficiency and service levels.

The MFIs falls under the concept of mobile facilities (Alarcon-Gerbier & Buscher, 2022) in the literature. While Mobile Facility Location Problem (MFLP) and its variants have been extensively studied (Pashapour et al., 2024; Bayraktar et al., 2022; Raghavan et al., 2019; Melo et al., 2006), these studies do not address the management of shared resources (e.g. delivery bikes in our case) stored within mobile facilities, nor do they consider resource sizing. Conversely, research on shared vehicle systems typically assumes that parking facilities are fixed and static (Qu et al., 2021), overlooking scenarios where facilities have mobility capabilities - a trend with increasing considerations.

We summarize our contributions as follows: We establish the feasibility of the MFI approach by optimizing overall system costs for on-demand delivery services. We develop and compare two mathematical formulations: arc-based and route-based models. We demonstrate the applicability and generalizability of the MFI concept across various canal layouts and demand scenarios. Finally, we validate the proposed approach through a case study on a meal delivery platform in Amsterdam.

2 Problem Statement

We consider an on-demand delivery platform operating in an urban area connected by canals, which is discretized into equal-sized hexagonal *zones* $\mathcal{Z} = \{z\}$. Zones where MFIs operate are denoted as $\mathcal{Z}^M \subseteq \mathcal{Z}$, and those accessible to riders as $\mathcal{Z}^R \subseteq \mathcal{Z}$. The planning horizon is divided into equal-length *periods* $\mathcal{T} = \{t\}$. We define the problem on a time-space network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, where $\mathcal{N} = \{(z,t)|z \in \mathcal{Z}, t \in \mathcal{T}\}$ contains time-space *nodes*, and $\mathcal{A}$ is the set of arcs. This network is composed of two subgraphs: $\mathcal{G}^M = (\mathcal{N}^M, \mathcal{A}^M)$ for MFIs and $\mathcal{G}^R = (\mathcal{N}^R, \mathcal{A}^R)$ for riders.

In $\mathcal{G}^M$, $\mathcal{N}^M = \mathcal{Z}^M \times \mathcal{T}$ contains nodes where MFIs can operate, and $\mathcal{A}^M$ contains arcs for MFI movements. An arc $(z,t)(z',t')$ denotes MFI travel from z at t to z' at t', where Z_z^+ are adjacent zones of z connected by canals. Successor and predecessor nodes for (z,t) are defined as $N_{z,t}^{M+} = \{(z',t')|z' \in Z_z^+, t' = t + DIS_{zz'}\}$ and $N_{z,t}^{M-} = \{(z',t')|z' \in Z_z^+, t' = t - DIS_{zz'}\}$, respectively, where $DIS_{zz'}$ is the distance between z and z'. Similarly, in $\mathcal{G}^R$, $\mathcal{N}^R = \mathcal{Z}^R \times \mathcal{T}$ contains nodes where riders operate, and $\mathcal{A}^R$ contains rider movement arcs $(z,t)(z'',t'')$. Successor and predecessor nodes for (z,t) are defined as $N_{z,t}^{R+} = \{(z'',t'')|z'' \in \mathcal{Z}, t'' = t + DIS_{zz''}\}$ and $N_{z,t}^{R-} = \{(z'',t'')|z'' \in \mathcal{Z}, t'' = t - DIS_{zz''}\}$, respectively.

Demand for bike pickups and returns

Observation 1. After picking up a bike at a facility, a rider proceeds to her first order collection. If the facility and the first order collection point are in the same zone, the idle travel time for bike pickup is the shortest. Thus, we define the demand for bike pickup of a shift occurring at the location and time of the first order collection. Similarly, we define the demand for bike return of the shift occurring at the location and time of the finishing of the last delivery. The opportunity cost of rider idle time is included in the objective function to be minimized.

The probability distribution of the number of riders collecting first orders in z during t, denoted as random variable X_{zt}, can be estimated from historical rider itinerary data. The platform can impose a customer service level Δ, determining the number of riders deployed to z and t, denoted as d_{zt}, such that:

$$P(d_{zt} \geq X_{zt}) \geq \Delta.$$

Additionally, a transition probability $n_{zt}^{z't'}$ is estimated from historical data, indicating the likelihood of a rider starting in z at t and finishing in z' at t'. Using this probability, the expected number of bikes to be returned from z' at t', denoted as $r_{z't'}$, is calculated as:

$$r_{z't'} = \sum_z \sum_t n_{zt}^{z't'} d_{zt}.$$

Satisfying demand for bike pickups and returns

The goal is to satisfy demands for bike pickups and returns with minimum total system cost which includes capital investments and opportunity cost of rider idle time. We consider a set of electric waterborne vessels $v \in \mathcal{V}$, each with a fixed capacity Q^{MFI}. MFIs operate from a depot equipped with charging facilities and selectively visit docking points to load or unload bikes. The locations of candidate docking points are assumed to be known, and a docking point is established only if visited by an MFI. Each docking point has a limited staging area for temporarily holding bikes. MFIs must periodically return to the depot for recharging, with the time between returns defined as the *interval.* Riders are instructed by the platform to pick up or return bikes at either MFIs, docking points, or via self-fulfillment. By "self-fulfillment", a rider (A) finishing her shift is instructed to head to another zone to give her bike to a rider (B), who starts his shift. In this case, rider B's bike pickup and rider A's return are satisfied at the same time.

3 Mathematical Model

Arc-based formulation

MFI route constraints. For each MFI $v \in \mathcal{V}$, let the binary variable $\delta^v = 1$ if v is deployed, and $x^v_{(z,t)(z',t')} = 1$ if v travels from z to z' starting at t and arriving at t'. The planning horizon (e.g., a day) is divided into equal-length intervals (e.g., 4 hours) $L = \{1, 2, \ldots, |L|\}$, with each interval comprising multiple periods (e.g., 10 minutes). Thus, $\mathcal{T} = \{T_1, T_2, \ldots, T_{|L|}\}$, where $|L| = \frac{|\mathcal{T}|}{|T_1|}$, and $\tilde{T} = \{|T_1|, 2|T_1|, \ldots, (|L|-1)|T_1|\}$ is the set of interval-cut periods. Let z_o denote the depot zone. Constraints (1) ensure the usage of MFI v. Constraints (2) require each deployed MFI to return to the depot by the end of the planning horizon. Constraints (3) enforce flow conservation at time-space nodes. Constraints (4) ensure no more than two MFIs stop at the same node simultaneously, except at the depot. Constraints (5) ensure periodic returns to the depot for recharging.

$$\delta^v = \sum_{(z',t') \in N^{M+}_{z_o,1}} x^v_{(z_o,1)(z',t')}, \quad \forall v \in \mathcal{V} \tag{1}$$

$$\sum_{(z',t') \in N^{M+}_{z_o,1}} x^v_{(z_o,1)(z',t')} = \sum_{(z',t') \in N^{M-}_{z_o,|\mathcal{T}|}} x^v_{(z',t')(z_o,|\mathcal{T}|)}, \quad \forall v \in \mathcal{V} \tag{2}$$

$$\sum_{(z',t') \in N^{M+}_{z,t}} x^v_{(z,t)(z',t')} = \sum_{(z',t') \in N^{M-}_{z,t}} x^v_{(z',t')(z,t)}, \quad \forall v \in \mathcal{V}, \quad \forall z \in \mathcal{Z}^M \setminus \{z_o\}, \quad \forall t \in \mathcal{T} \tag{3}$$

$$\sum_{v \in \mathcal{V}} x^v_{(z,t)(z,t+1)} \leq 1, \quad \forall z \in \mathcal{Z}^M \setminus \{z_o\}, \quad \forall t \in \mathcal{T} \setminus |\mathcal{T}| \tag{4}$$

$$x^v_{(z_o,t)(z_o,t+1)} = 1, \quad \forall v \in \mathcal{V}, \quad \forall t \in \tilde{T} \tag{5}$$

$$\delta^v \in \{0,1\}, \quad \forall v \in \mathcal{V} \tag{6}$$

$$x^v_{(z,t)(z',t')} \in \{0,1\}, \quad \forall v \in \mathcal{V}, \quad \forall (z,t),(z',t') \in \mathcal{A}^M \tag{7}$$

We define the binary variable $\zeta_z = 1$ if the candidate docking point in zone z is visited by an MFI and thus established. Constraints (8) enforce this condition, with M_1 set as $|\mathcal{V}|(|\mathcal{T}|-1)$.

$$\zeta_z \leq \sum_{v \in \mathcal{V}} \sum_{t \in T \setminus |\mathcal{T}|} x^v_{(z,t)(z,t+1)} \leq M_1 \zeta_z, \quad \forall z \in \mathcal{Z}^M \tag{8}$$

$$\zeta_z \in \{0,1\}, \quad \forall z \in \mathcal{Z}^M \tag{9}$$

Bike pickups and returns satisfaction. We define the following non-negative integer variables: $y^{PM,v}_{(z,t)(z'',t'')}$, representing the number of riders picking up bikes from MFI v in z at t and riding to collect first orders in z'' at t''; $y^{RM,v}_{(z'',t'')(z,t)}$, representing the number of riders returning bikes to MFI v in z at t from last deliveries in z'' at t''; $y^{PD}_{(z,t)(z'',t'')}$, for riders picking up bikes at the docking point in z at t and riding to collect first orders in z'' at t''; $y^{RD}_{(z'',t'')(z,t)}$, for riders returning bikes to the docking point in z at t from last deliveries in z'' at t''; and $y^{SF}_{(z,t)(z'',t'')}$, for riders finishing last deliveries in z at t and riding to z'' at t'' to hand over bikes to waiting riders. Constraints (10) and (11) state that an MFI allows bike pickups and returns only when it is stationary. Constraints (12) and (13) ensure that a candidate docking point allows bike pickups and returns only if it is established. Constraints (14) and (15) state that the demand for bike pickups and returns in zone z at period t can be met by MFIs, docking points, or self-fulfillment.

$$y^{PM,v}_{(z,t)(z'',t'')} \leq d_{zt} x^v_{(z,t)(z,t+1)}, \quad \forall v \in \mathcal{V}, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T} \setminus |\mathcal{T}|, \quad \forall (z'',t'') \in N^{R+}_{z,t} \tag{10}$$

$$y^{RM,v}_{(z'',t''),(z,t)} \leq r_{zt} x^v_{(z,t),(z,t+1)}, \quad \forall v \in \mathcal{V}, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T} \setminus |\mathcal{T}|, \quad \forall (z'',t'') \in N^{R-}_{z,t} \tag{11}$$

$$y^{PD}_{(z,t)(z'',t'')} \leq d_{zt} \zeta_z, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T}, \quad \forall (z'',t'') \in N^{R+}_{z,t} \tag{12}$$

$$y^{RD}_{(z'',t''),(z,t)} \leq r_{zt} \zeta_z, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T}, \quad \forall (z'',t'') \in N^{R-}_{z,t} \tag{13}$$

$$\sum_{v \in \mathcal{V}} \sum_{(z'',t'') \in N^{R-}_{z,t} \cap \mathcal{N}^M} y^{PM,v}_{(z'',t'')(z,t)} + \sum_{(z'',t'') \in N^{R-}_{z,t} \cap \mathcal{N}^M} y^{PD}_{(z'',t'')(z,t)} + \sum_{(z'',t'') \in N^{R-}_{z,t}} y^{SF}_{(z'',t'')(z,t)} = d_{zt}, \quad \forall (z,t) \in \mathcal{N}^R \tag{14}$$

$$\sum_{v \in \mathcal{V}} \sum_{(z'',t'') \in N^{R+}_{z,t} \cap \mathcal{N}^M} y^{RM,v}_{(z,t)(z'',t'')} + \sum_{(z'',t'') \in N^{R+}_{z,t} \cap \mathcal{N}^M} y^{RD,v}_{(z,t)(z'',t'')} + \sum_{(z'',t'') \in N^{R+}_{z,t}} y^{SF}_{(z,t)(z'',t'')} = r_{zt}, \quad \forall (z,t) \in \mathcal{N}^R \tag{15}$$

$$y^{PM,v}_{(z,t)(z'',t'')} \in \mathbb{Z}_{\geq 0}, \quad \forall v \in \mathcal{V}, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T} \setminus |\mathcal{T}|, \quad \forall (z'',t'') \in N^{R+}_{z,t} \tag{16}$$

$$y^{RM,v}_{(z'',t''),(z,t)} \in \mathbb{Z}_{\geq 0}, \quad \forall v \in \mathcal{V}, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T} \setminus |\mathcal{T}|, \quad \forall (z'',t'') \in N^{R-}_{z,t} \tag{17}$$

$$y^{PD}_{(z,t)(z'',t'')} \in \mathbb{Z}_{\geq 0}, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T}, \quad \forall (z'',t'') \in N^{R+}_{z,t} \tag{18}$$

$$y^{RD}_{(z'',t''),(z,t)} \in \mathbb{Z}_{\geq 0}, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T}, \quad \forall (z'',t'') \in N^{R-}_{z,t} \tag{19}$$

$$y^{SF}_{(z,t)(z'',t'')} \in \mathbb{Z}_{\geq 0}, \quad \forall (z,t)(z'',t'') \in \mathcal{A}^R \tag{20}$$

MFI and docking point inventory. We first describe the MFI inventory. Let the non-negative integer I^v_{zt} represent the number of bikes stored in MFI v located in z at t. If an arc $(z,t)(z',t')$ is part of the route of MFI v, the inventory at node (z',t') equals the inventory at (z,t) plus the loaded bikes and minus the unloaded ones, as expressed in Constraints (21). Constraints (22) ensure that the inventory does not exceed the capacity Q^{MFI} or that no inventory is considered at time-space nodes not on the route of the MFI.

$$x^v_{(z,t)(z',t')} I^v_{z't'} = x^v_{(z,t)(z',t')} \left(I^v_{zt} + \sum_{(z'',t'') \in N^{R-}_{z,t}} y^{RM,v}_{(z'',t''),(z,t)} - \sum_{(z'',t'') \in N^{R+}_{z,t}} y^{PM,v}_{(z,t)(z'',t'')} \right),$$
$$\forall v \in \mathcal{V}, \quad \forall (z,t) \in \mathcal{N}^M, \quad \forall (z',t') \in N^{M+}_{z,t} \tag{21}$$

$$I^v_{zt} \leq \frac{Q^{MFI}}{2} \left(\sum_{(z',t') \in N^{M+}_{z,t}} x^v_{(z,t)(z',t')} + \sum_{(z',t') \in N^{M-}_{z,t}} x^v_{(z',t'),(z,t)} \right), \quad \forall v \in \mathcal{V}, \quad \forall (z,t) \in \mathcal{N}^M \tag{22}$$

$$I^v_{zt} \in \mathbb{Z}_{\geq 0}, \quad \forall v \in \mathcal{V}, \quad \forall (z,t) \in \mathcal{N}^M \tag{23}$$

For docking point inventories, let the non-negative integer variable I^D_{zt} represent the number of bikes parked at the docking point in z during t. The inventory at a docking point in z at t equals the inventory in the previous period, plus the bikes returned to it, minus the bikes borrowed, as expressed in Constraints (24). Constraints (25) ensure that inventory levels do not exceed capacity limits.

$$I^D_{z,t+1} = I^D_{zt} + \sum_{(z'',t'') \in N^{R-}_{z,t}} y^{RD}_{(z'',t'')(z,t)} - \sum_{(z'',t'') \in N^{R+}_{z,t}} y^{PD}_{(z,t)(z'',t'')}, \quad \forall z \in \mathcal{Z}^M, \quad \forall t \in \mathcal{T} \setminus |\mathcal{T}| \tag{24}$$

$$I^D_{zt} \leq \zeta_z Q^D, \quad \forall (z,t) \in \mathcal{N}^M \tag{25}$$

$$I^D_{zt} \in \mathbb{Z}_{\geq 0}, \quad \forall (z,t) \in \mathcal{N}^M \tag{26}$$

Objective function. The objective is to minimize the overall system cost, including capital investments and operational costs. The capital investment includes MFIs leasing J_1, bikes purchasing J_2, docking points establishment J_3. The operational costs include opportunity cost for rider idle time associated with MFIs and docking points J_4 and with self-fulfillment J_5.

Let c^{MFI} represent the daily MFI leasing cost, c^B the bike price converted to a daily rate, c^D the cost of establishing a docking point converted to a daily rate, c^{VoT} the value of a period for riders, and c^{SF} the cost per unit distance traveled for self-fulfillment. The objective function is then written as:

$$MIN \quad \Phi = J_1 + J_2 + J_3 + J_4 + J_5 \tag{27}$$

where:

$$J_1 = c^{MFI} \sum_{v \in \mathcal{V}} \delta^v \tag{28}$$

$$J_2 = c^B \Big(\sum_{v \in \mathcal{V}} I^v_{z_o,1} + \sum_{z \in \mathcal{Z}^M} I^D_{(z,1)}\Big) \tag{29}$$

$$J_3 = c^D \sum_{z \in \mathcal{Z}^M} \zeta_z \tag{30}$$

$$\begin{aligned} J_4 = c^{VoT} \sum_{(z,t) \in \mathcal{N}^M} \Bigg(& \sum_{(z'',t'') \in N^{R-}_{z,t}} \sum_{v \in \mathcal{V}} y^{RM,v}_{(z'',t'')(z,t)} DIS_{zz''} + \sum_{(z'',t'') \in N^{R+}_{z,t}} \sum_{v \in \mathcal{V}} y^{PM,v}_{(z,t)(z'',t'')} DIS_{zz''} \\ & + \sum_{(z'',t'') \in N^{R-}_{z,t}} y^{RD}_{(z'',t'')(z,t)} DIS_{zz''} + \sum_{(z'',t'') \in N^{R+}_{z,t}} y^{PD}_{(z,t)(z'',t'')} DIS_{zz''} \Bigg) \end{aligned} \tag{31}$$

$$J_5 = c^{SF} \sum_{(z,t)(z'',t'') \in \mathcal{A}^R} y^{SF}_{(z,t)(z'',t'')} DIS_{zz''} \tag{32}$$

Constraints linearization

Constraints (21) can be linearized as follows:

$$\begin{aligned} & Q^{MFI}(1 - x^v_{(z,t)(z',t')}) I^v_{z't'} \geq I^v_{zt} + \sum_{(z'',t'') \in N^{R-}_{z,t}} y^{RM,v}_{(z'',t'')(z,t)} - \sum_{(z'',t'') \in N^{R+}_{z,t}} y^{PM,v}_{(z,t)(z'',t'')}, \\ & \quad \forall v \in \mathcal{V}, \quad \forall (z,t) \in \mathcal{N}^M, \quad \forall (z',t') \in N^{M+}_{z,t} \end{aligned} \tag{33}$$

$$\begin{aligned} & Q^{MFI}(x^v_{(z,t)(z',t')} - 1) I^v_{z't'} \leq I^v_{zt} + \sum_{(z'',t'') \in N^{R-}_{z,t}} y^{RM,v}_{(z'',t'')(z,t)} - \sum_{(z'',t'') \in N^{R+}_{z,t}} y^{PM,v}_{(z,t)(z'',t'')}, \\ & \quad \forall v \in \mathcal{V}, \quad \forall (z,t) \in \mathcal{N}^M, \quad \forall (z',t') \in N^{M+}_{z,t} \end{aligned} \tag{34}$$

Route-based formulation

We define an MFI route as a list of ordered nodes that the MFI is situated at in the time-space network. The difference between the arc-based and route-based formulation is that the set of candidate routes are generated beforehand, thus the complex routing constraints 1 - 5 are removed from the route-based formulation.

4 Results And Discussion

Input generation scheme

We define two service areas: Area-4, consisting of 37 hexagonal zones arranged in 4 circles, and Area-6, with 91 hexagonal zones arranged in 6 circles. Two geographical distribution types of demand are considered: **U** (uniform distribution of bike pickups and returns across the service area) and **C** (75% of bike pickups occur in the center and 75% of returns in the outskirts). The area center is a circle with a radius of r zones from the innermost zone, where $r = 2$ for Area-4 and $r = 3$ for Area-6. We consider MFI capacity is 50 bikes and candidate docking point capacity is 1 bike. Table 1 summarizes the instance characteristics. Instances are named accordingly; e.g., 'A4-P36-S40-**U**' represents Area-4, a 36-period planning horizon, 40 riders, and uniformly distributed demand.

Table 1: Instance characteristics.

Characteristics	Possible Choices
Area size	Area-4, Area-6
Planning horizon	36 periods, 48 periods, 72 periods
Number of riders	40, 60, 80
Demand geographical distribution type	**U**, **C**

Computational performance of the two models

We conduct the experiments using Python and Gurobi Optimizer version 11.0.0. All experiments are carried out on a computer with a 2.4 GHz CPU, 8 GB of RAM, and an 8-core processor. Each instance is solved with a time limit of 4 hours.

We replicate the Amsterdam canal network and choose **U** as a representative case. We select 18 instances varying in the area size, planning horizon, and number of riders as shown in Table 1. The results show that solving time increases with the number of zones, periods, and riders. For Area-4, when the number of riders is 40 or 60, the solving times for both formulations are under one minute. For Area-6, this is also true for planning horizons of 36 and 48 periods. However, when the number of riders reaches 80, neither model converges to optimality within the time limit, except for the smallest case "A4-P36." Additionally, when converging to optimality, the solving time of the route-based formulation is consistently shorter than that of the arc-based formulation, demonstrating the efficiency of the route-based model for small- and medium-sized instances. We also further experimented increasing instance size (e.g., 96 periods), in this case, generating all candidate routes becomes impossible, whereas the arc-based formulation can still find a feasible solution.

Impact of city layout

We apply our model on different city layouts to demonstrate the generalizability and applicability of our approach. We replicate four canal typologies (Figure 1) from real cities: Amsterdam (noted as Network-1), Leiden (Network-2), Venice (Network-3), and Fredrikstad (Network-4). We use instance "A4-P48-S40" as a representative case and consider the two demand geographical distribution types **U** and **C**. For each of the two distribution types, we generate three random patterns separately: {**U1**, **U2**, **U3**} and {**C1**, **C2**, **C3**}.

The daily cost of an MFI is set at 810.00 €, covering leasing, energy, and maintenance. The average bike price in the Netherlands is estimated at 865.00 €, with a service life of three years, resulting in a daily cost of 0.79 €per bike. The cost of a docking point is set at 0.27 €per day, based on the annual fee of 100.00 €charged by the Netherlands train operator for a bike storage. The gross hourly salary of a rider is 14.77 €, making the opportunity cost of one period of idle time 2.46 €.

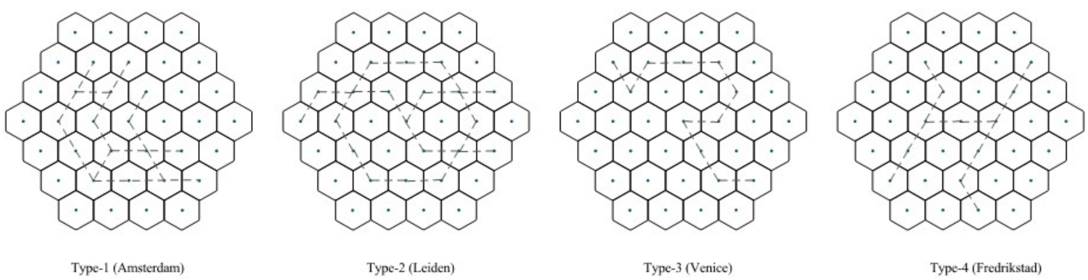

Figure 1: Canal network typologies replicated from Amsterdam, Leiden, Venice, and Fredrikstad

Table 2 presents the average value of system performance indicators of the three random demand patterns for each geographical distribution type **U** and **C** and four network typologies. Column 'Distrb.' indicates the geographical distribution type of demand. Column 'Idle' presents the average rider idle time, and column 'Obj.' for the average total system cost. Under 'Capital Investment,' the column 'Cost' records the average total capital investment, 'Bikes' presents the average number of purchased bikes, and 'DP' the average number of docking points. Under 'Operational Cost,' the column 'Total' indicates the average total operational cost, 'Self-FF.' reflects the average cost associated with self-fulfillment, and 'Per DP' shows the operational cost averaged per docking point. For each canal network typology, the row 'Diff.' calculates the percentage difference in the average value of indicators between **C** and **U**, computed as $(\mathbf{U}-\mathbf{C})/\mathbf{C}$.

As shown in the table, under type **U**, riders spend 17.81% to 25.40% more idle time for bike pickups and returns, and the overall redistribution cost is around 5% higher. In terms of capital investment, type **U** requires 20% to 78% more docking points to be established but needs around 4% fewer bikes, resulting in a slightly lower overall capital investment. However, operational costs under type **U** are, on average, 20% higher than those under type **C**. While the total operational cost is higher, the cost per docking point is generally lower for **U** (except in Network 1), primarily due to the increased number of docking points. Additionally, self-fulfillment costs are lower under type **U**. These results highlight the importance of considering city layout when deploying MFIs, as cities with a more uniformly distributed layout tend to incur higher overall costs and longer rider idle times.

Table 2: Comparison between **C** and **U** for four canal network typologies under case A4-P48-S40.

Network	Distrb.	Idle (min)	Obj.(€)	Capital investment			Operational cost (€)		
				Cost (€)	Bikes	DP	Total	Self-FF.	Per DP
1	C	14.67	1123.69	835.05	30.00	5	288.64	22.96	53.14
	U	17.75	1183.59	834.27	28.67	6	349.32	18.04	55.21
	Diff.	21.00%	5.33%	-0.09%	-4.43%	20.00%	21.02%	-21.43%	3.90%
2	C	14.71	1124.42	834.96	30.00	4.67	289.46	26.24	60.74
	U	17.33	1176.02	834.90	28.67	8.33	341.12	13.12	39.36
	Diff.	17.81%	4.59%	-0.01%	-4.43%	78.37%	17.85%	-50.00%	-35.20%
3	C	14.92	1128.25	834.69	30.00	3.67	293.56	31.16	71.56
	U	18.71	1202.54	834.36	28.67	6.33	368.18	17.22	55.41
	Diff.	25.40%	6.58%	-0.04%	-4.43%	72.48%	25.42%	-44.74%	-22.57%
4	C	14.88	1127.61	834.87	30.00	4.33	292.74	27.06	61.63
	U	17.92	1186.96	834.36	28.67	6.33	352.6	14.76	53.34
	Diff.	20.43%	5.26%	-0.06%	-4.43%	46.19%	20.45%	-45.45%	-13.45%

Case study in Amsterdam Canal area

In this section, we apply our model to a meal delivery platform in Amsterdam using rider itinerary records from September 13, 2021, to October 10, 2021. The canal course is manually outlined for a gridded service area of 91 zones (Figure 2), with each zone having an edge length of 200 meters and a center-to-center distance of 347 meters. One available MFI is considered, operating at a speed of 4 km/h due to busy waterway transport. We consider the planning for a typical day from 9:00 to 24:00. The MFI must return to the depot every 8 hours for recharging. The data reveals a high density of meal pickups and drop-offs in the canal area, with demand nearly uniformly distributed. After averaging monthly rider schedules to one day and excluding riders operating outside the selected area, we obtain an average of 45 riders per day for the canal area. All other parameters follow the previous section.

Benchmarking again stationary facility. We first define the base case of the MFI strategy which considers the average daily number of riders, which is 45, and name it as "MFI-Base". We further construct a benchmark that mimics the stationary facility operations in the current practice. We solve the model to an optimality gap of 3%.

In Table 3, row "Impr." presents the percentage difference between the indicator values of MFI-Base and the benchmark. The solutions suggest both the MFI-Base and benchmark require 31 bikes for the 45 riders to conduct services. As can be seen from the table, there is a 17.07% saving in the overall system costs and a 35.03% reduction in the average rider idle time after applying the

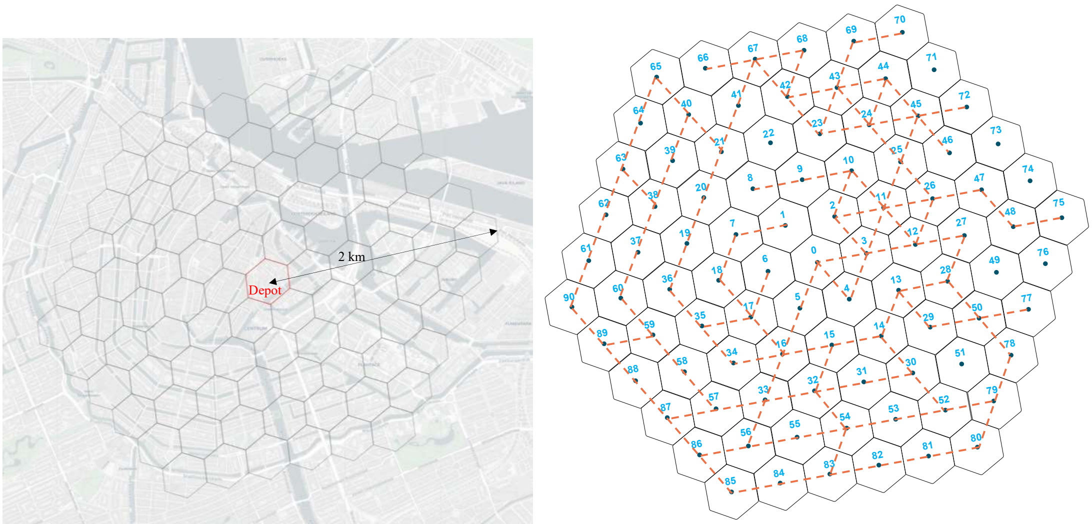

Figure 2: Amsterdam canal network

MFI strategy, which demonstrates the economic benefits of our strategy based on the system cost and rider time productivity.

Table 3: Comparison between the MFI-Base and the benchmark.

Case	Obj. (€)	Idle (min)
Benchmark	1656.13	37.11
MFI-Base	1373.44	24.11
Impr.	17.07%	35.03%

The day of the week. We further demonstrate the stability of MFI-Base. Once the system configuration (MFI leasing, docking point locations, and the number of bikes) is decided, it remains fixed for a long time. Historical data indicates slight variations in customer orders throughout the week, with weekends typically experiencing higher order volumes. To account for this, we define two scenarios: Weekday and Weekend. In the Weekday scenario, we assume 75% of the number of riders in the MFI-Base, while the Weekend scenario considers 125%. Both scenarios maintain the **U**-type demand geographical distribution. We consider two situations: (1) 'Fix,' where the MFI can only visit docking points selected in the MFI-Base configuration, and (2) 'Free,' where the MFI can freely visit any candidate docking points.

The experiment results show that there is only a slight increase in the indicator values for the 'Fix' configuration compared to 'Free', with increases of 1.19% for Weekday and 0.48% for Weekend. Rider idle time also only increases slightly, by 3.81% for Weekday and 1.10% for Weekend. The results indicate that the MFI-Base design, based on the average daily rider number, remain effective for slightly varying rider shift patterns on weekdays and weekends, demonstrating the stability of the MFI-Base deployment.

5 Conclusion

This study investigates the Mobile Fleet Inventory (MFI) strategy for on-demand delivery services. We develop a mixed-integer optimization model to address the problem, balancing infrastructure investments and operational costs to minimize overall MFI system costs. Computational results reveal that the route-based formulation is more effective than the arc-based formulation for small- and medium-sized inputs. By experimenting with different city layouts and canal network typologies, we demonstrate the generalizability of the MFI strategy and analyze the impact of city layouts (uniform or centric) on system performances. A case study in the Amsterdam Canal area highlights the superiority of the MFI strategy over stationary facility operations, achieving a 17.07% reduction in overall system costs and a 35.03% decrease in average rider idle time. The case study also demonstrates the stability and applicability of the MFI strategy in accommodating slight variations in demand patterns throughout the week.

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