Harnessing the Power of Inland Waterways
A Case Study on Sustainable Urban Logistics in Amsterdam

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Harnessing the Power of Inland Waterways: A Case Study on Sustainable Urban Logistics in Amsterdam

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Abstract: With the rapid population growth, urban areas encounter substantial challenges like congestion, increased emissions, and pressure on existing infrastructure. In response to these challenges, we explore the advantages of integrating inland waterways and last-mile delivery in urban logistics networks. The objective is to design an optimal urban logistics network for HoReCa businesses in the center of Amsterdam by establishing the transshipment locations and simultaneously considering the infrastructure strain and congestion issues. We formulate the problem as a two-echelon location routing problem with time windows and propose a hybrid solution approach to determine the location of transshipment points and the waterway and last-mile routing decisions. We further develop an agent-based discrete-event simulation framework to investigate vessel traffic patterns. The results show significant cost savings of approximately 28% compared to traditional truck-based systems. Incorporating light electric vehicles reduces vehicle weight by 43% and travel distances within the city center by approximately 80%. Our simulation results show that while modal shift minimally impacts waterway transit time, attention to potential strain on canal infrastructures is vital. Further analysis should address increased vessel traffic density, especially in areas with degraded quay walls, to prevent infrastructure degradation.

Keywords: Urban Logistics; Modal Shift; Waterways; Optimization; Simulation

Introduction

As urbanization continues its rapid pace, cities face formidable challenges such as congestion, emissions, and strained infrastructure. In this respect, exploring alternative transportation modes emerges as a promising avenue, particularly in harnessing the potential of inland waterways. Amsterdam, a city known for its historic canals, is particularly affected by the strain on public spaces, congestion, and the maintenance of bridges and quay walls. The constant movement of heavy vehicles on the roadways accelerates the wear and tear of bridges and quay walls, jeopardizing their structural integrity.

In light of these challenges, there is a growing motivation to remove heavy loads from roadways and shift them to the waterways within Amsterdam. However, despite the potential benefits, there is a lack of research and operational insights into waterway-based urban logistics. Unfortunately, the absence of such transshipment points poses a significant challenge to achieving the desired modal shift in Amsterdam.

Motivated by the aforementioned significance and the existing gap, we explore the advantages of integrating inland waterways and last-mile delivery in Amsterdam's HoReCa urban logistics network. We first formulate the problem as a two-echelon location routing problem with time windows and develop an efficient hybrid solution approach to design the network. We further develop an agent-based discrete-event simulation framework using the Open source Transport Network Simulation (OpenTNSim) python package to investigate vessel traffic patterns. By analyzing these patterns, we can assess the feasibility of shifting to this alternative mode of transportation and determine the capacity of the canals to accommodate increased traffic. Finally, through a comprehensive case study, the advantages of implementing a waterway-based distribution chain are assessed in the city center of Amsterdam.

This study contributes to the existing literature by crafting an optimized logistics framework designed for urban waterway distribution. It emphasizes the consideration of canal classifications and vessel laytime restrictions. The paper introduces innovative elements through its integrated modeling assumptions, often overlooked in traditional urban distribution models. These encompass transshipment point establishment (location), the integration of electric vehicles, synchronization, and the utilization of moving jacks alongside light electric vehicles. To effectively tackle this problem, a novel advanced solution algorithm has been formulated.

Literature Review

In this section, an overview of the existing literature focusing on waterborne urban logistics is provided. Despite its promise, there is limited exploration within the literature concerning waterborne transport in urban logistics.

Researchers such as Janjevic and Ndiaye [1], Maes et al. [2], Miloslavskaya et al. [3], and Wojewódzka-Król and Rolbiecki [4] have examined successful instances of waterborne urban logistics on a global scale. Several initiatives have been introduced in these papers such as Beer Boat in Utrecht, “Vracht door de gracht” in Amsterdam, Vert Chez Vous in Paris, and Sainsbury’s in London.

Kortmann et al. [5] studied the potential of waterborne distribution for same-day delivery to Amsterdam shopkeepers. They devised a simulation model to scrutinize the system's performance and ascertain the optimal fleet size. Their findings suggest that waterborne distribution could be an efficient and sustainable delivery mode in Amsterdam.

Gu and Wallace [6] developed an optimization model for waterborne urban logistics that explored the use of autonomous vessels. Their model addressed facility location, fleet allocation, and routing decisions concerning vessel operations in Bergen, Norway. Divieso et al. [7] examined the feasibility of employing waterways for urban logistics in Brazil. They identified global waterway urban logistics practices and conducted a comparative analysis focusing on Belém, a city in Brazil. Their findings underscored Belém's potential for utilizing waterways. Nepveu and Nepveu [8] assessed the feasibility of introducing urban waterway transport in Amsterdam by examining the success and failure factors for such a modal shift.

Two-Echelon Location Routing Problem

Problem Description

This paper considers a multi-modal two-echelon location-routing problem with time windows. The transportation network encompasses inland waterways and roadways. In the first echelon, vessels travel from a central hub to specific Transshipment Points (TPs), where they unload goods. Last-mile delivery then commences using Light Electric Vehicles (LEVs) or moving jacks. Demand points in proximity to TPs are served by moving jacks rather than LEVs.

The problem is modeled on a directed graph G(*V*, *E*), where *V* represents the set of vertices and *E* is the set of arcs. V includes the set of vertices in the first echelon (V_1) and second echelon (V_2). The set V_1 involves the central hub (CH) and the transshipment locations (TP). The set V_2 is comprised of the vehicle depots (VD), the transshipment locations (TP), and the demand points (HRC). $E = \{(i,j) | \, i,j \in V, i \neq j, (i,j) \in A \cup B\}$ where *A* and *B* are the sets of admissible arcs for the first and second echelon, respectively. The distance between any two nodes in the first echelon, is not driven only based on the shortest path method but concerning different canal classes. Thereby, the distance between two identical nodes can differ for various vessel types with different sizes. Figure (1) illustrates a typical solution on the described graph.

Mathematical Model

The remainder of the notations which are used to formulate the model are as follows:

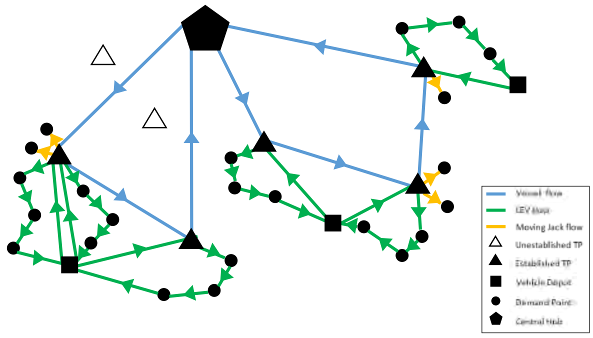

Figure 1 The graph of the problem

Parameters

D_i	Demand of $i \in HRC$
S_i^{ID}	Service time of vertex *i* (*ID =I* first echelon, *ID=II* second echelon)
T_{ijk}^{ID}	Travel time of arc (*i,j*) for (*ID =I* Vessel, *ID=II* LEV) k
T_{ij}^{III}	Travel time of arc (*i,j*) for moving jacks
AL_i	Allowed laying time at TP *i*
TA_i, TB_i	Lower and upper bounds for admissible service time at vertex *i*
CAP_i	Capacity of TP $i \in TP$
Q_k^{ID}	Capacity of (*ID =I* Vessel, *ID=II* LEV) *k*
DL	Driving range limit for LEVs
C_{ijk}^{ID}	Cost of traveling arc (*i,j*) by (*ID =I* Vessel, *ID=II* LEV) k
DIS_{ij}	Average traveling distance of arc (*i,j*), $i, j \in V_2$
DTr	Threshold distance to use moving jacks
FC_i	Period equivalent fixed cost of establishing TP $i \in TP$
l_{ij}	1: if demand point $j \in HRC$ is located at a distance shorter than *DTr* from point $i \in TP$ 0: otherwise
m_i, M_i	Lower and Upper bounds for the left-hand side of the respective constraints

Variables

x_{ijk}^{ID}	1: if (*ID =I* Vessel, *ID=II* LEV) *k* travels from *i*$\in V_1$ to *j*$\in V_1$ 0: otherwise
u_{ij}	1: if the demand point $j \in HRC$ is served by a moving jack from TP $i \in TP$ 0: otherwise
y_i	1: if TP $i \in TP$ is established 0: otherwise
p_{ijk}	1: if the items of the demand point $j \in HRC$ are delivered by vessel $k \in K_1$ to $i \in TP$ 0: otherwise
$v_{k\hat{k}i}$	1: if LEV $\hat{k} \in K_2$ meets vessel $k \in K_1$ at $i \in TP$ 0: otherwise
st_{ik}^{ID}	Time when (*ID =I* Vessel, *ID=II* LEV) *k* starts to service vertex *i*
st_{ij}^{III}	Time when a moving jack assigned to serve $j \in HRC$ starts to service vertex $i \in TP \cup HRC$
at_{ik}^{I}	Time when vessel $k \in K_1$ arrives at vertex *i*
q_{ik}	The amount delivered by vessel $k \in K_1$ to the TP $i \in TP$
pu_{ijk}	Auxilary binary variable

$$\boldsymbol{P_1}: min\ Z = \sum_{k\in K_1}\sum_{i\in V_1}\sum_{j\in V_1} C^{I}_{ijk} x^{I}_{ijk} + \sum_{k\in K_2}\sum_{i\in V_2}\sum_{j\in V_2} C^{II}_{ijk}\, x^{II}_{ijk} + \sum_{i\in TP} FC_i\, y_i \quad (1)$$

$$\sum_{j\in TP} x^{I}_{ijk} \le 1 \qquad \forall i \in \{CH\}, k \in K_1 \quad (2)$$

$$\sum_{i\in V_1} x^{I}_{i\upsilon k} - \sum_{j\in V_1} x^{I}_{\upsilon jk} = 0 \qquad \forall \upsilon \in TP, k \in K_1 \quad (3)$$

$$\sum_{i\in V_1} x^{I}_{ijk} \le y_j \qquad \forall j \in TP, k \in K_1 \quad (4)$$

$$at^{I}_{jk} = \sum_{i\in V_1} (st^{I}_{ik} + S^{I}_{i} + T^{I}_{ijk}) x^{I}_{ijk} \qquad \forall j \in V_1, k \in K_1 \quad (5)$$

$$st^{I}_{ik} \ge at^{I}_{ik} \qquad \forall i \in V_1, k \in K_1 \quad (6)$$

$$st^{I}_{ik} + S^{I}_{i} - at^{I}_{ik} \le AL_i \qquad \forall i \in TP, k \in K_1 \quad (7)$$

$$\sum_{i\in TP} q_{ik} \le Q^{I}_{k} \qquad \forall k \in K_1 \quad (8)$$

$$q_{jk} \le M_1 \sum_{i\in V_1} x^{I}_{ijk} \qquad \forall j \in TP, k \in K_1 \quad (9)$$

$$q_{ik} = \sum_{j\in HRC} D_j\, p_{ijk} \qquad \forall i \in TP, k \in K_1 \quad (10)$$

$$\sum_{k\in K_1}\sum_{i\in TP} p_{ijk} = 1 \qquad \forall j \in HRC \quad (11)$$

$$p_{ijk} \le \sum_{\upsilon\in V_1} x^{I}_{\upsilon ik} \qquad \forall i \in TP, k \in K_1 \quad (12)$$

$$\sum_{k\in K_1}\sum_{j\in HRC} D_j\ p_{ijk} \le CAP_i \qquad \forall i \in TP \quad (13)$$

$$DTr - DIS_{ij} \le M_2 l_{ij} \qquad \forall i \in TP, j \in HRC \quad (14)$$

$$DTr - DIS_{ij} \ge m_1(1 - l_{ij}) \qquad \forall i \in TP, j \in HRC \quad (15)$$

$$y_i + l_{ij} \le 1 + u_{ij} \qquad \forall i \in TP, j \in HRC \quad (16)$$

$$y_i + l_{ij} \ge 2u_{ij} \qquad \forall i \in TP, j \in HRC \quad (17)$$

$$\sum_{i\in VD}\sum_{j\in V_2} x^{II}_{ijk} \le 1 \qquad k \in K_2 \quad (18)$$

$$\sum_{i\in V_2} x^{II}_{ijk} \le y_j \qquad \forall j \in TP, k \in K_2 \quad (19)$$

$$\sum_{i\in V_2} x^{II}_{i\upsilon k} - \sum_{i\in V_2} x^{II}_{\upsilon jk} = 0 \qquad \forall \upsilon \in TP \cup HRC, k \in K_2 \quad (20)$$

$$\sum_{k\in K_2}\sum_{i\in V_2} x^{II}_{ijk} + \sum_{i\in V_2} u_{ij} = 1 \qquad \forall j \in HRC \quad (21)$$

$$\sum_{i\in V_2}\sum_{j\in V_2} DIS_{ij}\, x^{II}_{ijk} \le DL \qquad \forall k \in K_2 \quad (22)$$

$$\sum_{i\in V_2}\sum_{j\in V_2} D_j\ x^{II}_{ijk} \le Q^{II}_{k} \qquad \forall k \in K_2 \quad (23)$$

$$st^{II}_{ik} \ge (st^{II}_{ik} + S^{II}_{i} + T^{II}_{ijk}) x^{II}_{ijk} \qquad \forall i,j \in V_2, k \in K_2 \quad (24)$$

$$st^{III}_{jj} = (st^{III}_{ij} + S^{II}_{i} + T^{III}_{ij}) u_{ij} \qquad \forall i \in TP, j \in HRC \quad (25)$$

$$st^{II}_{i\hat{k}} - st^{I}_{ik} - S^{I}_{i} \ge m_2(1 - v_{k\hat{k}i}) \qquad \forall i \in TP, k \in K_1, \hat{k} \in K_2 \quad (26)$$

$$st^{III}_{ij} - st^{I}_{ik} - S^{I}_{i} \ge m_3(1 - pu_{ijk}) \qquad \forall i \in TP, j \in HRC, k \in K_1 \quad (27)$$

$$p_{ijk} + u_{ij} \le 1 + pu_{ijk} \qquad \forall i \in TP, j \in HRC, k \in K_1 \quad (28)$$

$$p_{ijk} + u_{ij} \ge 2pu_{ijk} \qquad \forall i \in TP, j \in HRC, k \in K_1 \quad (29)$$

$$v_{k\hat{k}j} \le \sum_{i\in V_1} x^{I}_{ijk} \qquad \forall j \in TP, k \in K_1, \hat{k} \in K_2 \quad (30)$$

$$\sum_{k\in K_1} v_{k\hat{k}i} = \sum_{j\in V_2} x^{II}_{ij\hat{k}} \qquad \forall i \in TP, \hat{k} \in K_2 \quad (31)$$

$$\sum_{k\in K_1}\sum_{i\in TP} v_{k\hat{k}i} \le 1 \qquad \forall \hat{k} \in K_2 \quad (32)$$

$$\sum_{\hat{k}\in K_2} v_{k\hat{k}i} + u_{ij} \ge p_{ijk} \qquad \forall i \in TP, j \in HRC, k \in K_1 \quad (33)$$

$$TA_j \sum_{i\in V_2} x^{II}_{ijk} \le st^{II}_{jk} \le TB_j \sum_{i\in V_2} x^{II}_{ijk} \qquad \forall j \in HRC, k \in K_2 \quad (34)$$

$$TA_j \sum_{i\in TP} u_{ij} \le st^{III}_{jj} \le TB_j \sum_{i\in TP} u_{ij} \qquad \forall j \in HRC \quad (35)$$

$$x^{I}_{ijk}, x^{II}_{ijk}, y_i, p_{ijk}, v_{k\hat{k}i}, u_{ij}, pu_{ijk} \in \{0,1\} \qquad \forall i,j \in V, k \in K \quad (36)$$

$$st^{I}_{ik}, st^{II}_{ik}, st^{III}_{i}, q_{ik} \ge 0 \qquad \forall i,j \in V, k \in K \quad (37)$$

(1): The objective function - to minimize expenses involving travel and establishment costs.
(2): Each vessel departs from the central hub at most once.
(3): First echelon flow constraints.
(4): A TP can only be visited if it is established.
(5) & (6): Consistency of arrival and service times.
(7): Admissible laying times.
(8): Vessel capacity limits.
(9): A vessel visits a TP, its delivery volume could be non-zero.
(10): Quantities delivered to a TP satisfy the demand.
(11): Each demand point is served by one TP.
(12): A TP can serve a demand point only if it is established.
(13): Capacity limits of TPs.
(14)-(17): The allocation of moving jacks to demand points in proximity to TPs.
(18): Each LEV departs from one of the vehicle depots at most once.
(19): An LEV can access a TP only if it has been established.
(20): Flow constraints in the second echelon.
(21): Each demand point is served either by an LEV or a moving jack.
(22): Limited driving range of LEVs.
(23): Capacity limits of LEVs.
(24)-(25): Consistency in the service times of LEVs and moving jacks.
(26)-(29): Synchronization constraints, ensuring consistency in service times when vessels are synchronized with LEVs or moving jacks.
(30)-(33): Synchronization process between vessels and LEVs.
(34)-(35): Time windows.
(36)-(37): Types of variables used.

Solution Methodology

Our Two-Echelon Location Routing problem is solved by a hybrid solution algorithm that decomposes the problem into two nested sub-problems, including the first-echelon and second echelon problems. We first develop an Adaptive Large Neighborhood Search (ALNS) metaheuristic to determine the location and routing decisions in the second echelon. Then, based on the provided results, we apply a Branch and Price (B&P) algorithm using the Dantzig-Wolfe decomposition principle to transform the first echelon routing model into a master problem and a subproblem. Algorithm 1. provides the pseudocode of our proposed solution methodology.

Algorithm 1. Two-Echelon Location Routing Algorithm

Input: Input Parameters Data
Output: Best-found feasible solution (S_f^*)

```
Obj(S_f^*) = ∞
Generate the initial solution for the second echelon (S_in^2)
Based on S_in^2 generate the initial solution for the first echelon (S_in^1)
S_in = {S_in^1, S_in^2}
while termination criteria are not met
    S_f^2* ← ALNS(S_in^2)   Apply ALNS to generate the best feasible solution for the second echelon
    S_f^1* ← B&P(S_f^2*)    Based on S_f^2* generate the best feasible solution for the first echelon applying B&P
    S_f = {S_f^1*, S_f^2*}
    if Obj(S_f) ≤ Obj(S_f^*)
        S_f^* ← S_f
    end if
    S_in ← S_f
end while
return S_f^*
```

In order to generate the initial solution, we apply the K-means clustering algorithm to specify the number and location of established transshipment points. We further apply the Semi-Parallel Construction (SPC) heuristic proposed by Paraskevopoulos et al. [9] to complete the second-echelon routes.

Adaptive Large Neighborhood Search

We have adopted ALNS at the core of our algorithm for the second stage, adjusting it to our problem by allowing infeasible solutions, using specific destroy and repair operators, and applying local search for intensification. Alongside commonly known destroy operators like Random, Worst, Shaw, and Route removal, we utilize Transshipment point removal, opening, and swap as destroy operators. Our ALNS also applies Greedy, Regret, and SPC-based insertions, altering the SPC heuristic by adding demand points to existing and new routes while ensuring capacity constraints are met.

Branch and Price

Once the solution of the second echelon is obtained, the problem at the first echelon is seen as a split delivery vehicle routing problem with time windows, where the established transshipment points are seen as the demand points. Next, we need to specify the demand and the time windows at TPs. Since split deliveries are admissible, we cannot treat the set of all allocated demand points of a TP as a unit point. This is because all points visited by a single LEV should be served by a unique vessel due to synchronization constraints. Accordingly, we will have the accumulation of demands served by each LEV as one unique demand, located at its initial TP and with time windows respecting the time windows of all those demand points. Then, we need to create copies of TPs with demands equal to the demand of points served by a moving jack or accumulated demand of each LEV. In this way, the problem at the first echelon is transformed into a classic VRP with time windows, to solve which there exists extensive research applying branch and price.

Agent-Based Discrete-Event Simulation

Although the modal shift to waterways has the potential of reducing congestion, improving efficiency, and promoting environmental sustainability while alleviating the strain on Amsterdam's infrastructure, further analysis is needed to evaluate the feasibility and potential benefits, considering infrastructural limitations and canal characteristics. Accordingly, we develop an agent-based discrete-event simulation framework using the Open source Transport Network Simulation (OpenTNSim) python package to investigate vessel traffic patterns before and after this modal shift.

The canal network is represented as a graph G(V, E), where V represents the set of vertices and E is the set of edges. Each vessel is considered to be an agent moving on the graph with different attributes such as speed and capacity. Based on the routing patterns and size of the vessels, we consider six vessel classes, including fixed-path passenger vessels (cruise vessels), semi-fixed-path passenger vessels (random cruise vessels), random-path passenger vessels (pleasure crafts), construction freight vessels, waste freight vessels, and finally our proposed HoReCa freight vessels.

In order to develop a model that can reproduce the existing traffic patterns over the canals of Amsterdam, we need to get insights into the day-to-day traffic flow over the canals. In this respect, we have carried out data analysis on the data provided by Waternet and Municipality of the Amsterdam (MoA). Waternet provided data on seven measurement points over the city center. Each point measures the number of vessels passing by each hour and the direction in which they are sailing. The result of our data analysis provides the average inter-arrival time of vessels of each class based on which vessels are injected into the canal network.

In order to analyze the effects of this modal shift on traffic and infrastructure of canals (quay walls), we examine two key metrics in four traffic scenarios. Initially, we assess the average transit time for various vessel types. Additionally, we evaluate vessel traffic density specifically across canals affected by damaged bed levels. This approach allows for a more in-depth investigation into the impact on both transit efficiency and infrastructure utilization.

Results and Discussion

Optimization Results

To validate our mathematical model and solution algorithm, we compared it with CPLEX on instance sets featuring 5-25 customers, 1 or 2 LEV depots, and 2 to 4 transshipment points within a 2-hour computing limit. Our algorithm notably performs well, achieving optimal solutions within shorter times for sets of 5, 10, and 15 customers, with a zero gap between the results obtained by CPLEX and our algorithm. Even for instances with 20 and 25 customers where CPLEX didn't reach global optimality in two hours, its solutions were within a 0.7% gap from the objective function's linear relaxation in branch and bound iterations. In these cases, our algorithm matched or outperformed CPLEX in delivering equal or better results.

Here, we provide an optimal design for the distribution chain of restaurants and cafés located in Amsterdam's historical center. The municipality has specified a set of potential locations for transshipment points and has classified them into poor, moderate, and spacious points based on the available space on the quay. In order to estimate the daily demand of these businesses (in m3), we have incorporated a Deep Neural Network (DNN). To obtain train data for our DNN, demand data were collected through field trip. Figure (3) illustrates the result of solving the problem for the case of Amsterdam.

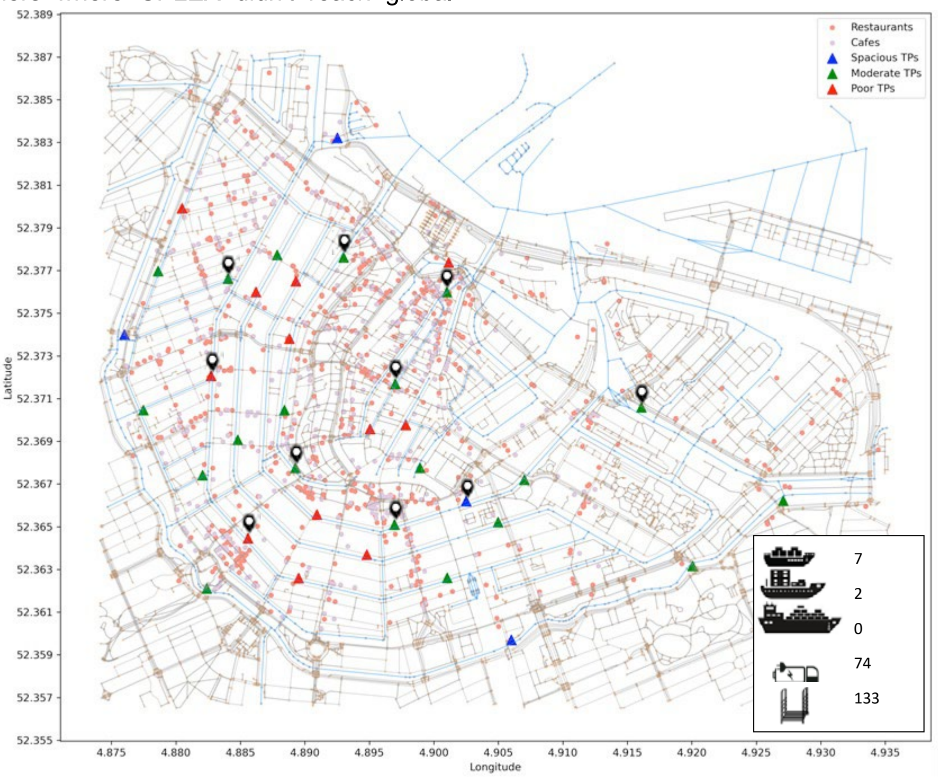

Figure 3 Case study Results

The case study results (Figure 3) show 10 strategically placed transshipment locations in densely populated city areas. To serve restaurants and cafés efficiently, we use seven small and two medium vessels; large vessels aren't viable due to canal limitations. In the next stage, 74 LEVs and 133 moving jacks transport items to final destinations. Well-placed transshipment points have cut down the needed LEVs by using moving jacks for nearby waterway locations.

Next, we compare the designed distribution chain with the one currently implemented in Amsterdam, for which trucks with a weight limit of 3500 kg deliver the items to demanded spots. Figure (4) compares these two distribution chains in terms of the total cost, the total number of applied road vehicles, their associated weight, and the average distance driven by each vehicle within the city center.

The analysis shows that using waterways for food distribution has a substantial advantage in overall cost, potentially saving about 28% compared to trucks. Even though more vehicles are used in this system, they are lighter, resulting in a 43% reduction in total vehicle weight in the city center. Additionally, the waterway method reduces the average distance traveled within the city center by 80% when serving HoReCa spots compared to trucks. This decrease in travel distance could ease

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traffic congestion, enhance efficiency in time and fuel use, and reduce emissions.

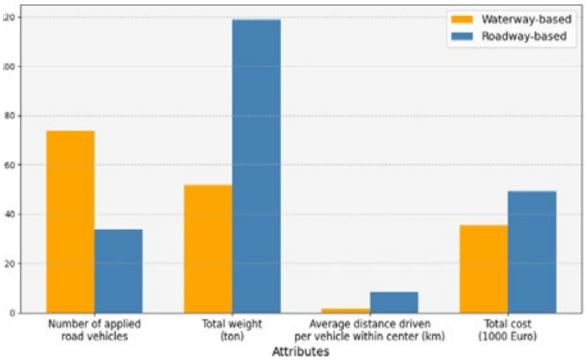

Figure 4 Comparison between waterway-based and roadway-based logistics chain

Simulation Results

The following figures illustrate the outcomes derived from our investigation into the impact of modal shift on traffic and infrastructure of canals. Figure 5 displays the average transit times across different vessel types, providing a comparative analysis of their respective efficiencies following the modal shift. Figure 6 depicts the changes in vessel traffic density (number of vessels within an hour) over canals before and after modal shift in scenario 1. To make our analysis robust, both figures represent the average result of ten simulation runs.

Figure 5 illustrates that the introduction of a modal shift exhibits minimal impact on waterway traffic. Specifically, in scenarios with low and very low traffic volume, the observed differences remain negligible, indicating little variation despite the change. As traffic volume escalates to high and medium levels, the average transit time sees a maximum increase of approximately 2 percent. This marginal delay translates to less than a 5-minute extension in transit time, showcasing that even under heightened traffic conditions, the impact of modal shift on waterway traffic remains limited.

Figure 6 illustrates that over some canals the modal shift can result in maximum changes of traffic density that varies between 8 to 12 vessels per hour. This particularly is important for canals specified by a location mark, which have deteriorated quay walls. The increase in the number of navigating vessels can lead to the increased propeller wash worsening the status on the infrastructure. This highlights the pressing need for in-depth investigation of the impact of this modal shift on infrastructure that may result in abandoning navigation through some parts of the network.

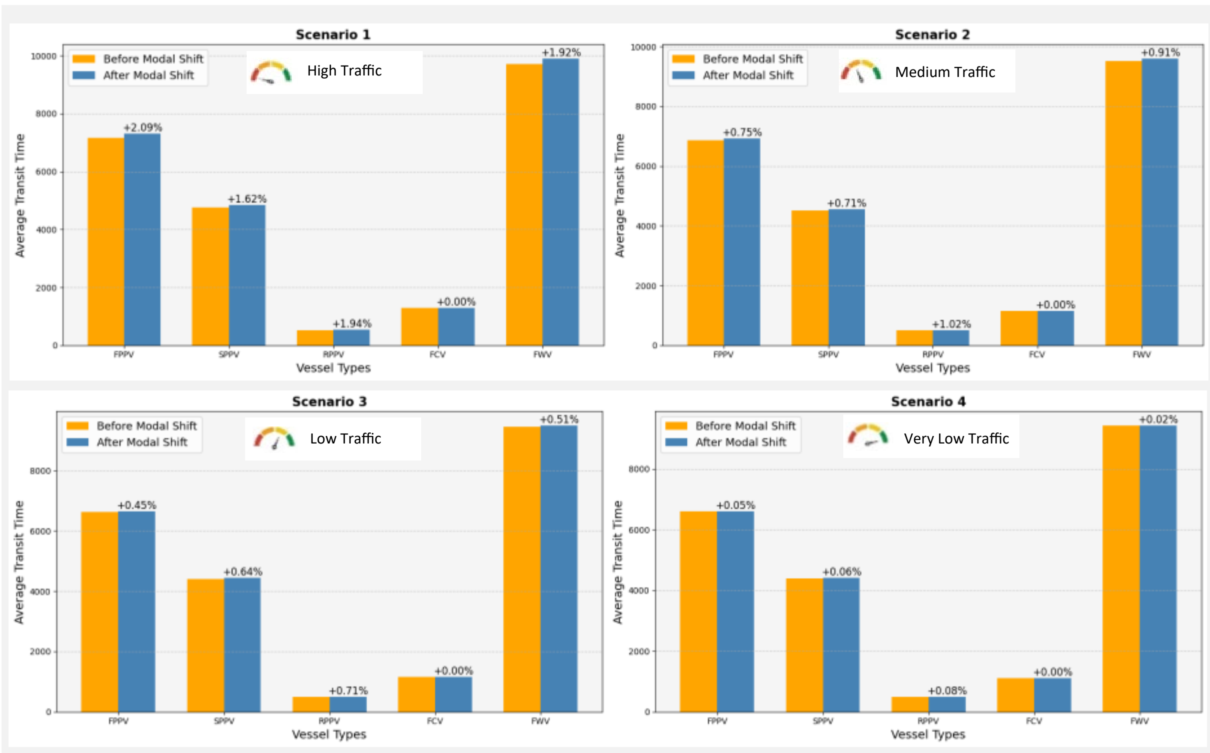

Figure 5 Average transit time per vessel type before and after modal shift

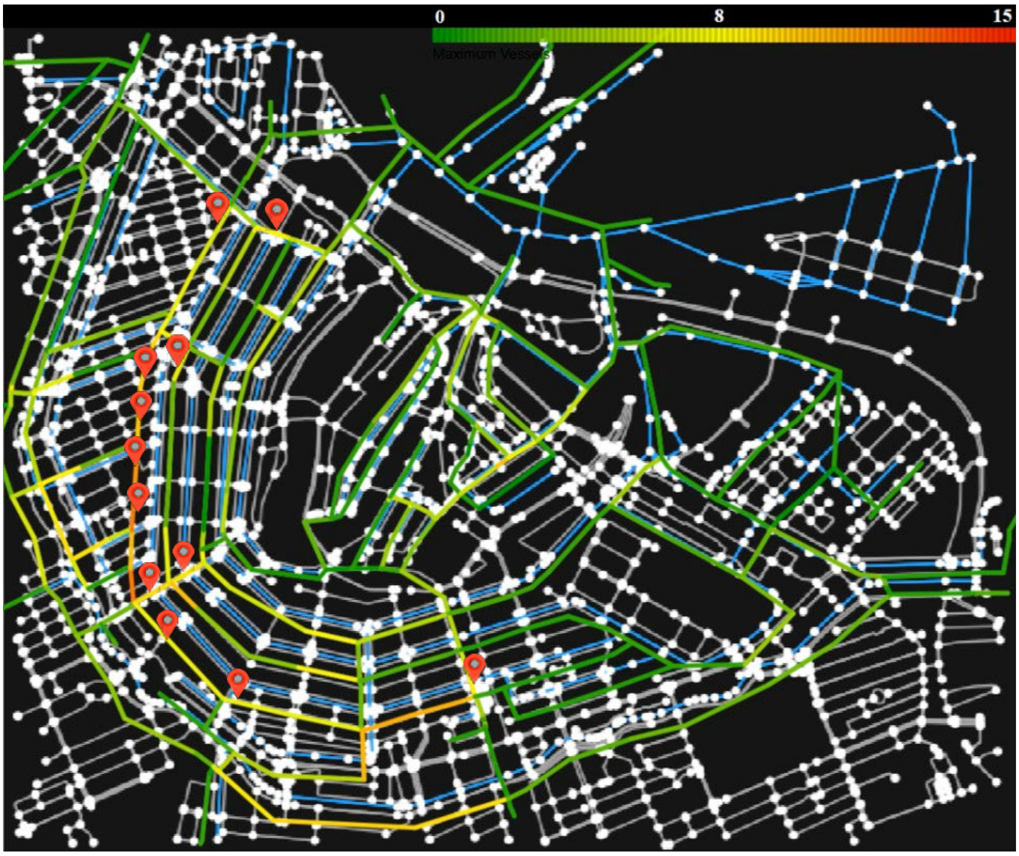

Figure 6 The changes in vessel traffic density over canals before and after modal shift

Discussion and Conclusion

This study focuses on enhancing Amsterdam's urban logistics efficiency by proposing an optimized network utilizing both waterways and last-mile delivery. Our proposed urban logistic network integrates waterways and last-mile delivery via road transport, formulated as a two-echelon location routing problem with time windows. An innovative hybrid solution approach was developed. Our algorithm consistently outperformed previous methods, demonstrating its effectiveness in solving benchmarks and creating new ones. This emphasizes how investing in algorithm development improves business operations.

Our investigation into the waterway-based distribution showed compelling advantages over traditional truck-based systems. Comparing costs, vehicle weight, city travel distance, and environmental impact, we found substantial benefits. Implementing the waterway system led to approximately 28% cost savings compared to trucks, with lighter vehicles reducing city center vehicle weight by 43%. This not only benefits infrastructure but also offers a more adaptable delivery system. Moreover, the waterway approach drastically cut city travel distances by 80%, potentially easing traffic, enhancing efficiency, and reducing emissions. Electric vehicles in this setup further lowered carbon emissions, highlighting environmental advantages.

Building upon our simulation results, it is crucial to underscore that while the impact of modal shift on waterway traffic remains relatively limited in transit time extension, the potential strain on specific canal infrastructures cannot be overlooked. Further analysis should explore mitigation strategies to address increased vessel traffic density and thereby potential infrastructure degradation, especially in areas with deteriorated quay walls.

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