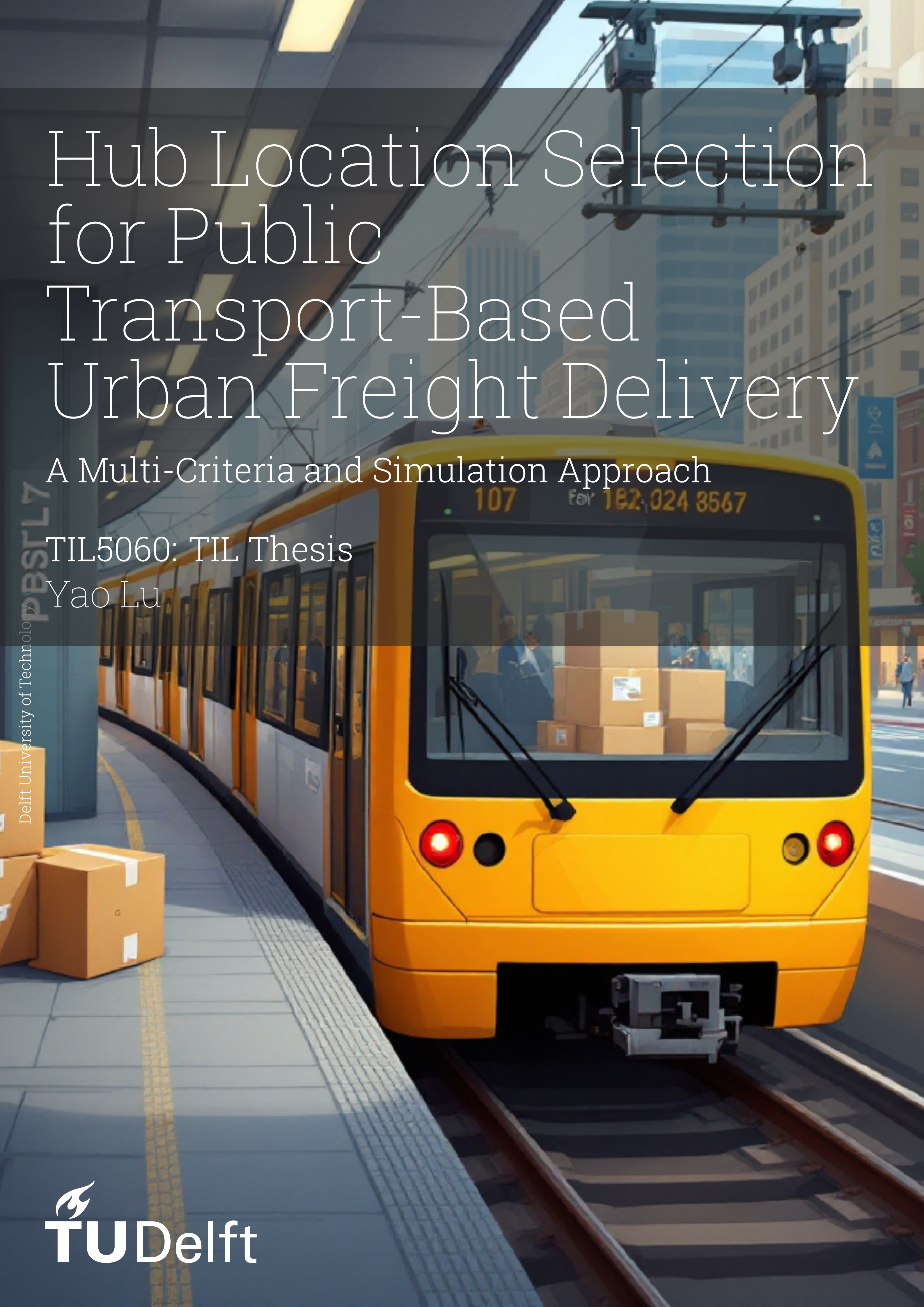

Hub Location Selection for Public Transport-Based Urban Freight Delivery

A Multi-Criteria and Simulation Approach

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Summary

Freight transport is essential for accommodating contemporary populations and fostering economic development in urban environments. However, the escalating demand for various freight goods is resulting in heightened congestion within metropolitan areas and on roadways, substantially increasing emissions. The escalating occurrence of commercial logistics vehicles, coupled with the expansion of e-commerce and growing demand for fast delivery, has exacerbated the adverse effects associated with freight transport. These effects encompass heightened energy consumption, intensified road congestion, and increased air pollution, leading to the essential pursuit of alternative, sustainable urban freight solutions.

The integration of freight delivery within existing public transport networks presents a compelling opportunity to alleviate the aforementioned negative impacts. Leveraging the underutilised capacity of public transit can effectively address the needs of intra-urban logistics while maintaining cost efficiency. Nonetheless, previous research on this topic has predominantly centred on operational issues while presuming simplified transit routes, neglecting the intricate, multi-modal nature of extensive urban transit systems. In effect, the strategic design of freight hubs within public transit networks is of paramount importance for the operational viability of integrated public and freight transport systems. Specifically, public transport stations can be freight hubs to avoid the necessity of constructing additional logistics infrastructure while enabling the efficient movement of goods along fixed transit routes that adhere to predetermined schedules. However, there exists a notable scarcity of both empirical and theoretical research focused on hub locations within combined passenger and freight networks.

This study develops a novel framework for the selection of public transport stations to serve as freight hubs within the context of urban Public Transport-Based Freight Delivery (PTF). In order to comprehensively evaluate the qualitative and quantitative factors influencing hub locations, a multi-criteria decision analysis (MCDA) is conducted utilising the Best-Worst Method (BWM). This method results in the establishment of a robust set of hub selection criteria, thoroughly assessed by experts in relevant fields. The criteria are applicable to diverse categories of hubs, assessing the extent to which candidate transit stations are equipped to facilitate freight operations. Subsequently, a simulation is undertaken to assess the viability of the proposed hub configurations within real-life settings. The conducted sensitivity analyses for both methodologies demonstrate the degree to which the criteria are influenced by various hub types and the performance of hubs under realistic constraints.

The MCDA results indicate that accessibility, including proximity to major transport networks and freight origins and demands, is crucial when identifying most freight hubs. Capacity and costs also play a key role in establishing integrated freight hubs, in addition to accessibility. On the other hand, the simulation findings illustrate the importance of balancing network reach, hub handling capability, and financial constraints. Using only major hubs could be cost-effective and emission-friendly but unable to satisfy much demand. Routing freight through a predetermined sequence of hubs that requires a mandatory transfer enhances the freight handling rate but leads to substantially increased costs and emissions due to the compulsory transfers involved. A network promoting hubs that are close to freight destinations without mandatory transfers balances cost-effectiveness and network utilisation but necessitates careful budget allocation. In general, financial factors greatly influence system viability, outweighing operational constraints such as hub capacity or transit time. Hub setup costs significantly impact network scalability, particularly in hierarchical networks that use additional transfer hubs.

Overall, this study effectively demonstrates the critical factors for establishing integrated freight hubs through a combined MCDA and simulation approach, highlighting the trade-offs associated with various hub compositions regarding network utilisation, coverage, and overall costs. Future research may utilise this multi-criteria and simulation framework to further investigate these factors or modify it as necessary. Meanwhile, to put PTF initiatives into practice, policymakers should take into account the trade-offs associated with implementation, as indicated by this study.

Contents

List of Figures

List of Tables

1
Introduction

1.1. Research Context and Problem

Freight transport is essential for thriving urban areas with dense populations and competitive business sectors. With over 50% of the population residing in cities [7], the continuous provision of goods is vital for enhancing urban liveability [47]. However, freight transport contributes approximately 8% of global greenhouse gas (GHG) emissions, or up to 11% when accounting for warehouses and ports [3]. Compounding the problem, demand for urban freight is projected to triple by 2050 [40]. This growth creates environmental and logistical pressures as urban congestion, air pollution, and inefficiency in freight transport intensify. Consequently, both freight operators and municipal authorities face growing challenges in balancing efficiency, sustainability, and cost-effectiveness [24][47].

In freight transport, goods are picked up from producer locations (pre-haul), transported over long distances (long-haul), and delivered to customers (end-haul) [67]. With the rapid growth of e-commerce, last-mile deliveries (LMDs) to dispersed urban residences have surged, increasing congestion and emissions and reducing opportunities for shipment consolidation [6]. In the meantime, due to the increasing number of logistics vehicles, the rise of just-in-time (JIT) deliveries, and growth in urbanisation globally, the negative impacts caused by freight transport are being worsened [11]. These include energy consumption, road congestion, GHG emissions, air pollution, and safety concerns with freight vehicles, resulting in a spurred search for alternative urban freight solutions that can alleviate these negative societal and environmental impacts.

A promising approach is the integration of freight transport within existing public transport networks, a strategy that could address these issues by reducing the reliance on dedicated delivery vehicles and utilising idle capacity on public transit. Various public transport modes, such as light rail [10], metro [41], and tram [31], could serve as conduits for urban freight, offering significant potential to reduce road congestion and emissions. Harnessing public transport for freight movement can create additional revenue streams for transit providers and provide a sustainable alternative for freight transport [6]. This model, known as Freight on Public Transportation (FPT) [29], Freight on Transit (FOT) [22], or Cargo Hitching [72], involves transporting both goods and passengers within the same network, addressing intra-urban delivery needs. As public transit networks often operate below capacity [19][44], it can be a promising alternative for freight delivery. This thesis defines the term "Public Transport-Based Freight Delivery (PTF)" as the coordinated movement of people and goods using transit services on fixed urban routes.

While pilot studies and projects demonstrate the feasibility of PTF models, their focus has been primarily on operational issues—namely scheduling, routing, and capacity adjustments to accommodate freight without disrupting passenger service [33][37][53]. Zurich's Cargo Tram, for instance, successfully operates by transporting large items during off-peak hours to avoid passenger conflicts, showing how PTF can function under specific conditions [50]. Despite their success, such initiatives have faced challenges such as logistical coordination, stakeholder agreement, and public acceptance, highlighting the operational complexities involved in mixed-use transit systems. Yet, the majority of studies remain limited to tactical and operational focuses and do not delve into the fundamental strategic planning that would be crucial for the broader adoption of PTF.

A key element that has received little attention in PTF research is the strategic design of hubs within public transit networks. Hubs are crucial as they serve as central nodes for consolidating, transferring, and managing freight flows, allowing goods to be processed, sorted, and directed efficiently across an urban network [30]. In passenger transport, a public transport network is composed of differently sized stations with varying transfer and connecting services, and the central stations can be identified as the major hubs. Similarly, in the context of PTF, the passenger stations act as freight hubs. As such, the strategic placement and configuration of these hubs are also essential for the operational efficiency of the system. Many studies to date have focused on single-line or closed-loop public transport routes [6][53], which do not accurately represent the complex, multi-modal networks characteristic of large urban transit systems. In smaller towns with limited services, a single transit line may suffice. In major urban centres with extensive networks, identifying optimal hub locations for freight consolidation, deconsolidation, and storage requires more sophisticated planning. Taking trams as an example, the success of a freight tram scheme relies on the existing infrastructure, freight demand needs, and cross-docking facilities. A freight tram in a city should be close to commercial areas and have convenient access to major road or rail facilities to facilitate an attractive consolidation [61]. Therefore, using public transport stations, which already have some infrastructure built that may be changed to accommodate freight operations or space to install logistics facilities, has the possibility to greatly lower the costs of building new city logistics infrastructure.

In all, the effective placement of hubs can be transformative for PTF systems. By acting as primary nodes where goods are bundled, organised, and transferred, strategically located hubs facilitate smooth, reliable freight movement across transit routes. Hub locations, however, introduce challenges that are distinct from the tactical and operational problems. It requires a high-level approach that considers spatial accessibility, service frequency, and proximity to demand clusters, balancing these factors to maximise network efficiency while minimising transport costs and distances [48][68][42]. Research on the hub location problem (HLP) in logistics demonstrates its critical role in conventional networks, but there is little empirical or theoretical work that extends this concept to public transport-based freight systems, leaving a critical gap in PTF research.

Addressing this gap by optimising hub locations would enhance the efficiency of urban transit-based freight systems. This thesis aims to explore this under-researched area, contributing a pioneering analysis on the optimal placement of hubs within public transport-based freight systems. The operational and tactical aspects are not directly looked at in this study; instead, realistic assumptions are made due to practical limitations. By focusing on strategic hub planning, the study aims to improve the long-term viability of mixed-use freight networks and create a framework for similar uses in the future.

1.2. Research Objectives

The primary objective of this study is to develop an urban freight delivery system that utilises public transport as the main transport mode. More specifically, the study aims to design a strategic hub placement framework for PTF systems. The objectives are as follows:

- Objective 1: To identify criteria for selecting public transport stations as freight hubs within a public transport-based freight system.
- Objective 2: To explore possible network configurations for integrating public and freight transport, using stations as hubs of varying levels to optimise system performance.
- Objective 3: To systematically analyse the effects of different hub configurations on the efficiency and sustainability of a public transport-based freight system.

1.3. Research Questions

Based on the study objectives, the main research question is as follows:

How can we optimally plan the hubs of a public transport-based freight delivery (PTF) system?

The main research question is decomposed into the following sub-research questions, together with which it fulfills the goal of this study:

- RQ1: What are the criteria for selecting public transport stations to be hubs in a public transport-based freight delivery (PTF) system?
- RQ2: How can the identified criteria be used to rank public transport stations as different levels of freight hubs?
- RQ3: What are the possible network configurations comprising different levels of hubs?
- RQ4: How can the performance of the proposed hubs be evaluated under realistic urban scenarios?

The objective of RQ1 is to discover the functionalities that existing public stations should have or modifications needed to act as freight hubs so that a set of comprehensive criteria can be formed, supporting the use of public transit stations as freight hubs. RQ2 aims to score and rank candidate stations based on the identified criteria. The goal of RQ3 is to develop hub categories that can be applied in PTF and generate realistic configurations. Lastly, RQ4 simulates the performances of the proposed hub uses under real-life conditions.

1.4. Research Approach

This research begins with exploring the concept and scope of a transit-based freight system from the existing literature. Specifically, how freight transport functions can be added to public transport networks, and further using transit stations as freight hubs, is investigated. The literature review thus inevitably explores existing implementations of PTF systems, whether successful or discontinued. Most importantly, the role of hubs in facilitating efficient freight flows using transit networks and impacting factors on the hub locations are identified. Finally, gaps in current research are summarised, emphasising the importance of strategic hub planning in developing PTF systems.

Building on the findings of the literature review, a comprehensive set of criteria to select transit stations as freight hubs is provided. These criteria are designed to reflect the operational, logistical, and ease-of-use requirements of a PTF system, which are as follows:

- Cargo Requirements: Factors such as product vulnerability, demand volatility, and security needs.
- Connectivity: The level of integration within the public transport network, service frequency, and intermodal connectivity.
- Costs: Investment, operational, and maintenance or upgrade costs associated with operating public transport station-based freight hubs.
- Capacity: The physical space, infrastructure, equipment, and operational capability at each candidate station.
- Accessibility: Proximity to demand and supply locations, access to road networks and active transport modes, and digital access to tracking and navigation technologies.

To select suitable stations from a list of candidates, the Best-Worst Method (BWM), a robust Multi-Criteria Decision Analysis (MCDA) tool, is employed. The hubs are categorised as primary (for freight access), secondary (transfer), and local hubs (for drop-off and last-mile pickup). A panel of experts, including public transport and freight transport specialists, is interviewed and surveyed to identify the best and worst criteria for hub evaluation. Then, pairwise comparisons are conducted to assess the relative importance of criteria, using a structured scale to ensure consistent answers. Using a solver of the BWM, the relative weights of criteria are then derived, of which the reliability is ensured through consistency checks. These criteria weights are used to evaluate candidate hubs and rank them as primary or local hubs based on their suitability for freight operations. The outputs of this process are prioritised lists of hubs, primarily addressing RQ2. The ranking of secondary hubs, though, is done via centrality evaluations based on the network composition instead of pre-defined criteria by experts, unlike primary and local hubs.

Afterwards, several hub configurations are generated, which answer RQ3. Finally, a simulation is conducted to validate the prioritised hubs in a case study of a representative urban area in The Netherlands.

Various hub configurations under realistic urban conditions are simulated to support answering RQ4. One of the main data sources is a multi-agent freight simulator, the Multi-Agent Simulation System for Goods Transport (MASS-GT), developed with rich real-world freight data. On the other hand, information about public transport stations is collected, depending on the available data in the case study area. The simulation results are analysed for actionable recommendations for urban planners and transport authorities. In addition, limitations and future directions of this study are also drawn. Table 1.1 provides an overview of the methods used in this study, while Figure 1.1 illustrates the overall solution approach.

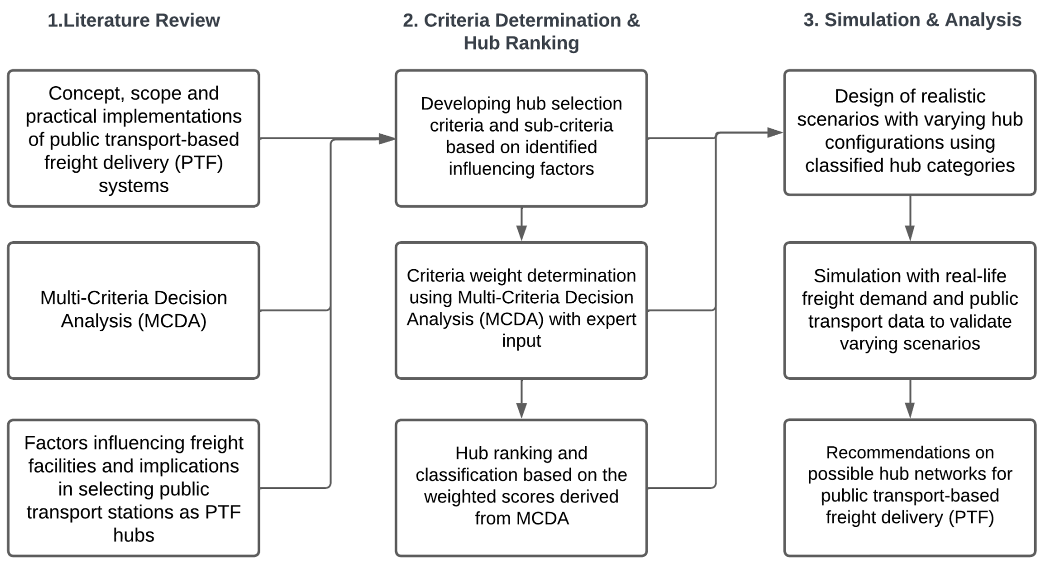


Figure 1.1: Methodology

Table 1.1: Method per Sub-Research Question (RQ)

Sub-Research Question (RQ)	Method(s)	Output
1. What are the criteria for selecting public transport stations to be hubs in a public transport-based freight delivery (PTF) system?	Literature Review	Comprehensive evaluation criteria for hub selection and ranking
2. How can the identified criteria be used to rank public transport stations as different levels of freight hubs?	Literature Review, Multi-Criteria Decision Analysis (MCDA)	Lists of hubs classified as primary, secondary, and local
3. What are the possible network configurations comprising different levels of hubs?	Multi-Criteria Decision Analysis (MCDA), Simulation	Hub configurations
4. How can the performance of the proposed hubs be evaluated under realistic urban scenarios?	Simulation	Performance evaluation of realistic scenarios with identified hub configurations

1.5. Research Outline

Following Chapter 1: Introduction, Chapter 2 discusses the findings from the literature during the initial research. Chapter 3 outlines the methodology used in this study. Chapter 4 presents the selection criteria for public transport stations to act as freight hubs. Chapter 5 simulates the implementation of the proposed model in a case study. Lastly, discussions, conclusions, and recommendations for future research and implementation are provided in Chapter 6.

2 Literature Review

This chapter discusses the findings of the literature survey. The objective is to understand the problem background, draw gaps upon existing studies, and help develop methodology. Firstly, an overview of the concept of PTF is provided, and existing practices are explored. Then, the relevant problems and modelling techniques for PTF systems are highlighted, revealing what is discovered and undiscovered in this field. Studies on one of the main methods, Multi-Criteria Decision Analysis (MCDA), are also reviewed. In addition, the factors influencing the location of freight hubs are explored. Finally, conclusions on the literature review are given.

2.1. Public Transport-Based Freight Delivery (PTF)

Using public transport to deliver freight for parts of the whole logistics journey relies on using the excess capacity of passenger transport vehicles combined with traditional or innovative pre-haul or last-mile solutions. Using public transit for freight represents an “efficient and environmentally friendly” solution that maximises existing resources through shared infrastructure, vehicles, and spaces within public transport networks, addressing many of the challenges associated with costly LMD [29]. The transport of goods may also generate supplementary revenue for public transport providers, creating opportunities to improve service levels by increasing frequency and coverage [6][22]. Integrating freight with transit networks also has the potential to decrease the costs of goods transport and significantly reduce road congestion and CO_2 emissions [22][25]. Furthermore, with appropriate design, the reduction of conventional logistics activities could significantly decrease the number of road accidents [25]. A conceptual PTF system from existing research can be seen in Figure 2.1.

Combining public and freight transport could contribute to three axes towards sustainable city transport [70]. The first is to enhance the allocation of road space for the movement of private and public motorised road transport passengers, as well as the movement of cargo by private motorised road transport. The second objective is to transition passengers and goods from private motorised road transport to public transport modes, including buses, trams, metros, and car and bike-sharing systems. The last relates to installing distribution infrastructure, such as centralised hubs, urban delivery stations, and storage facilities in urban passenger locations (e.g., car parks and public transport terminals), reducing unnecessary travel and parking. Shifting more freight flow to public transport vehicles, which is the aim of this study, clearly fulfils the second goal.

The advantage of using public transport is profound when moving freight during the pre-haul and long-haul processes [50]. This suggests the necessity of considering suitable delivery options at the last mile. Nevertheless, public transit vehicles, which are responsible for the middle leg of the freight journey, can be easily connected with sustainable LMD services. For instance, self-collection points for customers and LMD vehicles at stations could facilitate the temporary consolidation and storage of parcels when the capacity of transit and LMD vehicles is not aligned [6]. In [55], a case study in a medium-sized Brazilian city was conducted, showing that an appropriately sized parcel locker network, installed at transit stations, can provide accessible and equitable services for residents with the easy means of walking or cycling. However, there are rarely other studies that focus on the determination of the appropriate types of stations and self-collection facilities. The majority of research on integrated passenger and freight transport focuses on tactical or operational decisions such as scheduling and routing, as discussed in Section 2.1.2.

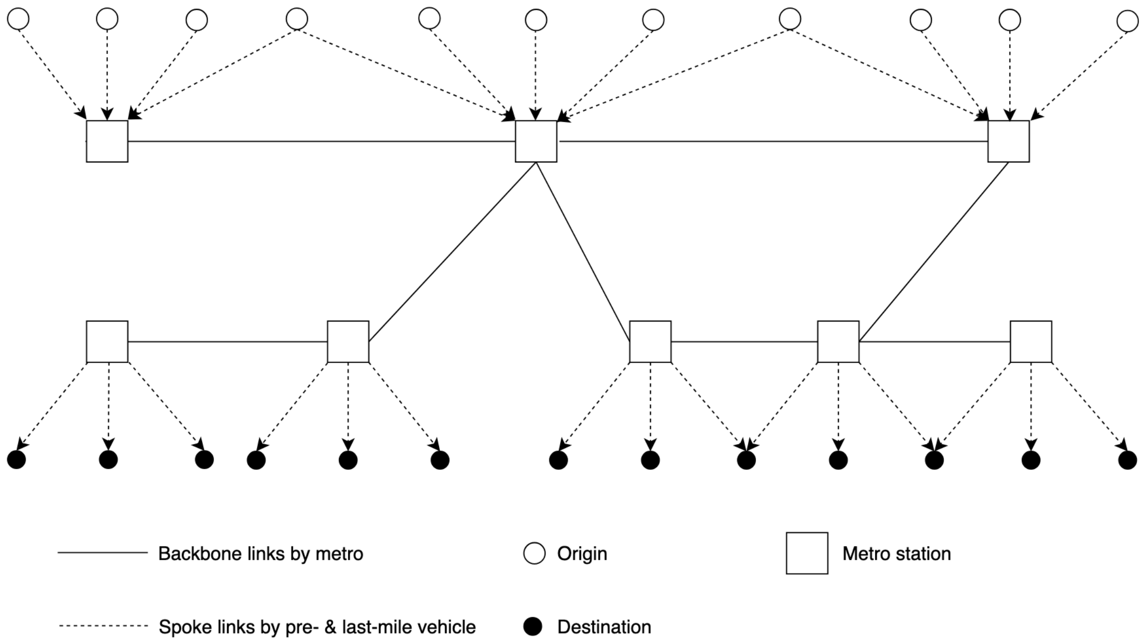


Figure 2.1: Concept of Public Transport Freight Delivery (PTF) [41]

2.1.1. Successful and Failed Implementations

Examples of freight on public transport projects can be found worldwide, though many of these projects were implemented and discontinued shortly, with only a few remaining in operation. PTF strategies are promising but largely experimental due to the complexities of integrating freight within a passenger-focused transit system, which often requires designated times and routes to prevent passenger disruption [22].

CarGoTram, Dresden

Since 2001, Volkswagen's factory and logistics centre have been linked by the CarGoTram in Dresden, Germany [50]. The factory, which is situated in the historic city centre, has restricted stock capacity and waiting areas. Volkswagen selected rail due to its longstanding and well-developed rail network, continuous flow, effective tram lines, and environmentally and city-friendly transport system. The CarGoTram concept comprises a single departure point, destination, operator, and client. Passenger trains are prioritised within the public rail network. The tram system is a loop system that utilises curtain-side trailers to facilitate loading. The impact of this project is that the city centre of Dresden experiences a decrease in traffic and CO_2 emissions.

CityCargo, Amsterdam

In 2007, City Cargo Amsterdam introduced the Cargo Tram initiative in Amsterdam, The Netherlands, with the objective of reducing emissions from goods transport within the city, a contributing factor to air pollution, congestion, and ambient noise [50]. The company developed a fleet of environmentally friendly vehicles for transporting cargo via the city's underutilised streetcar tracks and electric delivery vehicles. The pilot project consisted of two GVB (Gemeentevervoerbedrijf, the public transport authority of Amsterdam) cargo trams that were specially adapted and supplied by trucks at the end station of tram 1 in Osdorp. The trams functioned on a designated route within the city from 7 a.m. to 11 p.m. To avoid interruptions to standard traffic schedules, the trams were designed to adhere to the routes of existing passenger vehicles. In 2012, the trial successfully facilitated an investment of €100 million in a fleet of 52 cargo trams, which were designated to distribute goods from four peripheral ”cross docks” to 15 inner-city centres. The project was discontinued in 2009 because of financial issues, even though the system was promoted as cost-effective.

Cargo Tram, Zurich

The Zürich Cargo Tram, a novel service that was introduced in 2003, offers a cost-effective and efficient method of transporting bulky waste from the city’s vast tram network in Zurich, Switzerland [50]. The service was put forward by ERZ (Entsorgung und Recycling Zürich), which is in charge of garbage disposal activities, and VBZ (Verkehrsbetriebe Zürich), the local tram company. The goal is to relocate road refuse collection, establish facilities for the period when working people are not at work, and decrease road haulage. The service initially consisted of four stations but has since grown to nine. The Cargo Tram is priced at €20,000, substantially less than the cost of an equivalent road vehicle. Since its launch, the service has significantly reduced road haulage and emissions [73], while receiving positive acceptance from the local residents.

Monoprix, Paris

Monoprix, a supermarket brand in France, has implemented a system that combines rail and eco-friendly vehicles powered by natural gas to distribute non-perishable products to 90 stores in Paris, aiming to reduce the city’s congestion issues [50]. Soft drinks, domestic goods, and personal care products comprise the freight. The system has demonstrated its efficiency and adaptability by reducing the use of petroleum by 700,000 km, reducing environmental pollution, and lowering transport expenses. This case illustrates the challenges involved in establishing freight rail transport within urban environments, including the need for substantial logistics facilities limited by the railway infrastructure and specific retail entities that necessitate the daily transport of minimal merchandise to the city. In total, the Monoprix project resulted in a reduction of fuel of 70,000 litres, CO_2 emissions of 337 metric tons, NO_x emissions of 25 metric tons, and 12,000 fewer lorry trips into Paris’s central districts [74].

The above examples highlight the potential of public and freight transport models to reduce environmental impacts and enhance the efficiency of urban logistics. Each case demonstrates how designated routes and operational timing (e.g., during off-peak periods) can facilitate freight transport using public transit networks without disrupting passenger service. Projects such as Zurich’s Cargo Tram and Dresden’s CarGo Tram underscore the importance of well-structured systems where freight is moved seamlessly alongside passenger flows by utilising non-peak capacities and clearly defined loading areas. Despite differences in operational scale and objectives, these case studies share common success factors: minimalistic network structure, careful scheduling, and simple routes, all of which ensure the project implementation without sophisticated planning. With sufficient policy support, PTF approaches can be a feasible and valuable addition to sustainable urban logistics solutions.

2.1.2. Modelling Techniques

The majority of literature on PTF networks focuses on optimising the operational or tactical planning needs of these systems. Currently, more than 70% of research on PTF systems investigates operational problems, while those on strategic or tactical decisions are merely more than 10%, respectively (Figure 2.2). The emphasis of operational and tactical studies usually involves the coordination and synchronisation of public transport vehicles and LMD couriers, i.e., scheduling and/or routing of these vehicles. These studies can be referred to as the Pickup and Delivery Problem with Time Windows and Scheduled Lines (PDPTW-SL) [32][33][34][35], variants of the dial-a-ride problem (DARP) [4][23][46][52], or a two-echelon vehicle routing problem with transshipment (VRPT) to public transport [71]. While most of them assumed a naive network, one considered a few independent lines without transshipment [72], and a few others studied interconnected lines and transfer nodes [39][66][41] [77].

Although operational and tactical decisions are of vital importance in daily operations, the planning of PTF problems revolves around strategic choices first. Prior to considering public transit vehicles’ sizing, service frequency, timetabling, and LMD, it is essential to strategically consider long-term aspects, including the selection of departure, transshipment, and arrival stations, as well as the allocation of storage areas in the stations in the beginning [9]. One study recognised that there is a notable deficiency of research concerning the selection of locations for shared facilities [55]. Furthermore, as depicted in Figure 2.2, most literature emphasises the development of quantitative algorithms for addressing routing issues in combined public and freight transport networks by analysing pilot projects. Most integrated systems, however, are small-scale prototypes, increasing the difficulty of assessing their actual advantages as artificial data is used in quantitative analyses [54].

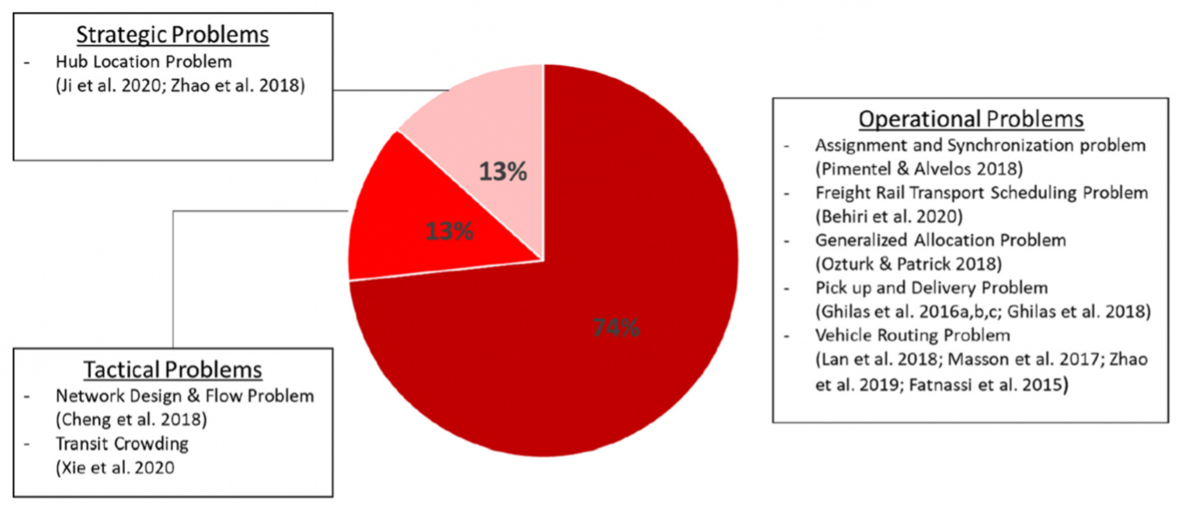


Figure 2.2: Distribution of Studies on Public Transport Freight Delivery (PTF)

In terms of simulation, minimal studies utilise simulation to model or implement the design of a public transport-oriented freight problem. Multi-agent models, one of the quantitative methods for assessing freight transport [75], model complicated freight transport networks in detail. The model's agents can represent shippers, LSPs, and regulatory authorities, each with their own goals and behaviours, helping the simulations to be increasingly realistic and dynamic [26]. By involving all major stakeholders' expectations and conflicts and any possible constraints, the potential consequences of a system could be well foreseen, whether positive or negative, supporting better decision-making by multiple stakeholders [8]. However, most of the existing studies only applied multi-agent models to either passenger or freight transport, not the two combined [49]. One of the limited examples can be seen in [37] where a combined optimisation and simulation approach was used to schedule concurrent passenger and freight transport using established infrastructure, despite the fact that it remained at the tactical operations of this integrated transport system.

2.2. Hub Location Problem (HLP)

PTF systems are often sophisticated multi-tier systems, as can be seen in Section 2.1. Researchers have studied complex multi-tier systems that carry commodities from a depot to an intermediate point, specifically focusing on facility location problems (FLPs). FLPs entail choosing locations for facilities at one or more layers and sometimes routing choices. A summary of the multi-tier distribution system can be seen in [17][57]. Having numerous starting points and destinations, these systems thus often function through hubs. Hubs can be referred to as points of "consolidation, connecting, and switching for flows between origin-destination pairs," which reduces the number of direct connections required in a transport network [30]. In freight transport systems, hubs streamline freight flows by minimising the number of required transfers, thereby reducing total transit distances and enhancing network efficiency. Hub location problems (HLPs) are then a subtype of FLPs that specifically tailor to strategically placing the central points for goods transfer [36][60].

In the context of PTF systems, HLP models face unique challenges because they must integrate freight within a system optimised for passengers. Alumur et al. [5] emphasise that hub models require careful consideration of "the topology of the access and inter-hub networks" to balance freight and passenger needs effectively. Hub-and-spoke networks, typical in HLP, reduce the number of connections between origin and destination pairs by consolidating flows at hubs. However, the design of dual-purpose hubs for combined passenger and freight transport must balance freight and passenger volumes while ensuring spatial accessibility and seamless integration with the transit network. Prior research on multimodal transport hubs has highlighted the importance of accessibility considerations [48], network integration strategies [42], and policy-oriented land-use planning [68] to enhance hub performance in urban settings.

The application of hub location models to PTF systems remains challenging due to the divergent needs of passenger and freight flows. In hub networks, it is rather complex to select the location of hub facilities and allocate customers to them due to variations in traffic patterns and the dual functionality required in PTF systems [30]. As such, determining optimal hub locations for freight within a public transit system demands sophisticated modelling techniques capable of incorporating multi-dimensional constraints. These constraints include accessibility, proximity to high-demand areas, capacity limitations, and the integration of freight-specific requirements within the spatial and temporal structure of transit systems. A few studies that address hub location challenges in the context of delivering goods using public transit are seen in [28] [41][43][76].

2.3. Multi-Criteria Decision Analysis (MCDA)

Selecting optimal hub locations within public transport-based freight systems requires a multi-dimensional approach that considers varying requirements, constraints, and objectives as a whole. Multi-Criteria Decision Analysis (MCDA) refers to making decisions through structured approaches that allow systematic evaluation of alternatives with respect to multiple criteria (attributes) [51]. MCDA methods allow the incorporation of both quantitative and qualitative factors in decision-making, thus providing a structured approach to prioritising hub locations.

2.3.1. The Best-Worst Method (BWM)

The Best-Worst Method (BWM) is an MCDA approach designed to derive criteria weights from decision-makers' judgments systematically and consistently. The BWM was developed to address some limitations of traditional MCDA methods, including the Analytic Hierarchy Process (AHP), to require fewer pairwise comparisons and offer higher consistency in outputs [64][65].

The BWM begins by identifying the best (most important) and worst (least important) criteria for the decision problem. Pairwise comparisons are then made between the best criterion and all others, and similarly, between all criteria and the worst criterion. These comparisons form the "Best-to-Others" (BO) and "Others-to-Worst" (OW) vectors, which are used to compute optimal weights by solving a linear optimisation model [64][65]. The major advantages of the BWM are as follows:

- Reduction in Pairwise Comparisons: The BWM prioritises the best and worst criteria rather than comparing all criteria, thereby decreasing mental workload and time [64][65].
- Improved Consistency: The consistency ratio in the BWM provides a measure of reliability for the pairwise comparisons, where values approaching zero signify higher consistency [64][65].
- Flexibility in Decision Contexts: The BWM can accommodate multi-optimality and interval weighting, making it adaptable to dynamic and uncertain scenarios [64][65].

2.4. Factors Impacting Freight Hub Locations

To use public transit stations as hubs for freight delivery, one of the essential considerations is the compatibility of cargo with varying types of stations. The real-life implementations listed in Section 2.1.1 utilised different transit modes to transport distinguishing products, and understanding which cargos could be serviced by which public transit vehicles is indeed critical [50]. Table 2.1 displays the detailed characteristics of five general urban logistical flows: construction, facilities, catering, parcels, and reverse [20][61]. Reverse logistics flows such as domestic waste have a promising potential to be delivered by public transport vehicles (e.g., trams) [61], as supported by the Cargo Tram project in Zurich, Switzerland [50]. In terms of product size and value, through a comparative analysis of several pilot projects, low-volume, high-value products have the greatest potential for delivery by urban rail transit [50].

The second important aspect is the characteristics the public transport stations should have to be capable of freight transport. In this regard, it is necessary to incorporate two aspects: 1) the types of public transit stations and their existing characteristics (designed for passenger transport), and 2) the

Table 2.1: Suitability of Urban Freight Flows with Public Transport [20][61]

Freight Flow	Suitability with Public Transport	Reasons
Construction	Not Suitable	• Requires point-point-point and Just-In-Time (JIT) or urgent deliveries • Items are often heavy and fragmented; normal public transport vehicles may not be capable of carrying them • Volumes can be large; the physical space at usual transit stations are not sufficient
Facilities (Goods, Persons and/or Services)	Not Suitable	• Includes transport of persons and services, resulting in potential trips to public transit stations by private vehicles for people to get to the stations; however, public transit stations are not designed to provide large parking facilities for private vehicles • Ad-hoc trips are more likely, while public transport services are usually frequent and scheduled
Catering	Partially Suitable	• Diverse suppliers and various small point-to-point deliveries in the city • Frequent, non-refrigerated goods can easily delivered by public transport vehicles • On-demand, priority deliveries where receivers value delivery speed may not be applicable
Parcels	Suitable	• For business-to-consumer deliveries, collection points are recommended to be used to enable flexible pickup by customers and significant CO_2 emission reduction • For business-to-business trips, deliveries should mostly be made during company hours • Groceries should not be considered since refrigeration technology at public transport vehicles is unlikely to be installed
Reverse (Waste)	Suitable	• Waste collection trips can be regular and made at night, thus not having to interrupt passenger services • Waste collection is relatively manageable due to it being a specific task, compared to general freight delivery, which involves more complex logistics

factors influencing the location decisions of urban intermodal logistical facilities. Currently, there are no studies that explicitly examine the attributes and related factors of transit station-based freight hubs, though some authors have investigated the factors related to freight distribution facilities and logistics centres. Onstein et al. [56] identified seven primary elements that affect enterprises' decisions about spatial distribution structures that are essential for organisations to structure their distribution networks to enhance logistics and service levels. Specifically, the following criteria are relevant to this research:

1. Demand factors: Client demand, demand volatility, and demand dispersion, which are extrinsic to the organisation and affect the configuration of distribution networks to accommodate diverse

client requirements.

2. Service Level factors: A company's capacity to fulfil customer expectations about delivery time, delivery dependability, and response; essential for sustaining elevated client satisfaction.
3. Factors influencing Product Characteristics: Product value density, packaging density, and perishability, influencing the storage and transport of items inside the distribution network.
4. Factors influencing Logistics Costs: Internal elements aimed at reducing expenses related to transport, warehousing, and inventory management.
5. Location-Related factors: Proximity, accessibility, and resource-related sub-factors, evaluating the geographical and infrastructural elements that affect the location of distribution hubs.
6. Institutional factors: Legal and budgetary factors, including taxation, zoning regulations, and investment incentives, which potentially influence the viability of specific distribution sites.

Another set of evaluation criteria for determining logistics centres in general was developed by Ozmen and Aydogan [59]. Among the nine main criteria and forty-four sub-criteria that they explored, several could be relevant to public transport station-based freight hubs:

1. Land: 1) Size and shape of the land; 2) Ownership and tenure condition; 3) Land infrastructure factors (energy, water, road, telecommunication); 4) Land expansion potential; 5) Physical conditions (slope, topography, geological structure, natural disaster suitability).
2. Market: 1) Proximity to free zone; 2) Accessibility to public and private transport.
3. Social: 1) Urban traffic impact; 2) Social attraction and level of difficulty; 3) Employment contribution.
4. Transport: 1) Proximity to the city; 2) Proximity to production centres; 3) Proximity to consumption centres; 4) Proximity to the airport; 5) Proximity to the railway; 6) Proximity to the highway; 7) Proximity to port (sea); 8) Connectivity to other transport methods.
5. Environmental Effects: 1) Environment-friendly (noise, image, pollution, emission gases); 2) Energy efficiency.
6. Costs: 1) Basic construction/structure/building investment; 2) Cost for users (operational, labour, transport); 3) Transport cost; 4) Contribution to economic development.
7. Risk and Safety: 1) Safety and security; 2) Risk of accident.

While not exhaustive, several studies have investigated some of the main and sub-factors listed above. For social factors, a case study using buses to deliver parcels in a Dutch village was conducted whose results demonstrated that PTF systems could create job opportunities for people with disadvantaged job prospects [72]. In terms of cost, investment and operational costs are two of the major barriers at the same time; thus, they are significant sub-factors influencing the establishment of PTF services [22][27][74]. A major factor that impacts the success of PTF systems, which was not considered in the above sets of criteria, though, is the capability to pack and manipulate cargoes [54]. Public transit stations, or locations sufficiently close to them, are most likely to host the packing and manipulation of freight, including loading and consolidation.

For LMD, self-pickup is a sustainable trend. Self-pickup facilities such as parcel lockers and collection points can easily be installed at rail and metro stations [20][55][74]. To determine at which public transport stations to install parcel lockers, a 10-minute cycling distance can ensure the accessibility of lockers for both urban and rural citizens, as evidenced by a study conducted in a well-developed Brazilian city [55]. However, temperature-sensitive groceries require refrigeration and, consequently, temperature-controlled parcel lockers. Due to technical difficulty, refrigerated parcel lockers might not be viable in the near future. Nevertheless, both self-pickup at collection points and home delivery, or a combination of both, could be utilised for LMD to ensure the overall service quality [72].

2.5. Conclusions

Designing a network for the transit of freight flows into urban areas requires thorough consideration of both long-term and short-term operations. Literature indicates that urban rail transport, including trams, metro, and city trains, can effectively transport freight, particularly when adequate infrastructure is in place. Modification of transit infrastructure to transport goods is possible, and existing transit stations can serve as transfer or pickup points for LMDs. Public transit stations can accommodate a range of goods, contingent upon the specific characteristics of the station and the technology at hand.

Previous studies have utilised various optimisation models at the tactical or operational levels, such as the PDPTW-SL and VRPT, to coordinate schedules and plan routes for public transport and last-mile vehicles; however, there is a scarcity of research addressing strategic decision-making. Many of these studies either construct a synthetic network or leverage an existing one, leading to the predetermination of all demand, supply, and transfer nodes. Consequently, the authors focus on optimising tactical and operational decisions without assessing the initial appropriateness of the network. There exists a notable gap in the literature on the network planning of PTF systems. Current research does not offer guidance on selecting appropriate stations and types of goods for a PTF network. Furthermore, the analysis of real-scale projects that incorporate freight and public transport presents a substantial research possibility, given that the majority of existing studies concentrate on small-scale prototype projects.

The strategic development of a freight delivery network utilising public transport may be regarded as an FLP, or more specifically, an HLP. Utilising existing public transport stations can substantially reduce initial costs, as there is less investment for new infrastructure development. Nevertheless, planning the utilisation of public transit stations as freight hubs necessitates meticulous consideration, as multiple primary and secondary factors influence the decision regarding the location of these hubs. MCDA is capable of facilitating the determination of hub locations within a PTF network by considering both quantitative and qualitative factors, including public transport station capacity, goods characteristics, transit service quality, and investment and operational costs. Particularly, the BWM effectively determines the weight of all (sub-)criteria, enabling a reliable ranking of candidate public transport stations and categorisation of them into various hub levels. The results of the aforementioned MCDA, comprising a detailed set of criteria with assigned weights and prioritised lists of station-based hubs, can subsequently be simulated to evaluate specific use cases. Multi-agent modelling for freight transport is an effective technique for simulating various real-world applications related to this field.

3 Methodology

This chapter explains the approach to defining the hub selection criteria, determining hub rankings, and evaluating the ranked hubs through simulation. The methods include literature review, Multi-Criteria Decision Analysis (MCDA), and simulation to develop a hub network for PTF. The chapter sequentially explains these methods that establish hub criteria, rank hubs, and model their impacts on real-life conditions.

3.1. Criteria Identification

Rail-based urban public transport (e.g., trains, metro and light rail) is considered in this study. This is since rail stations are more likely to have substantial capacity for consolidation, transfer, and/or storage functions, as well as the provision of connections with sustainable LMDs, such as self-pickup points. This consideration simplifies the problem by neglecting the need to build additional consolidation or cross-docking facilities across the network for bus stations [61]. Moreover, as stated in the literature (Chapter 2), investment costs are a significant barrier to the realisation of PTF projects. Thus, utilising existing infrastructure to the highest extent, such as rail-based stations, could be beneficial in reducing implementation expenses.

Optimal hub locations were identified by evaluating candidate sites against specific strategic, tactical, and operational criteria. The criteria to select hub locations were established according to the influencing factors identified in the existing literature (Section 2.4). In the next step of MCDA (Section 3.2), selected experts were consulted to verify the criteria and add new ones if relevant. The finalised criteria served as direct inputs to the MCDA model, where each potential hub site is ranked based on evaluation scores. The criteria are introduced in Chapter 4.

3.2. Criteria Weights Derivation

Multi-Criteria Decision Analysis (MCDA) was utilised to rank potential hub locations in order of station suitability across multiple criteria. In the PTF system, the selection of hubs must reconcile various frequently opposing criteria, and the Best-Worst Method (BWM) offers a systematic approach to ascertain relative weights for them. The BWM provides considerable benefits compared to conventional techniques by minimising the number of pairwise comparisons and enhancing decision-making consistency, as explained in Section 2.3. The process incorporated expert input to identify the *Best* and *Worst* criteria, thereafter assessing the other criteria in relation to these benchmarks. The weighted criteria were then utilised to rank candidate hubs.

3.2.1. The Best-Worst Method (BWM)

The BWM comprised the following five steps:

1. Define the Criteria

As introduced in Section 3.1, selected experts were asked to review the initial criteria and add new ones if relevant before the criteria were finalised. The participant list in this step can be seen in Table 4.3, which also displays participants' information for other BWM stages.

2. Identify the Best and Worst Criteria

After the criteria were listed, a panel of experts, including freight or public transport researchers and specialists, evaluated them based on their expert judgments. The experts identified the *Best criterion* that they viewed as the most important and the *Worst criterion*, which in their opinions is the least important in the decision-making process of hub selection. Initially, both a BWM survey and an interview were distributed to the professionals to elicit criteria weights; however, as the survey was conducted anonymously, it was not possible to verify or clarify inconsistent responses. All survey responses exceeded acceptable consistency thresholds and could not be adjusted without making unverifiable assumptions about the participants' intent. Therefore, the survey results were excluded from the final analysis, and only interview results were used.

Note that while the number of participants in the interview was limited, this is considered acceptable given the nature of BWM, which focuses on capturing structured judgments from domain experts rather than statistical generalisation. Each participant had relevant expertise in freight transport, urban logistics, and/or public transport. Moreover, the consistency ratios for all three interviews, calculated in step 5, fell within acceptable thresholds.

3. Formulate Pairwise Comparisons

Then, pairwise comparisons were conducted to determine the relative importance of criteria:

1. **Best-to-Others (B-to-O) Comparison**: Experts rated the importance of the best criterion relative to all other criteria on a scale of 1 to 9;
2. **Others-to-Worst (O-to-W) Comparison**: Experts rated how important other criteria are compared to the worst criterion using the same scale.

Each number in the scale referred to a different level of relative importance:

- 1: Equal importance;
- 2: Somewhat between Equal and Moderate;
- 3: Moderately more important than;
- 4: Somewhat between Moderate and Strong;
- 5: Strongly more important than;
- 6: Somewhat between Strong and Very strong;
- 7: Very strongly important than;
- 8: Somewhat between Very strong and Absolute;
- 9: Absolutely more important than.

4. Calculate Criteria Weights

The pairwise comparisons from step 3 resulted in two vectors, including a_{Bj}, the Best-to-Others comparisons and a_{jW}, the Others-to-Worst comparisons.

Using these pairwise comparisons, the relative weights (w_j) of each criterion could be calculated. A set $J = 1, 2, ...j, ..., J$ was defined to be the set of criteria. The maximum absolute deviation (ξ) between the pairwise comparisons and the derived weights was minimised:

$$\min \xi \tag{3.1}$$

Subject to:

$$|\frac{w_B}{w_j} - a_{Bj}| \leq \xi, \qquad \forall j \in J \tag{3.2}$$

$$|\frac{w_j}{w_W} - a_{jW}| \leq \xi, \qquad \forall j \in J \tag{3.3}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{3.4}$$

$$w_j \geq 0, \qquad \forall j \in J \tag{3.5}$$

Where:

- w_B: Weight of the best criterion.
- w_W: Weight of the worst criterion.
- a_{Bj}: Best-to-Others comparison values.
- a_{jW}: Others-to-Worst comparison values.

5. Evaluate Input-Based Consistency Ratio

The reliability of an expert's answer was checked by the input-based consistency ratio (CR_j), revealing the consistency level of the pairwise comparisons for a criterion j [45].

$$CR = \max_j CR_j \tag{3.6}$$

Where:

$$CR_j = \begin{cases} \left| \frac{a_{Bj} \cdot a_{jW} - a_{BW}}{a_{BW} \cdot a_{BW} - a_{BW}} \right|, & a_{BW} > 1 \\ 0, & a_{BW} = 1 \end{cases} \tag{3.7}$$

CR is the global input-based consistency ratio for all criteria, which could be compared with the threshold values. Interested readers are referred to [45] for those thresholds.

6. Derive Final Weights and Hub Rankings

Finally, the criteria weights (w_j) derived from the BWM were applied to score and rank candidate hub locations. Each hub was evaluated against the criteria using performance scores obtained from transit data and qualitative assessments. The calculation of the scores of individual criteria and sub-criteria can be seen in Table 4.2. The weighted sum of scores for each hub determined its final ranking:

$$\text{Score}_{\text{Hub}} = \sum_{j=1}^{n} w_j \cdot \text{Criterion Performance}_{\text{Hub},j} \tag{3.8}$$

Steps 4 and 5 above were carried out using the BWM's Excel solver [63]. For primary (access) and local (egress) hubs as defined in Section 4.1, the BWM was carried out individually to determine the criteria weights for each hub type. The reason is that while the criteria are suitable for selecting freight hubs in general, hubs with varying functions emphasise the importance of each criterion differently. The outputs of the MCDA process were then lists of hubs per category (Section 4.1). While a station might rank highly in one hub type, this station could have a low score for another hub category. These rankings served as the input for the simulation, which is discussed in Section 3.3.

However, unlike primary and local hubs that were selected using the BWM, the selection of secondary hubs was not based on expert opinions but on the real network structure, as discussed in Section 3.3, following this section. The rationale for this approach stemmed from the practical constraints inherent in the BWM process, as well as the desire to avoid unduly burdening the participating experts. Including secondary hubs in the BWM would significantly increase the complexity and length of the survey or interview. If the ranking process included an excessive number of hub types, respondents might lose patience and provide unreliable responses. Moreover, comparing criteria weights for secondary hubs would extend the interview duration drastically, making it impractical for participants with limited availability. In addition, in real life, transfer facilities between origin and destination locations are mostly selected based on the network composition and patterns rather than pre-defined locations.

3.2.2. Verification

The robustness of the BWM was verified by a sensitivity analysis on the criteria weights. This sensitivity analysis examined how variations in decision-makers' judgments affect the final ranking of criteria. Instead of introducing arbitrary percentage changes to the weights, the standard deviations (SDs) of expert responses were incorporated to assess the robustness of the model. It was reasonable to deduce that the higher the standard deviations are, the more experts disagree on the weight of certain criteria.

First, the original weights were computed after checking their CR to be below the acceptable threshold. Then, the weightings provided by experts were adjusted by one SD for one criterion at a time, while other criteria remained unchanged. The changes in the final rankings and weight distribution were observed to determine model robustness. This process was done for each type of hub, or in other words, each set of the BWM results. The procedures were as follows:

1. **Baseline Weight Calculation**:
   - Compute the mean weight of all criteria according to expert responses.
   - Rank the criteria in descending order of importance.
2. **Introduce Variability Using Standard Deviations**:
   - Compute the standard deviation (SD) of the weight for each criterion.
   - Define upper and lower perturbations using:

   $$W_i^{upper} = W_i + \sigma_i, \quad W_i^{lower} = W_i - \sigma_i \tag{3.9}$$

   where W_i is the original weight and σ_i is the standard deviation.
3. **Normalise Adjusted Weights**:
   - Since perturbed weights may not sum to 1, normalise them:

   $$W_i^{adj} = \frac{W_i^{perturbed}}{\sum W_i^{perturbed}} \tag{3.10}$$

4. **Recompute Rankings**:
   - Rank the criteria based on the adjusted weights.
   - Compare the new rankings with the baseline rankings.

A ranking was considered sensitive if a small perturbation significantly altered the ranking order. If small variations in weights led to major ranking shifts, then criteria rankings were unstable. This meant that the BWM might not be robust enough or not the most suitable method for ranking freight hub selection criteria. If rankings remained largely unchanged, the BWM model was robust against judgment variations among different participants.

3.2.3. Validation

As the BWM relied on subjective expert judgments, direct empirical validation was challenging. Nevertheless, while full validation was limited due to the subjective nature of expert opinions, the response CR for each expert was calculated to ensure internal coherence. All CRss should be below the corresponding accepted thresholds. Furthermore, the sensitivity analysis, which was done for verification, could also serve as a validation step, as it assessed the robustness of the BWM. If the resulting rankings remained stable under minor perturbations, the method's reliability is supported. In addition, direct comparisons between the aggregated criteria weights and each expert's answers could be made to confirm the alignment between explicit judgments and derived weights using the method.

3.3. Simulation

Using the lists of ranked hubs from the BWM, different network configurations were constructed, and their performances on freight delivery were modelled for comparisons. The case study area of the simulation was Rotterdam-The Hague Metropolitan Area (MRDH), The Netherlands. The reason was that this area is a densely populated urban region with a high amount of freight flow and a well-connected multimodal public transport network. To conduct the simulation, information on public transport stations and freight demands was gathered. Station data on each criterion and sub-criterion (Section 4.2) was collected as detailed as possible; however, it should be noted that for some criteria, approximated values were needed due to data unavailability.

In the simulation, scenarios that utilised varying combinations of hubs were experimented with under fixed budget and capacity constraints to compare their performances under realistic conditions. Also, a variety of key performance indicators (KPIs) were used to evaluate the simulated network's performance, including the hubs used, the proportion of deliveries, the total hub and transport costs, and the emissions generated by the PTF system.

3.3.1. Steps

The simulation comprised six key steps, as illustrated in Figure 3.1. The details are as outlined below:

1. Data Preprocessing

The first step involved importing and preparing the datasets. Station data, including latitudes, longitudes, transport modes, and hub classification, and parcel demand data specifying the origin and destination zones were loaded. The pairwise distances between stations were computed using the Haversine formula [21]:

$$d_{ij} = 2R\arcsin\left(\sqrt{\sin^2\left(\frac{\phi_j-\phi_i}{2}\right)+\cos(\phi_i)\cos(\phi_j)\sin^2\left(\frac{\lambda_j-\lambda_i}{2}\right)}\right) \tag{3.11}$$

Where:

- d_{ij} is the great-circle distance between two stations i and j,
- R is the Earth's radius (6371 km),
- ϕ_i, ϕ_j are the latitudes of stations i and j,
- λ_i, λ_j are the longitudes of stations i and j.

2. Network Graph Construction

To construct the transport network, the distances between stations computed in step 1 were used. Each station operates a transport mode (e.g., train, metro, light rail), and the corresponding speed, cost per kilometre, and emission values were extracted from predefined transport mode parameters.

The calculation of travel weights was influenced by the delivery focus, depending on whether it was time- or cost-effective. The case study mainly used the time penalty to construct the network graph. In this way, the total travel weight was computed as distance divided by transport speed, with an additional transfer time penalty when switching between transport modes:

$$w_{ij} = \frac{d_{ij}}{s_m} + p_t \tag{3.12}$$

Where:

- w_{ij} is the travel weight between stations i and j.

- d_{ij} is the computed great-circle distance using the Haversine formula.
- s_m is the speed of the transport mode m at station i.
- p_t represents any transfer penalty time when switching between transport modes.

On the other hand, the weight calculation could also incorporate cost considerations, which are the distance multiplied by cost per kilometre, plus any transfer cost penalty if changing transport modes so that the routing minimised total transport expenses. The cost-type weight could be evaluated as below:

$$w_{ij} = (d_{ij} \times c_m) + p_c \tag{3.13}$$

Where:

- c_m is the cost per km of mode m,
- p_c is the transfer cost penalty.

Due to the limited scale of the study, the simulation mostly used the network graph constructed with time penalties. Nevertheless, the sensitivity analysis for the simulation involved experimenting with varying values of cost penalties to identify the trade-off between cost efficiency and network performance (Section 5.4.1).

3. Hub Selection

In reality, the implementation of PTF depends heavily on the monetary resources available. Thus, the final number of hubs was budget-constrained, which ensured that the total hub setup cost did not exceed a predefined limit. The budget constraint was defined as follows:

$$\sum_{h \in H} c_h \leq B_H \tag{3.14}$$

Where:

- c_h is the setup cost of hub h,
- H is the selected set of hubs,
- B_H is the total hub setup budget.

Based on the BWM results, hubs were selected differently for each scenario:

- **Scenario 1 (Minimal Hub Use):** Only top-ranked primary hubs were selected.
- **Scenario 2 (Hierarchical Network):** Hubs were selected hierarchically, following a strict routing order of Primary $\rightarrow$ Secondary $\rightarrow$ Local hubs.
- **Scenario 3 (Decentralised Network):** Primary and local hubs were available, promoting the primary and local connections.

Particularly, in scenario 2, the betweenness centrality was used to identify candidate secondary hubs to be selected in step 4: freight allocation. The centrality score was calculated as follows [16]:

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{3.15}$$

Where:

- σ_{st} is the total number of shortest paths from node s to t
- $\sigma_{st}(v)$ is the number of those paths that pass through node v

4. Freight Allocation

Once the network had been constructed, freight was allocated to hubs and routed based on predefined scenarios. For every scenario, the allocation process took into account hub capacities for realistic concerns. The capacity limit of each hub type was defined as the number of parcels able to be handled in a day. For each hub, this number varied:

- **Primary Hubs:** High capacity (e.g., 10,000 parcels/day);
- **Secondary Hubs:** Medium capacity (e.g., 5,000 parcels/day);
- **Local Hubs:** Low capacity (e.g., 2,500 parcels/day)

.

Parcel allocation followed one of three strategies, according to the scenario:

- Minimal (Scenario 1): Parcels were only allocated to primary hubs. For a parcel to be assigned, its nearest origin and destination stations must be primary hubs. The route was then determined as a direct path between the selected primary hubs.
- Hierarchical (Scenario 2): A structured hub sequence was enforced:
  1. The **origin** station was assigned to the closest primary hub.
  2. The **destination** station was assigned to the nearest local hub.
  3. A **secondary hub** was introduced as a transfer station based on centrality scores and spatial proximity to the local hub.
- Decentralised (Scenario 3): Parcels moved through primary and local hubs where the connection was mostly primary-primary or primary-local. If no direct path existed between a primary and local connection, another primary hub was used as an intermediate transfer point.

If a hub reached full capacity, parcels were either rerouted to an alternative hub or held back if no feasible alternative existed. If no feasible path existed at all, the parcel was excluded from allocation. The final output consisted of a list of allocated parcels and their respective routes.

5. Used Hub Classification

In the freight allocation step, the hub category of a selected station is not explicitly stored; thus, in this step, the classification of used hubs was done, where the stations actually used in each scenario were categorised into primary, secondary, and local. This classification is based on the scenario and precomputed station rankings.

For each scenario, primary hubs were selected from the set of used hubs by checking which ones fall within the top 50 stations with the lowest primary hub rank values (i.e., a lower value means a higher rank). The 50 stations with the smallest primary rankings were selected, and those that were also in the used hubs set were filtered. The number 50 was obtained from dividing the total budget by the individual primary hub setup cost, representing the maximum number of primary hubs possible. It was ensured that only actively used stations with high primary rankings were classified as primary hubs. Similarly, local hubs were identified by checking which used hubs were within the top 149 stations with the lowest local hub rank values. The choice of 149 corresponds to the total number of stations in the network, as the maximum possible number of local hubs is greater than that. For scenario 2, the used secondary hubs were identified by filtering the active ones from the top 100 most central stations based on betweenness centrality scores. This number was randomly chosen to allow sufficient candidate secondary hubs, as there are 149 stations in total. To avoid redundancy, overlaps between hub types are resolved by removing any station already classified as a primary or local hub from the secondary hub set.

6. Budget Verification

To ensure that each scenario remained financially viable, an additional step was incorporated to check compliance with the predefined total budget. Each hub type was assigned a unit cost: primary hubs were assumed to incur the highest cost due to their infrastructural significance, followed by secondary and then local hubs, which were comparatively less costly to establish. The total budget expenditure was then computed by summing the number of hubs in each category multiplied by their respective unit costs. This total was compared against the fixed budget limit allocated for hub setup in the simulation. If the total cost exceeded the budget, it indicated that the selected hub configuration was infeasible under the current financial assumptions, which would need to be modified to pass this step.

7. Performance Evaluation

Finally, for each scenario, the delivery rate was calculated as the number of freight delivered divided by the total demand. Other key performance indicators (KPIs), the transport cost and CO_2 emissions, were computed as follows:

$$C_{total} = \sum_{(i,j) \in R} d_{ij} \times c_m + p_c \tag{3.16}$$

$$E_{total} = \sum_{(i,j) \in R} d_{ij} \times e_m \tag{3.17}$$

Where:

- C_{total} is the total transport cost,
- E_{total} is the total emissions (kg CO_2),
- e_m is the emission per km of mode m,

To interpret the results, several visualisations were generated to demonstrate how well different network configurations perform. Geographic distributions of used hubs, showing their locations and hub categories, were created for all scenarios. The movement of parcels between hubs under each scenario was also plotted, displaying the intensity of cross-hub freight flows. Additionally, the different hubs where the parcels were originating and designating were depicted as well.

The full code of the simulation, undertaken in Python, can be seen in Appendix B.

3.3.2. Verification

Verification for the simulation was necessary to ensure that the algorithms function as intended. The simulation was verified by 1) checking whether the allocated routes followed the expected hub-based paths and 2) a sensitivity analysis on key parameters used.

Check of Allocated Freight Routes

The first verification step ensured that the computed travel paths adhere to the intended hub structure rather than taking direct detours that violate scenario constraints. To evaluate this, the total computed path distance of each allocated freight route was compared against the expected shortest path distance within the assigned hub structure:

$$\sum_{i=1}^{n-1} d(i, i+1) \approx \sum_{i=1}^{n-1} d^*(i, i+1) \tag{3.18}$$

Where:

- n is the number of nodes in the computed freight route,
- $d(i, i+1)$ is the distance between consecutive nodes in the allocated path,
- $d^*(i, i+1)$ is the expected distance computed using the shortest path within the designated hub network.

If an allocated route was entirely contained within the assigned hub structure, no verification error was counted. Otherwise, the total computed path distance was checked against the expected path distance within the permitted hub structure. If a significant deviation was found, an error was logged for that route. Additionally, missing paths where no feasible route exists within the scenario constraints were recorded as verification failures.

Sensitivity Analysis

The sensitivity analysis for the simulation varied key parameters to evaluate how changes in inputs affect freight flow efficiency, cost, and emissions. Table 3.1 displays how the budget constraints, local hub quantity, and transport penalties were modified during this process. The results are shown in Section 5.4.1.

Table 3.1: Sensitivity Analysis for Simulation

Experiment	**Parameter to Change**	**Variation Levels**	**Expected Results**
Hub Capacity	Allowed parcels at a hub	±10%, ±30%, ±50%	Sensitivity of demand allocation to hub capacity changes
Hub Cost	Cost to set up one hub per type	±10%, ±30%, ±50%	Sensitivity of individual hub setup costs
Total Budget	Available budget overall	±10%, ±30%, ±50%	Impact of budget changes on freight volume
Budget Allocation	Proportion of total budget allocated to local hubs in Scenario 3	10% to 90%	Trade-off between primary and local hubs
Time Penalty	Value of time-based transfer penalty	±10%, ±30%, ±50%	Relationship between time efficiency and network performance
Cost Penalty	Value of cost-based transfer penalty	±10%, ±30%, ±50%	Relationship between cost efficiency and network performance

3.3.3. Validation

Validation ensures realistic simulation results by comparing model outputs with real-world freight transport data or similar studies. This study's pioneering nature precludes comparison with any similar studies. The validation of the simulation thus focused on the consistency of hub performances throughout different scenarios.

The behaviour of different hub configurations (see scenarios defined in Section 5.3.2) was validated by checking expected trends in different network configurations, which were:

- Scenario 1 (minimal hub use, Figure 5.4) should yield the lowest parcel delivery rate due to the limited reach of a network via solely primary hubs.
- Scenario 2 (hierarchical routing, Figure 5.5) should present a hub configuration with the widest spread but may introduce inefficiencies due to the mandatory use of every level of hubs in all deliveries.
- Scenario 3 (decentralised routing, Figure 5.6) should generate the medium freight flow across the scenarios, as it introduces local hubs in addition to primary hubs, unlike scenario 1, but does not explicitly deploy secondary hubs as scenario 2 does.

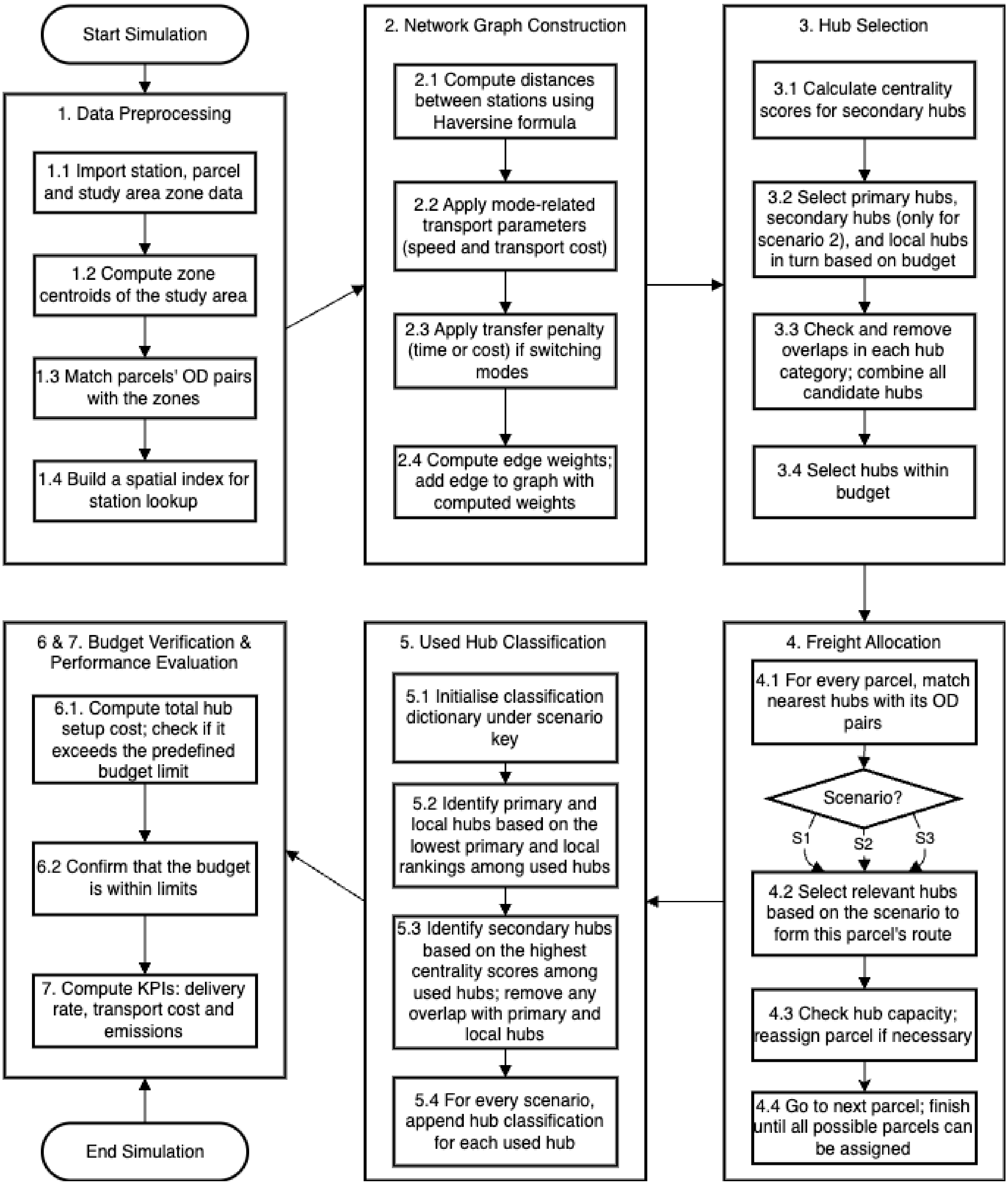


Figure 3.1: Simulation Steps

4

Hub Selection Criteria

Building upon Chapter 3: Methodology, this chapter details the identification of hubs and corresponding evaluation criteria. A hierarchical network of primary, secondary, and local hubs is established. A set of comprehensive criteria for selecting which stations to act as what types of hubs is provided. The weights of the criteria and that of the sub-criteria are calculated using the BWM, and their sensitivity is analysed.

4.1. Hub Categories

To facilitate freight distribution, consolidation, and transfer inside the metropolitan public transport system, the PTF model uses a multi-tiered hub network. For an efficient freight transport from origin to destination without compromising passenger services, each hub tier is operationally distinct. Specifically, the public transport stations, namely train, metro, and light rail, act as the following types of freight hubs:

- Primary Hubs (Access Hubs): Primary hubs play a central role in the PTF network. These hubs manage multimodal handling, long-term storage, and freight aggregation for long-haul transport. They consolidate freight inflows from LSPs and direct them to secondary hubs and/or local hubs. Primary hubs can thus accommodate the largest freight volumes and ensure smooth coordination between pre- and main-haul transport modes. As shown in Figure 4.1, primary hubs (blue squares) act as central nodes that aggregate goods from origins (grey circles) and redistribute them to the network.
- Secondary Hubs (Transfer Hubs): Secondary hubs serve as intermediary nodes that connect primary hubs to local hubs. Stations at critical intersections that can easily connect to most other stations are likely to be secondary hubs. They primarily handle mid-level transfers between primary and local network layers. As depicted in Figure 4.1, secondary hubs (yellow squares) bridge the gap between central consolidation points and local distribution nodes.
- Local Hubs (Egress Hubs): Local hubs are positioned near demands, such as residential or commercial areas, to support end-point delivery operations. These hubs are only for connection with LMD, such as direct collection by last-mile vehicles or customers' self-pickup (e.g., via parcel lockers). Stations near demand clusters may be local hubs due to their proximity to destinations, minimising last-mile costs and road congestion. Local hubs (green squares in Figure 4.1) are possibly closer to demand locations (destinations, in pink circles) and handle smaller freight volumes since the goods have been redistributed via primary and secondary hubs already.

As can be observed from Figure 4.1, in the proposed PTF network of this study, freight originates from varying sources (grey circles, which can be warehouses or LSPs' distribution centres), before flowing into primary hubs (blue squares). The primary hubs consolidate and transfer freight to secondary hubs (yellow squares), which act as intermediary points connecting the primary hubs to local hubs when no direct connections exist, if necessary. Otherwise, the primary hubs can also route freight to other primary or local hubs directly. The local hubs, marked by green squares, are positioned near freight destinations, enabling LMD through pickup facilities or staging areas for last-mile carriers. The freight eventually reaches its destination (pink circles), which can be residences or companies for business receivers, for instance. The arrows represent the directions that goods flow through the network, demonstrating how they are aggregated, transferred, and distributed.

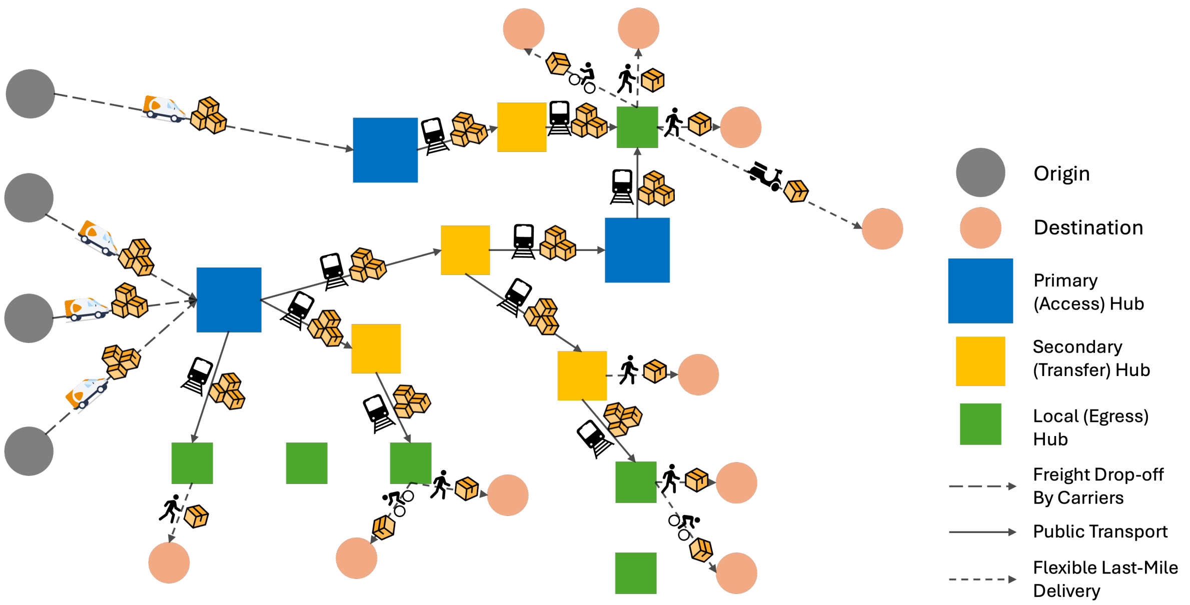


Figure 4.1: Proposed Public Transport-Based Freight Delivery (PTF) System

4.2. Selection Criteria

Based on findings from the literature (Section 2.4) and expert consultation, the final list of criteria is identified and displayed in Table 4.1. Overall, five main criteria, namely cargo characteristics, costs, connectivity, capacity, and accessibility, are defined, including relevant sub-criteria. Table 4.2 displays how the scores of the main and sub-criteria are evaluated.

Cargo requirements encompass the properties of the goods that the stations should be able to handle. The sub-criteria include vulnerability, demand volatility, and security. Vulnerability considers whether the cargo requires special handling to ensure quality during transit when the items are fragile. Demand volatility reflects the regularity and urgency of freight needs, which may vary significantly across goods. This attribute addresses the capability of a station to operate fixed or flexible freight schedules. As public transport has fixed routes and timetables, freight with regular delivery schedules may be more suitable for a wider range of stations. Security refers to the measures necessary to protect high-value goods, as this leads to the need for enhanced facilities to address theft or damage risks.

Cost considerations are crucial to assessing the economic feasibility of integrating public transport with freight delivery. The sub-criteria include investment costs, operational costs, and maintenance & upgrade costs. Investment costs refer to the upfront expenses required for retrofitting public transport stations to handle freight, such as installing storage or consolidation facilities. Operational costs involve ongoing expenditures such as labour, equipment usage, and utilities. Maintenance & upgrade costs include the long-term expenses associated with maintaining and upgrading infrastructure for freight handling.

Connectivity evaluates the integration of hubs within the public transport network, which influences their ability to facilitate multimodal usage. Sub-criteria consist of service frequency, service coverage, and proximity to other transport modes. Service frequency measures the number of services operating within a specific time frame (e.g., daily or weekly), depending on the desired delivery frequency. Service coverage considers how many destinations can be accessed from the station, with wider coverage supporting better network integration. Proximity to other transport modes highlights the potential for intermodal transfers, making stations closer to other rail-based stations ideal.

Capacity examines the physical and operational capability of a hub to handle freight volumes effectively. The sub-criteria are physical space, equipment & labour, and expansion potential. Physical space refers to the available area for sorting, storing, and transferring goods, crucial for accommodating varying freight quantities, especially consolidated goods from the origins or for transfer. Equipment & labour assess whether the hub has the necessary logistics infrastructure and trained personnel to efficiently manage freight. Expansion potential evaluates the ability to scale up operations as freight demand grows, which could play a greater role in the long term.

Accessibility focuses on the ease with which goods and vehicles can reach and operate within the hub. The sub-criteria include proximity to demand locations, proximity to supply locations, access to road networks, access to active modes, and digital accessibility. Proximity to demand and supply locations ensures hubs are situated near key freight origins and destinations, resulting in reasonable transit time and costs. Access to road networks facilitates smooth pre-haul and last-mile connections, while access to active modes (e.g., cycling or walking) encourages self-pickup customers or active couriers. Digital accessibility represents having smart systems and IoT platforms that enable smooth freight handling and coordination with passenger services, as the freight operations are not to distort passenger experiences at any stations.

4.3. Criteria Weights

4.3.1. Survey and Interview

As discussed in Chapter 3, the weights of the criteria were obtained through MCDA, using the BWM, which required external inputs. To promote a higher response rate and allow flexibility for participants, the experts were invited to either fill out a BWM survey or participate in an interview to discuss their opinions on how the criteria weigh relative to each other. In total, 11 invitations were sent out, resulting in a response rate of 54.5% (6 out of 11). Particularly, 3 experts participated in an interview, while 3 others completed the survey. Even though the survey results could not be used, as explained in 3.2.1, a mixture of public and freight transport specialists participated in the interview; thus, diverse opinions were offered to this study. Nevertheless, apart from the anonymity, the survey questions were appropriately structured to obtain inputs for the BWM (Appendix A). The complete participant list is shown in Table 4.3.

For verification, Table 4.4 displays the consistency check results of the BWM, where the values in brackets represent the associated thresholds. It can be observed that all participant inputs demonstrated consistency, as all CRs were below their relative threshold values.

Reflecting on the BWM process, experts who participated in the interview provided feedback. The majority expressed optimism regarding the integration of passenger and freight transport and were eager to see the study's outcomes. However, one interviewee raised concerns about the application of the BWM, especially in relation to the context of the system. Although the interviewee understood the differences among different hubs and recognised that the BWM would be conducted once for each hub category, the lack of complete operational details of the PTF system hindered their ability to evaluate the criteria from the most comfortable perspective. Similarly, another expert who participated in the survey indicated that defining specific operational assumptions was essential for its completion, particularly concerning when and by whom the system is operated. This outcome is not surprising, as this study focuses on a high-level strategic design of combined public and freight transport networks; thus, a comprehensive description of the proposed system, including everyday operations, would be impractical. Nevertheless, all interviews were conducted successfully and delivered reliable results.

Table 4.1: Freight Hub Selection Criteria

Criteria	Sub-Criteria	Definition
Cargo Requirements	• Vulnerability • Demand Volatility • Security	• Handling of fragile goods • If the station can deliver goods needed on a regular basis or irregularly/urgently • Capability to provide additional security measures for high-value or sensitive goods
Costs	• Investment Costs • Operational Costs • Maintenance & Upgrade Costs	• Costs of initial investment of the stations and modification of vehicles • Day-to-day operational costs of additional equipment and labour • Long-term costs, including maintenance and eventual upgrades or replacements of infrastructure
Connectivity	• Service Frequency • Service Coverage • Proximity to Other Transit Modes	• Number of services in a certain time period (e.g., during peak hours or per day) • Number of routes possible and how many destinations can be reached • If it is a multi-modal transit station itself or close to other types of stations
Capacity	• Physical Space • Equipment & Labour • Expansion Potential	• Space available at the station for microconsolidation, storage and transfer • Capability to install logistics-related facilities and available staff • Potential for growth in freight operations
Accessibility	• Proximity to Demand Locations • Proximity to Supply Locations • Access to Road Network • Access to Active Modes • Digital Accessibility	• Closeness to demands (e.g., customer homes, locations of business receivers) • Closeness to supplies (e.g., warehouses and distribution centres) • Ease of access for pre- and last-mile operators travelling with road vehicles • Ease of access for pre- and last-mile operators travelling with active modes (e.g., biking and walking) • Presence of smart systems and digital platforms for the staff to manage freight flows and passengers to co-exist with freight activities in the station

Table 4.2: Evaluation of Hub Selection Criteria

Criterion	Sub-Criterion	Evaluation Method	Scoring System
Cargo Requirements	Vulnerability	Determine if the station can handle fragile goods based on facility capabilities.	Can Handle: 10; Not Handle: 0
	Demand Volatility	Assess whether the station supports fixed, flexible, or both freight schedules.	Fixed & Flexible: 10; Fixed Only: 5; Flexible Only: 5
	Security	Check if the station provides security measures for high-value goods.	Can Handle: 10; No: 0
Costs	Investment Costs	Estimate costs based on infrastructure complexity and retrofitting requirements.	Low: 3; Medium: 6; High: 9
	Operational Costs	Evaluate recurring costs (e.g., labour, energy) based on station size and complexity.	Low: 3; Medium: 6; High: 9
	Maintenance & Upgrade Costs	Assess long-term maintenance and upgrade costs based on station infrastructure.	Low: 3; Medium: 6; High: 9
Capacity	Physical Space	Evaluate available space for freight sorting, storage, and transfer operations.	Little: 3; Medium: 6; Good: 10
	Equipment & Labour	Assess availability of logistics infrastructure and trained personnel.	Little: 3; Medium: 6; Good: 10
	Expansion Potential	Assess future scalability based on surrounding space and infrastructure.	Little: 3; Medium: 6; Good: 10
Connectivity	Service Frequency	Calculate average frequency across morning, evening, and daily schedules.	High: 8–10 (freq > 20); Medium: 5–7 ($10 \leq$ freq ≤ 20); Low: 1–4 (freq < 10)
	Service Coverage	Evaluate the number of service lines and reachable destinations within the same mode.	High: 8–10 (lines/reach > 10); Medium: 5–7 ($5 \leq$ lines/reach ≤ 10); Low: 1–4 (lines/reach < 5)
	Proximity to Other Transit Modes	Check nearby availability of train, metro, and light rail modes.	Reduces proportionally from 10 for missing modes
Accessibility	Proximity to Demand Locations	Evaluate parcel count to determine proximity to demands.	High: 8–10 (parcel_count > 60); Medium: 5–7 ($40 \leq$ parcel_count ≤ 60); Low: 1–4 (parcel_count < 40)
	Proximity to Supply Locations	Evaluate average depot distance to determine proximity to freight origins.	High: 8–10; Medium: 5–7; Low: 1–4
	Access to Road Network	Combine metrics for road count and road length using weighted normalisation.	Weighted normalised score scaled to 1–10. Weights: Number of roads accessible = 0.6, Accessible road length = 0.4
	Access to Active Modes	Check the presence of biking/walking infrastructure for active mode accessibility.	Yes: 10; No: 0
	Digital Accessibility	Assess the presence of IoT systems and digital infrastructure for stakeholder navigation.	High: 10; Medium: 6; Low: 3

Table 4.3: Participants in the Best-Worst Method (BWM)

Participant	Industry	Title	Specialisation	BWM Stage(s)
1	Academia	Assistant Professor	Freight Transport & Logistics	Defining Criteria
2	Academia & Consultancy	Researcher	Freight Transport & Logistics	Defining Criteria, Survey
3	Consultancy	Advisor & Researcher	Freight Transport & Logistics	Survey
4	Academia	PhD	Supply Chain Management	Interview
5	Academia	Assistant Professor	Port & City Logistics	Interview
6	Consultancy	Researcher	Freight Transport	Survey
7	Academia	Professor	Public Transport & Mobility	Interveiw

Table 4.4: Consistency Check of the Best-Worst Method (BWM) Results

Participant	4	5	7
Consistency Ratio (CR) for Main Criteria			
Primary Hubs	0.0972 (0.3062)	0.2639 (0.3062)	0.2619 (0.2819)
Local Hubs	0.0972 (0.3062)	0.1667 (0.1898)	0.2143 (0.2819)
Consistency Ratio (CR) for Sub-Criteria			
Cargo Requirements	0.1667 (0.1667)	0.05 (0.1354)	0.05 (0.1354)
Costs	0 (0)	0.1667 (0.1667)	0.05 (0.1354)
Connectivity	0 (0.1309)	1 (1)	0.05 (0.1354)
Capacity	0.0972 (0.1359)	0.05 (0.1354)	0.1 (0.133)
Accessibility	0.0972 (0.3062)	0.15 (0.2306)	0.0714 (0.2958)

4.3.2. Weight Determination

The obtained weights for the main and sub-criteria are displayed in Tables 4.5 and 4.6, respectively. From Table 4.5, it can be observed that while accessibility is the highest-weighted criterion for primary hubs (0.3259), capacity is the most critical for local hubs (0.2954). This divergence indicates the different operational roles these hubs play. Primary hubs serve as major entry points into the urban freight network. Their high accessibility weight suggests that stakeholders prioritise easy access to key infrastructure, such as major roads, highways, and active mode connections. The importance of costs (0.2132) also suggests a focus on financial sustainability for large-scale major hubs, though capacity (0.2746) still plays a crucial role in primary hub operations. On the other hand, local hubs, which are more widely dispersed in urban environments, prioritise capacity (0.2954) slightly above accessibility (0.2320). This shift implies a greater concern for the ability to handle package volumes efficiently within constrained urban spaces. Interestingly, cargo requirements rank consistently as the lowest-weighted criterion for both hubs (0.0612 and 0.1137). This suggests that stakeholders consider freight property constraints to be relatively less critical compared to other considerations.

Table 4.5: Main Criteria Weights

Criteria	Primary (Access) Hubs	Local (Egress) Hubs
Cargo Requirements	0.0612	0.1137
Costs	0.2132	0.2076
Connectivity	0.1250	0.1514
Capacity	0.2746	0.2954
Accessibility	0.3259	0.2320

Table 4.6: Sub-Criteria Weights

Cargo Requirements	**Weight**
Vulnerability	0.2972
Demand Volatility	0.5118
Safety	0.1910
Costs	**Weight**
Investment Costs	0.4759
Operational Costs	0.2417
Maintenance & Upgrade Costs	0.2824
Connectivity	**Weight**
Service Frequency	0.175
Service Coverage	0.65
Proximity to Other Transit Modes	0.175
Capacity	**Weight**
Physical Space	0.6066
Equipment & Labour	0.2374
Expansion Potential	0.1560
Accessibility	**Weight**
Proximity to Demand Locations	0.1487
Proximity to Supply Locations	0.177
Access to Road Network	0.4794
Access to Active Modes	0.0818
Digital Accessibility	0.1135

Observing each criterion, the high weight assigned to accessibility (0.3259 for primary hubs, 0.2320 for local hubs) already indicates that decision-makers view the ease of reaching and integrating these hubs into transport networks as crucial to their effectiveness. The sub-criteria weights in Table 4.6 further highlight this; access to the road network (0.4794) is the most critical accessibility factor. This implies that experts emphasise the need for hubs to be well connected to primary logistics corridors. In the meantime, the relatively lower weight of access to active modes (0.0818) likely means that non-motorised transport integration is currently less of a priority for urban freight operations. Nevertheless, for cities with a well-developed active transport network (e.g., all cities in the Netherlands), this indicator may play a more important role even with a seemingly lower score.

The main criterion, costs (0.2132 for primary hubs, 0.2076 for local hubs), is consistently among the more influential criteria; however, the breakdown of its sub-criteria reveals some interesting priorities (Table 4.6). Investment costs (0.4759) have the highest weight, which suggests that initial infrastructure costs are a primary decision-making factor. This implies a concern among policymakers and logistics firms about the high capital expenditure required to establish hubs. Maintenance & upgrade costs (0.2824) rank as the middle, slightly higher than operational costs (0.2417), indicating that long-term sustainability may be somewhat deprioritised in favour of upfront development but is viewed as more important than immediate operational efficiency. While day-to-day expenses matter, future maintenance or upgrade costs are no less important.

For capacity, the higher weight assigned to it in local hubs (0.2954, compared to 0.2746 for primary hubs) suggests that stakeholders are more concerned with space constraints and operational capability at the last-mile level, reinforced by the sub-criteria weights. Physical space (0.6066) is by far the dominant factor, indicating that the available area for handling, sorting, and storing cargo could be a key limitation in operating PTF in urban environments. This reflects the reality of dense urban environments, where securing adequate room for last-mile operations is a persistent challenge. Meanwhile, equipment & labour (0.2374) and expansion potential (0.1560) weigh significantly lower, which indicates that while sufficient tools and staff and scalability are relevant, they are not the primary decision-making concerns in terms of operational capability.

Last but not least, connectivity (0.1250 for primary hubs, 0.1514 for local hubs) plays a moderate role in hub selection, with a slightly higher emphasis for local hubs. Among connectivity, the sub-criterion service coverage (0.65) dominates, highlighting a preference for widespread delivery service availability. In the meantime, service frequency (0.175) and proximity to other transit modes (0.175) share the same weight, emphasising that frequent services and multimodal integration (e.g., connecting to as many types of public transit) are not a priority, at least for stakeholders involved in this study. This likely reveals the fact that current urban freight transport primarily relies on road-based delivery rather than intermodal solutions.

4.3.3. Sensitivity Analysis

The sensitivity analysis was undertaken for the weights of the primary hubs, local hubs, and sub-criteria. For every (sub-)criterion, one standard deviation was added to or subtracted from the mean weight (baseline weight) at a time to observe how sensitive this (sub-)criterion is.

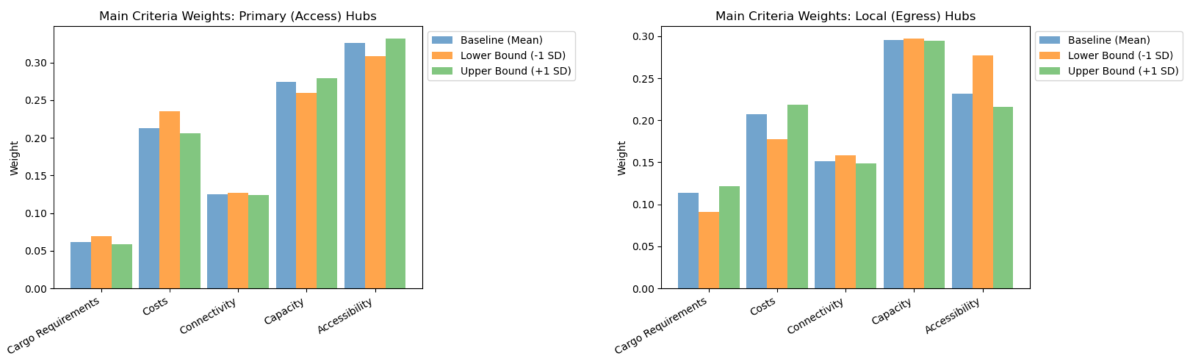
Primary (Access) Hubs

For primary hubs, accessibility remains the most influential criterion across all weight scenarios, followed by capacity and costs (Figure 4.2a). In the baseline and higher-bound scenarios, accessibility, capacity, and costs rank as the top three highest. Despite the fact that they all demonstrate significant changes in all scenarios, under the lower-bound scenario, the weight of costs increases from the third to the second highest. Meanwhile, cargo requirements and connectivity remain relatively stable across all scenarios, implying that they have minimal sensitivity to variations in expert opinions.

Observing the trends in sensitivity variations, accessibility remains dominant when selecting primary hubs but exhibits moderate sensitivity to expert weight adjustments. The trend of capacity is similar to that of accessibility, whereas costs demonstrate some variation across scenarios. Connectivity and cargo requirements show high resilience, though their rankings rise slightly in the lower-bound scenario. The high stability and the lowest weighting of cargo requirements indicate strong expert agreement that this is the least critical attribute for selecting primary hubs.

Local (Egress) Hubs

For local hubs, capacity weighs as the dominant criterion across all scenarios, with almost negligible variations (Figure 4.2b). While accessibility consistently ranks as the second-highest, in the lower-bound scenario, it weighs almost as high as capacity, implying a higher sensitivity than in primary hubs. Compared to primary hubs, cargo requirements and connectivity hold more significantly important roles. However, while connectivity shows a relatively high stability, the weight of cargo requirements fluctuates more, which is similar to the trend of costs. Although cargo requirements also rank the lowest for local hubs, this sensitivity implies a considerable variation in experts' perception of the importance of cargo-specific constraints for local hubs. Another similar trend to primary hubs is that costs and connectivity remain consistently the third and fourth most influential criteria for local hubs.



(a) Primary (Access) Hubs **(b)** Local (Egress) Hubs

Figure 4.2: Sensitivity Analysis on Main Criteria Weights

Sub-Criteria for Both Hubs

For cargo requirements (Figure 4.3a), the sub-criterion demand volatility consistently holds the highest weight, irrespective of weight variations. Vulnerability shows moderate sensitivity, as its ranking shifts from the second to third highest in the lower-bound scenario. On the other hand, safety remains almost constant in all scenarios, with minimal fluctuations. These suggest strong expert consensus on the importance of handling unpredictable fluctuations in parcel demand, while opinions on handling vulnerable cargo and safe delivery demonstrate some variability.

Regarding costs (Figure 4.3b), all sub-criteria weights fluctuate to a certain degree in different scenarios, though investment costs remain the most influential despite fluctuations. Operational costs maintain moderate importance, while maintenance & upgrade costs consistently rank the lowest. The high sensitivity of investment costs highlights varying professional views on the significance of upfront capital expenditures in hub selection. Similarly, the high sensitivity of maintenance & upgrade costs also suggests that decision-makers regard the long-term preservation and improvement costs differently.

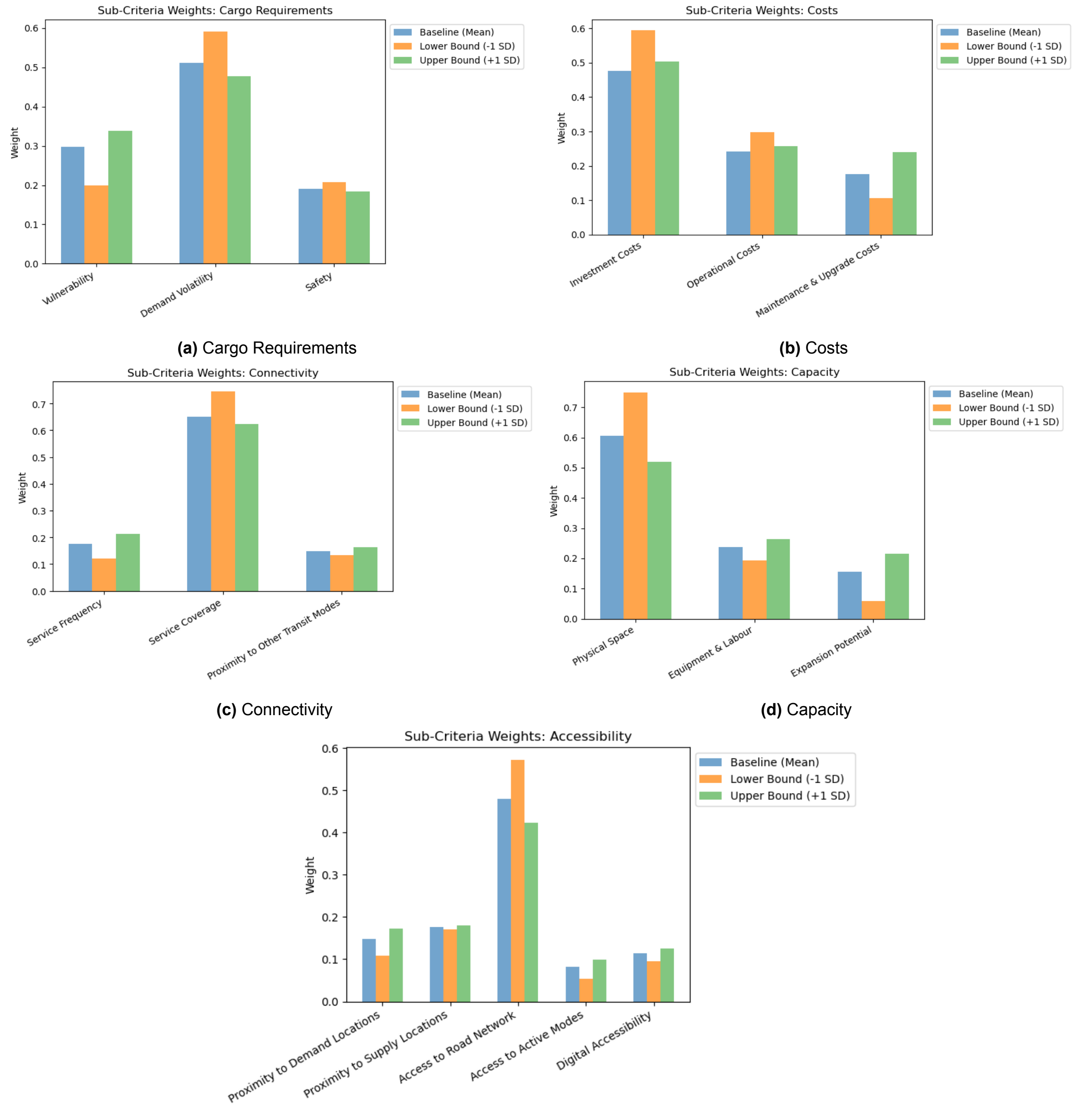
For connectivity (Figure 4.3c), service frequency remains the most dominant sub-criterion, while service frequency and proximity to other transit modes rank somewhat similarly. The dominance of service coverage indicates expert agreement that the broad coverage of PTF service is a critical factor in hub connectivity. On the other hand, despite the fact that the other two sub-criteria show fluctuations in their weights, the results suggest that frequent service and multimodal public transit connections are of less significance in comparison with service coverage.

In terms of capacity (Figure 4.3d), physical space is the highest-weighted factor, even though its weight changes significantly in the lower-bound scenario. The sub-criterion equipment & labour is relatively stable, remaining the second most important. On the other hand, expansion potential shows greater shifts, especially in the lower-bound scenarios, indicating higher sensitivity to expert variations. This outcome suggests a consensus on the importance of physical space, despite the differences in its exact weight, and agreement on equipment & labour playing a moderate role, while perspectives on future expansion vary more significantly.

Lastly, for accessibility (Figure 4.3e), while almost all sub-criteria demonstrate variations, access to road network remains the dominant sub-criterion. Although proximity to demand locations relatively fluctuates, access to supply locations remains stable. This reflects a consensus in experts opinions on the importance of being close to freight origins, compared to freight destinations. Moreover, variations in the importance of access to active modes and digital accessibility indicate differing expert priorities based on locational factors (e.g., whether the region has a well-developed active transport network and/or mature technology).

In summary, primary hubs prioritise accessibility and capacity, with cargo requirements being the least influential. For local hubs, capacity is the most important criterion, with minimal sensitivity to expert variations; however, cargo requirements and connectivity become more critical, while accessibility and costs still rank high. The most stable criteria for primary and local hubs are connectivity and capacity, respectively. Although accessibility remains dominant in all cases for primary hubs, capacity is apparently the dominant case for local hubs. Nevertheless, regardless of hub type, accessibility, capacity, and costs remain as the most important criteria, while connectivity and cargo requirements are of the lowest importance. These results indicate that the BWM is a robust method, even though it is somewhat sensitive to expert variations, as ranking shifts are reasonable and not extreme.

Particularly, the sub-criteria weights of connectivity appear to be the least sensitive, displaying minor shifts in weight distribution. Cost-related sub-criteria, especially investment and maintenance costs, exhibit high sensitivity, reflecting significant variations in expert perspectives on the initial investment and long-term system functionality. The most dominant sub-criteria across all scenarios are safety (cargo requirements), proximity to other transit modes (connectivity), and proximity to supply locations (accessibility), all of which hold minor importance. Interestingly, from Figure 4.3, it can be seen that no criterion has a consistently strong expert agreement across its sub-criteria. While some sub-criteria appear to be more stable, variations exist in most of the sub-criteria's decision-making importance.

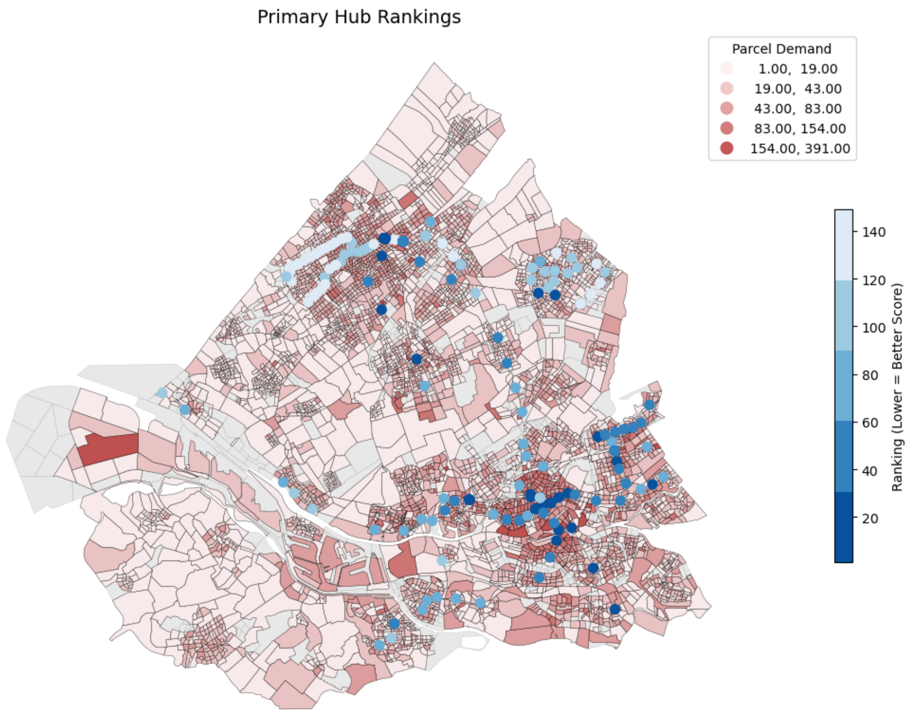


(a) Cargo Requirements **(b)** Costs **(c)** Connectivity **(d)** Capacity **(e)** Accessibility

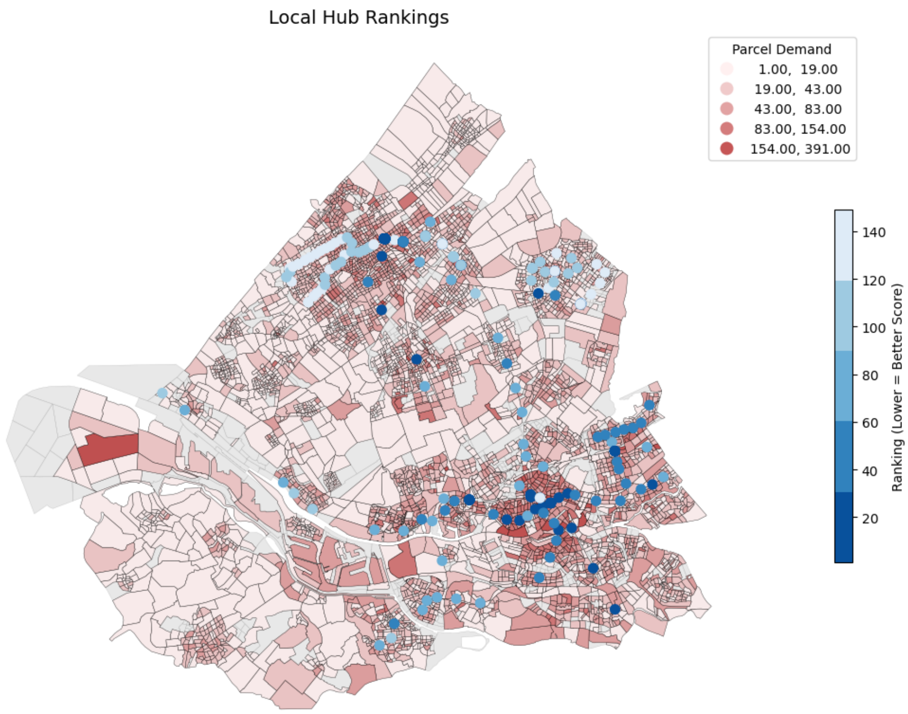
Figure 4.3: Sensitivity Analysis on Sub-Criteria Weights

4.4. Hub Rankings

Figure 4.4 shows the rankings of the public transport stations as either primary or local hubs. It can be seen that the majority of the stations rank similarly for both hubs. One reason could be that the weights of the criteria for primary and local hubs do not have drastic differences, resulting in similar station scores. Another reason could be that many stations have both 1) good access to parcel origins and destinations and 2) sufficient capability to operate freight.



(a) Primary Rankings



(b) Local Rankings

Figure 4.4: Primary and Local Hub Rankings

5 Case Study

This chapter presents the results of the case study using simulation. The study area and used data are first introduced. Subsequently, the scenarios and assumptions of the simulation-based case study are defined. Thereafter, the sensitivity analysis and the simulation outputs are demonstrated. Rather than optimise for a single objective, the simulation compares three plausible hub configurations that reflect realistic strategies urban freight planners may adopt. Their performance is evaluated through key metrics (parcel delivery rate, setup cost, transport cost, and CO_2 emissions), as defined in Chapter 3, offering insights into trade-offs between possible network designs.

5.1. Study Area

The case study area is the Rotterdam-The Hague Metropolitan Area (MRDH), in South Holland, The Netherlands. South Holland is one of the most economically advanced provinces in the Netherlands, including Europe's largest port, the Port of Rotterdam. This province is home to numerous international institutions and corporations. Specifically, MRDH includes the urban areas in this province and is home to about 2.4 million people, 1.3 million jobs, and 13.5% of the Dutch population [2]. Despite only occupying an area of 1213 km^2, MRDH produces 15% of the gross national product (GNP) collectively. South Holland has a robust transport network that includes roads, rail, water, and public transit [18], hence, MRDH has a well-connected transport network as well. Figure 5.1 depicts the study area of MRDH (coloured zones), with South Holland being the base map (grey area).

5.2. Data

5.2.1. Freight Demands

This study employs the Multi-Agent Simulation System for Goods Transport (MASS-GT) as the primary data source for freight movements in the study area. MASS-GT is an agent-based freight transport simulation model that integrates real-world logistics data to model urban and regional parcel flows [12][13][14][15]. The model has been extensively validated against empirical transport data and provides detailed, multi-source shipment information. In particular, the parcel demand module of MASS-GT simulates parcels within South Holland, including the case study area, MRDH. This module generates parcel demands based on sociodemographic and empirical logistics data, such as household information, average parcel demand volumes, and market share of all LSPs. The dataset includes the origin zones, destination zones, LSPs, and depots (LSPs' distribution centres), used as a demand input in this study. As MASS-GT specifically contains parcel information, the case study focuses solely on parcels.

Utilising MASS-GT as the demand source has several significant advantages. First, the model is built on observed logistics flows, ensuring high realism. Furthermore, unlike traditional freight models, MASS-GT tracks individual shipments, which aligns well with the hub-based delivery strategy examined in this study. Lastly, the model has been applied in several real-life applications in the Netherlands [12][14][15], proving its effectiveness and reliability in urban freight transport applications.

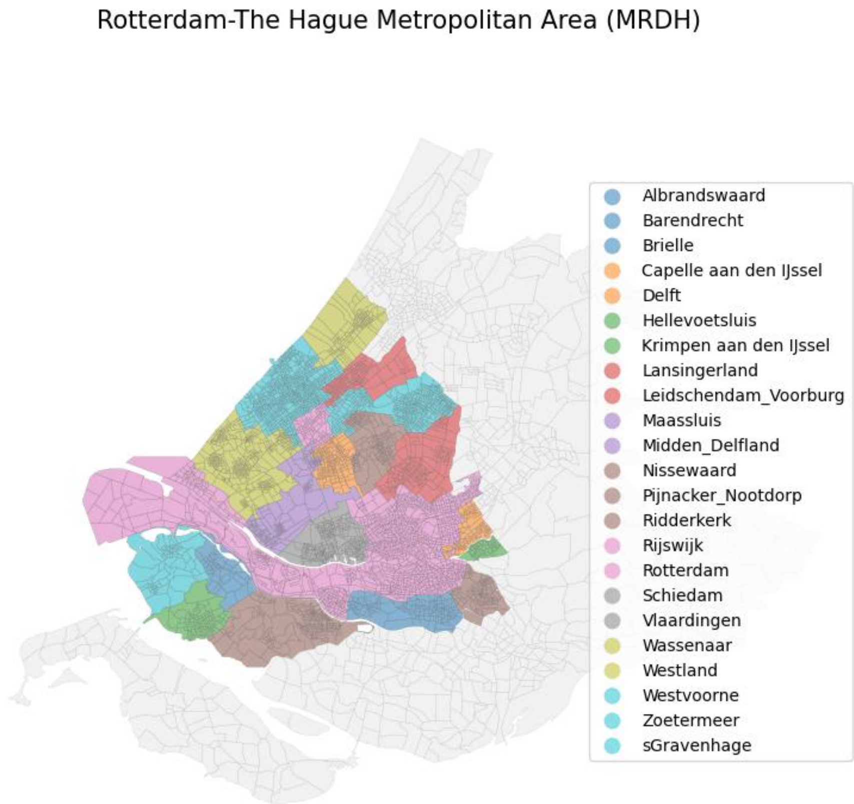


Figure 5.1: Study Area: Rotterdam-The Hague Metropolitan Area (MRDH)

Figures 5.2 and 5.3 display the parcel demand distribution and depots in the study area. Specifically, in Figure 5.2 the station locations are highlighted. The yellow dots represent train stations, the red circles refer to light rail stations, and the blue points are metro stations.

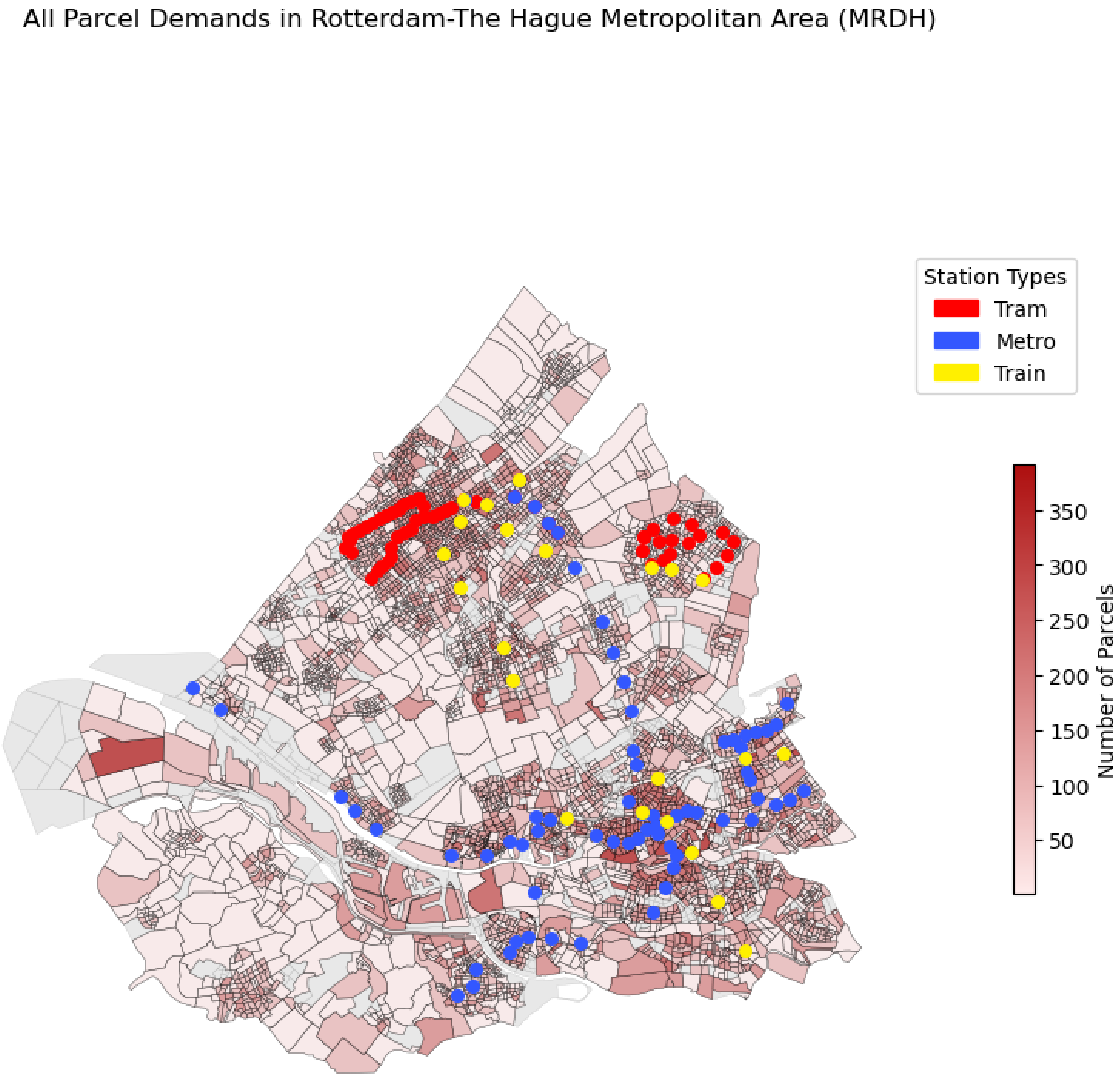


Figure 5.2: Parcel Demand Distribution in Rotterdam-The Hague Metropolitan Area (MRDH).

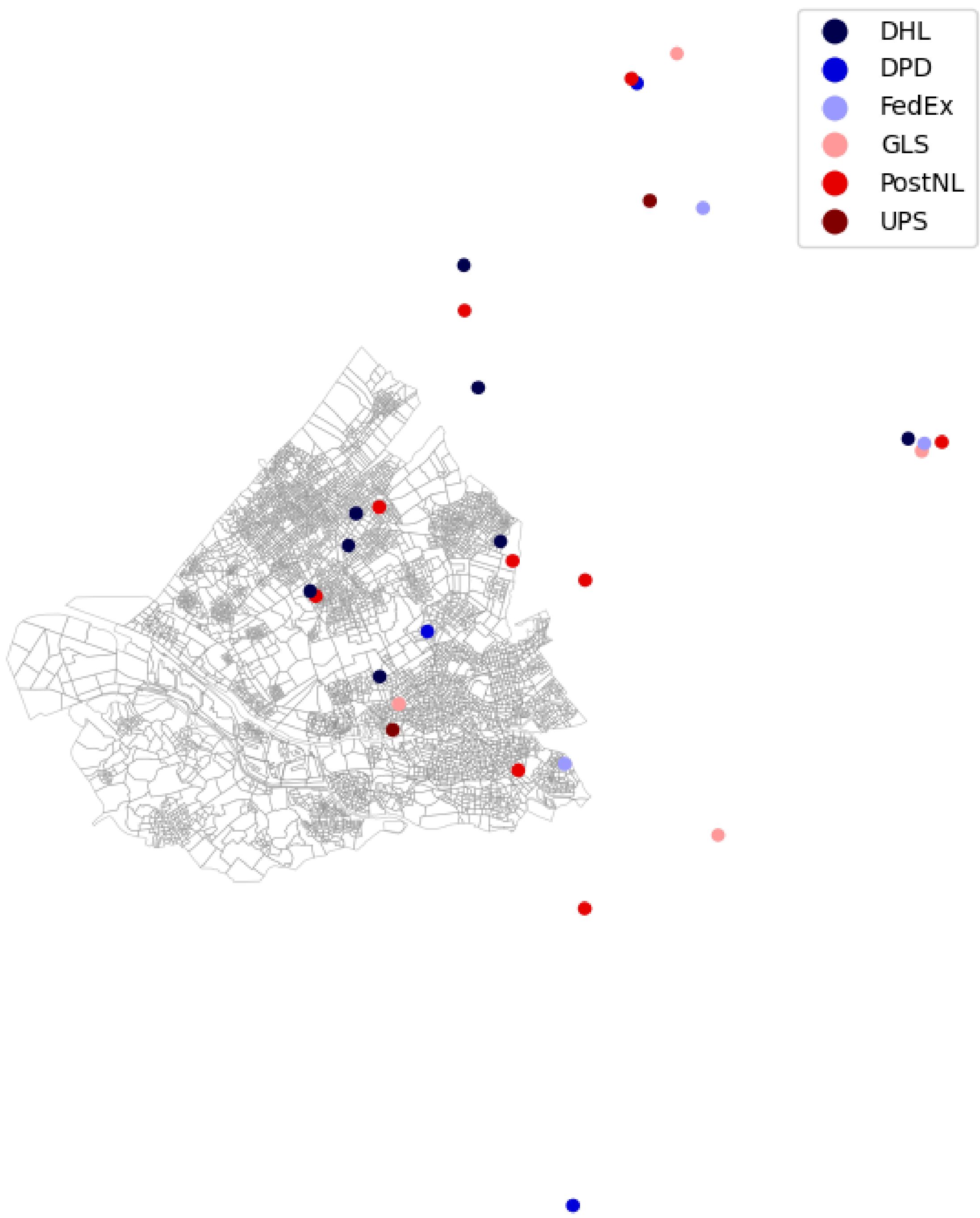


Figure 5.3: Depots of Parcels in Rotterdam-The Hague Metropolitan Area (MRDH)

5.2.2. Public Transport Stations

In total, there are 149 train, light rail, and metro stations in the MRDH used in the study. The train stations consist of all the NS stations in this region. The metro services include the metro lines A to D that are operated in Rotterdam, as well as RandstadRail's line E that runs between The Hague and Rotterdam. For light rail, the regional light rail lines 3, 4, and 34 from RandstadRail are included. These light rail routes are not the local tram lines in each city within MRDH (e.g., trams in Delft, The Hague, and Rotterdam). The reason is that if including the excessive number of local tram lines in this study, the simulation would be overcomplex and unrealistic to undertake in a limited time duration. The locations of the train, metro, and light rail stations in MRDH are obtained from the OpenStreetMap API, as represented by coloured circles in Figure 5.2.

GTFS data is used to calculate the sub-criterion service frequency for train stations [58]. Due to limited data availability, only static GTFS data for trains could be obtained. The service frequencies of light rail stations are calculated based on the fixed schedules of RandstadRail tram lines, namely 3, 4, and 34 [38]. Similarly, the timetable for Rotterdam and The Hague metro routes, including lines A to B, is used to obtain the frequencies of metro stations [62]. One day of timetable for both the light rail and metro is collected (0:00 - 24:00 on 17/01/2025).

5.3. Case Study Simulation

This section details the simulation assumptions and scenarios. Firstly, the operational assumptions of the case study are outlined. Next, the defined scenarios and corresponding schematic representations are provided. The simulation results are presented in Section 5.4.

5.3.1. Assumptions

Pre-Operations by Logistics Service Providers (LSPs)

Prior to entering the integrated delivery system, the parcels are transported to the public transport stations from the warehouses of the LSPs (e.g., PostNL, DHL, DPD, and FedEx). Each LSP is responsible for collecting their parcels, consolidating them in containers based on destinations (demand points), and delivering them to a public transport station that is the closest to them. To not overcomplicate the simulation, the transport from the LSP warehouses to the transit stations is not considered.

Operations at Public Transport Stations

At the public transport stations, the parcels will be loaded onto the public transport vehicles. It is assumed that LSPs transport their parcels to the stations on a predetermined basis and that the goods are loaded onto the vehicles within a reasonable amount of time based on the station capacity and availability. The loading of the goods can be done by station staff or employees of the LSPs.

Middle-Leg Transport by Public Transport Vehicles

A delivery trip starts once a vehicle departs from the corresponding origin station. The schedule of each public transport vehicle is known. Since, in general, trains, metro, and light rail operate frequently, it can be assumed that each vehicle departs at a station with a certain time interval. Thus, the schedule of individual vehicles is not considered, avoiding additional complexity for the study.

Exclusion of LMD

The goods are carried by public vehicles to stations close to demand points, which may be different from their departure stations. The goods are then unloaded from the vehicles, taken out of each container, and transshipped to LMD operators or temporarily stored at the arrival station before being picked up for LMD. A fixed time for unloading the containers from transit vehicles is assumed. The operations of LMD are not accounted for by this study. For demands that are close to the PT stations (e.g., within a 1- or 2-km radius), it is not unreasonable to assume that the goods could be easily picked up by the customers themselves and carried home by active modes such as walking and biking.

5.3.2. Scenarios

The scenarios are designed to evaluate varying hub configurations of the PTF network. In total, there are three scenarios developed that differentiate network structure and freight flow order (Figures 5.4 to 5.6):

- **Scenario 1: Primary Hub Use**
  Only primary hubs handle freight. All goods are routed directly between primary hubs near their origins and destinations, bypassing secondary and local hubs.
- **Scenario 2: Hierarchical Routing**
  Freight flows through primary, secondary, and local hubs, following the hierarchy strictly. Hub rankings and centrality scores are used to determine each primary and local hub pair and the ideal secondary hub for this pair, respectively.
- **Scenario 3: Decentralised Hub Network**
  Primary and local hubs handle freight; however, at least a proportion of the available budget is allocated to local hubs to promote the use of lower-cost, decentralised local hubs. While primary hubs remain available, they are not prioritised so as to reduce reliance on them.
  - Case 1: Direct route primary → primary;
  - Case 2: Direct route primary → local;
  - Case 3: Primary → primary → local: another primary hub is selected as a transfer point when there exists no direct primary → local route.

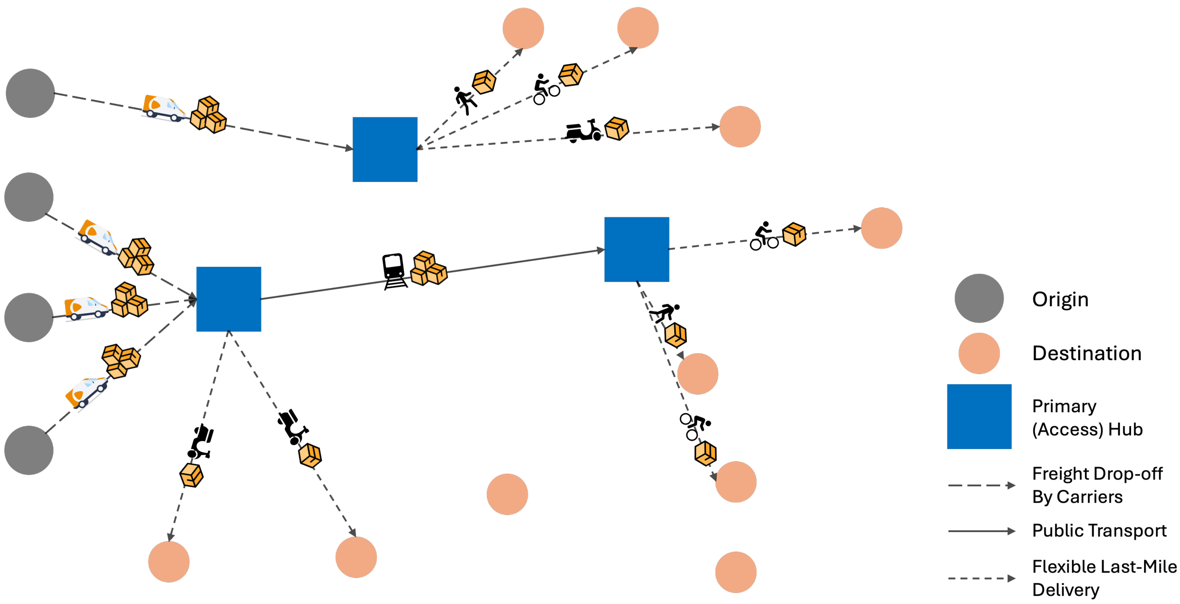


Figure 5.4: Scenario 1: Minimal Hub Use

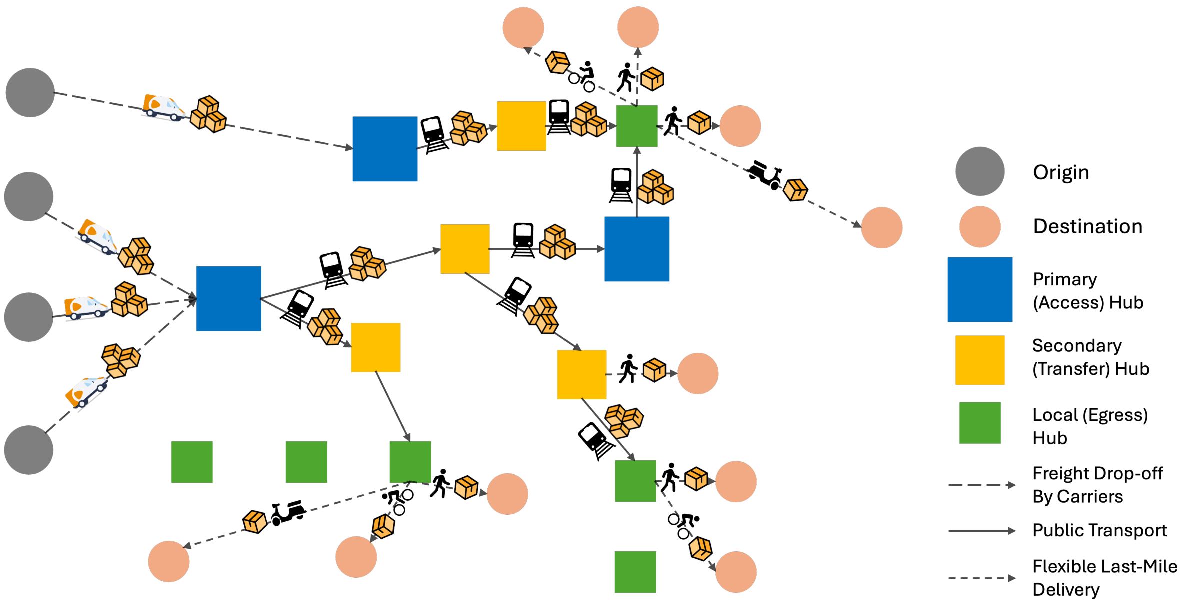


Figure 5.5: Scenario 2: Hierarchical Network

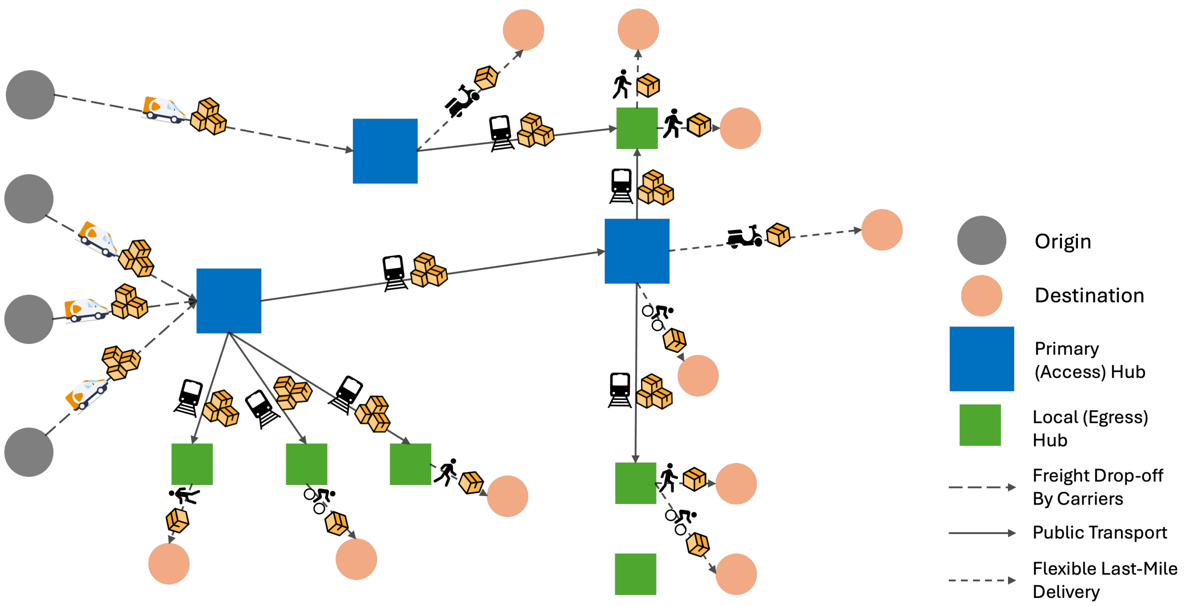


Figure 5.6: Scenario 3: Decentralised Network

5.4. Outputs

5.4.1. Sensitivity Analysis

The sensitivity analysis evaluates how variations in key parameters influence the simulation outcome, comprising hub capacity, hub setup costs, total budget, budget allocation to local hubs (in scenario 3), and transfer penalties (time and cost) (Figures 5.7 to 5.9). Full sensitivity analysis results are displayed in Tables C.1 to C.6 in Appendix C.

Figure 5.7 illustrates that changes in hub capacity significantly impact scenario 2. Scenarios 1 and 3 remain largely unaffected; thus, they are not included in Figure 5.7. In Scenario 1, the number of parcels, hub setup cost, transport cost, and CO_2 emissions are unchanged, regardless of capacity changes, suggesting that primary hubs are underutilised and are not capacity-constrained (Table C.1). Scenario 3's results are also stable across all capacity levels, indicating that the decentralised system is limited by other factors than hub capacity. In contrast, scenario 2 exhibits a notable increase in the proportion of parcels handled, total hub cost, and the number of secondary hubs used, though the quantities of primary and local hubs used are constant. Consequently, the transport cost and CO_2 emissions also rise, suggesting that the network utilisation rate is much higher.

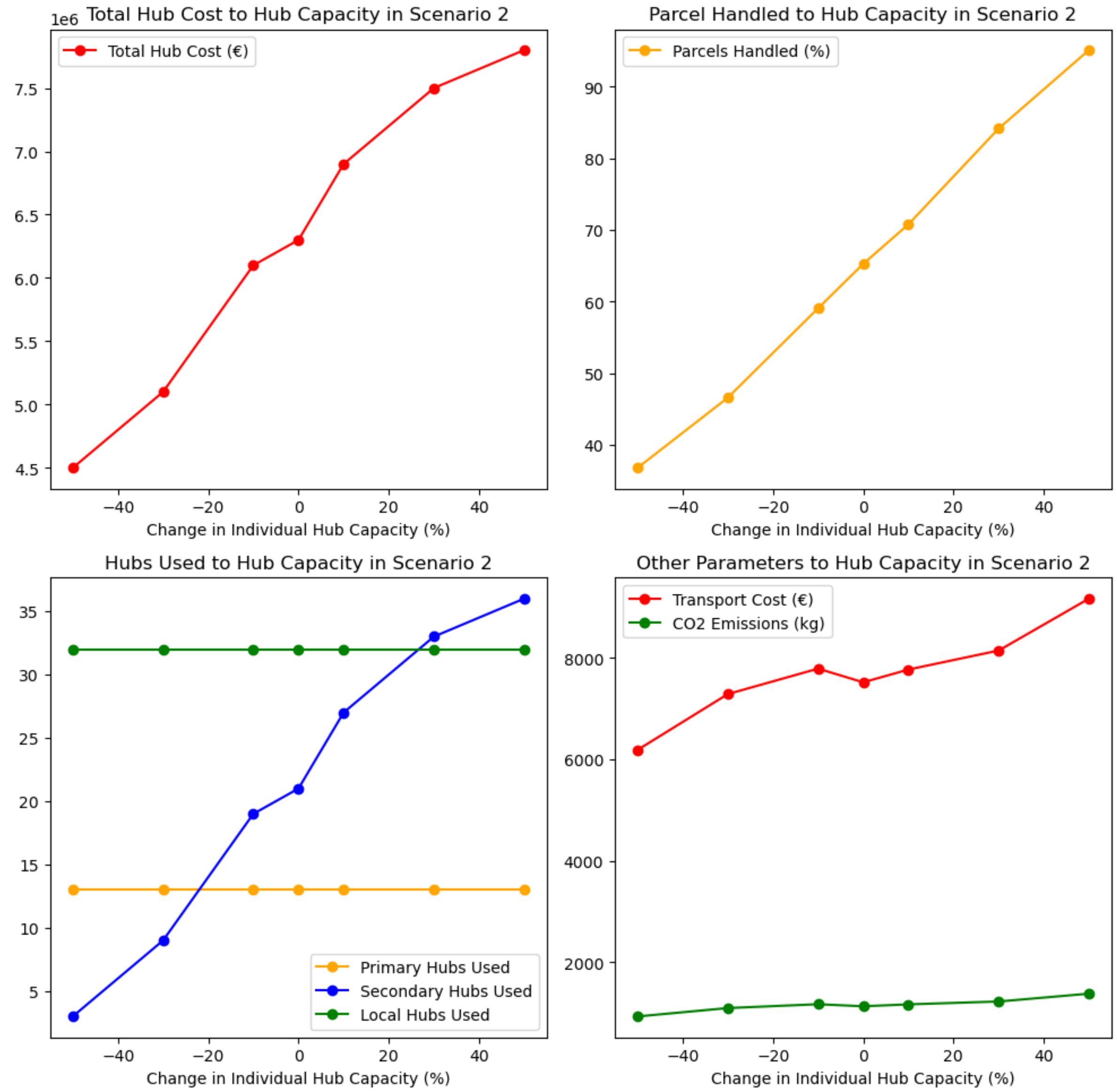
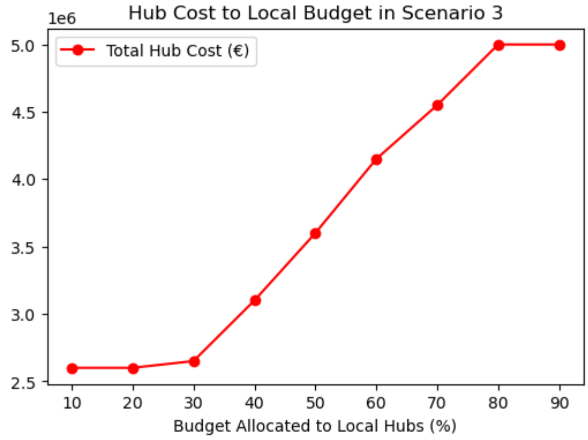
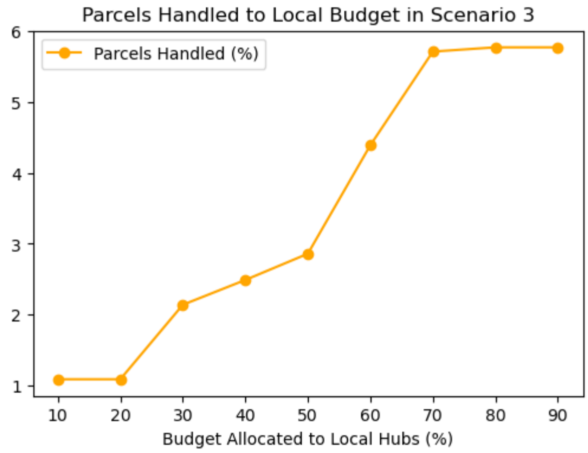


Figure 5.7: Sensitivity Analysis on Hub Capacity

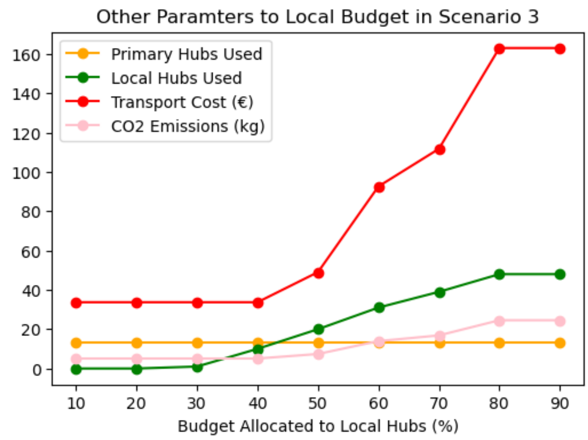
Since scenario 3 uniquely promotes local hubs, analysing the budget allocated to local hubs reveals how the network performs under a varying local hub number (Figure 5.8 and Table C.4). When less than 30% of the budget is allocated to local hubs, merely 1% of total parcels are delivered, with almost no local hubs activated. As the local budget increases, the number of used local hubs and the parcel processing rate drastically increase, along with the total hub and transport costs and CO_2 emissions. However, beyond 70% allocation, additional budget does not really further improve the parcel handling rate, as shown in Figure 5.8b, indicating network inefficiency at an overly high local budget.



(a) Total Hub Cost



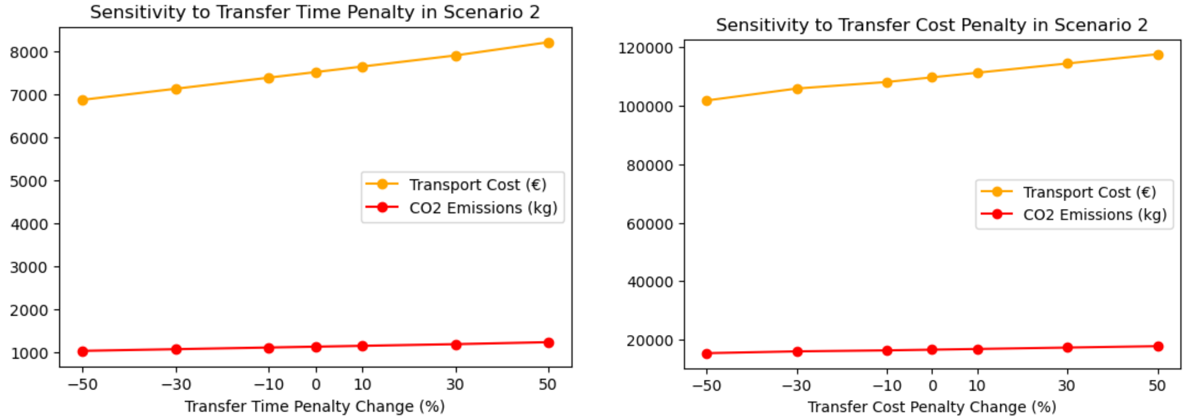
(b) Proportion of Parcel Handled (%)



(c) Other Parameters

Figure 5.8: Sensitivity Analysis on Local Budget Allocation

Regarding transfer penalties, only scenario 2 is sensitive to the time penalty, while scenarios 1 and 3 results remain mostly unaffected (not visualised). This suggests that the use of only primary and local hubs is not significantly impacted by time-based transfer penalties (Table C.5). In contrast, in scenario 2 (Figure 5.9a), the transport cost and CO_2 emissions grow as the time penalty increases. Similarly, a higher transfer cost penalty also leads to increases in the transport cost and CO_2 emissions in scenario 2 (Figure 5.9b), while scenarios 1 and 3's outputs are relatively constant. This suggests again that primary and local hub uses are not significantly affected by the transfer cost penalty.



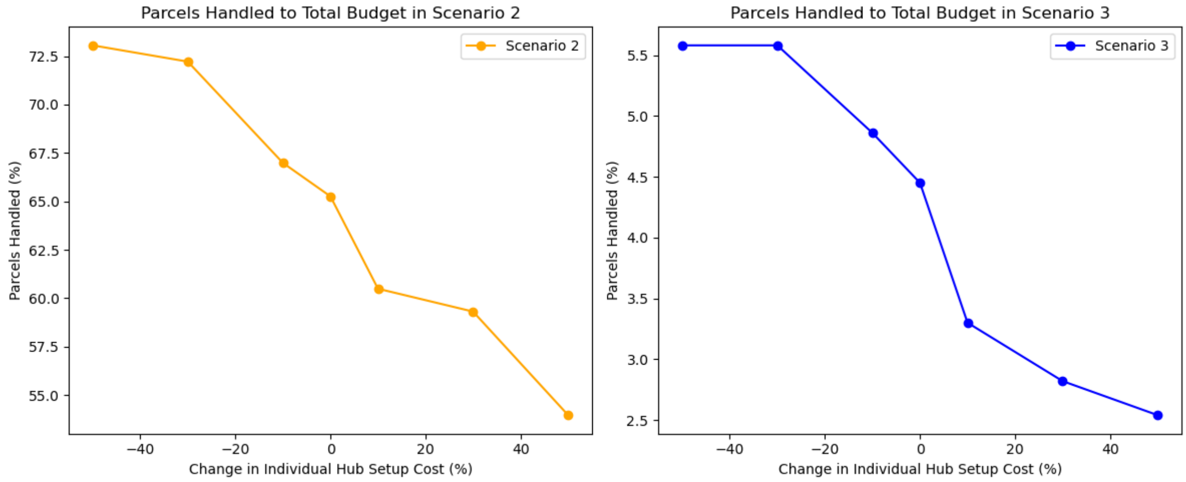
(a) Transfer Time Penalty

(b) Transfer Cost Penalty

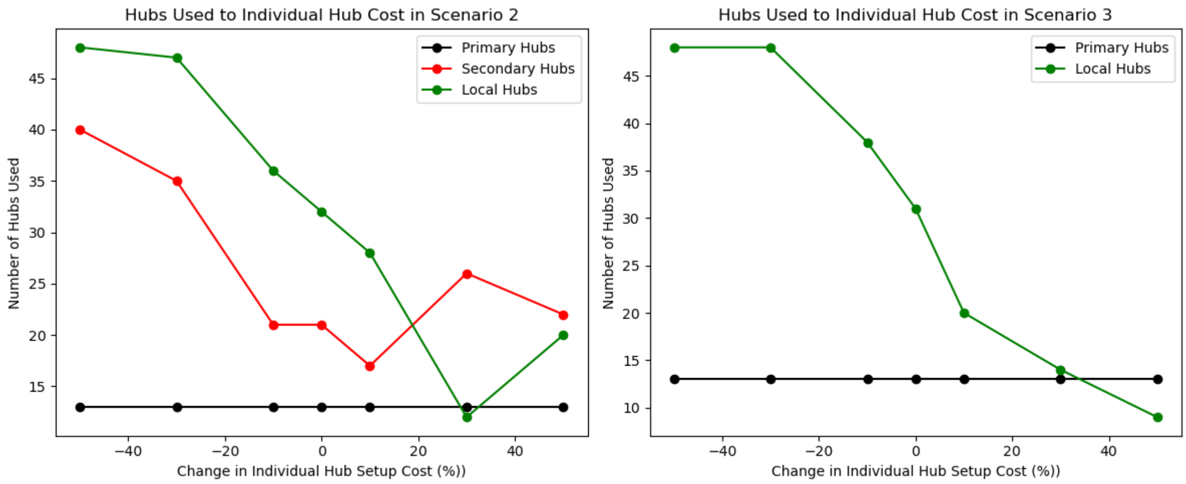
Figure 5.9: Sensitivity Analysis on Transfer Penalties

On the other hand, adjusting hub setup costs affects both scenarios 2 and 3 (Figure 5.10), while scenario 1 results remain unchanged (Table C.2). In scenarios 2 and 3, higher individual setup costs lead to fewer parcels being processed and a smaller number of hubs used (except primary hubs). This is not surprising, as the total budget is fixed; thus, higher unit costs result in fewer hubs. Nevertheless, the fluctuating transport expenses and CO_2 emissions in scenario 2 could suggest that the relationships between hub setup costs and them are non-linear. Fewer hubs could lead to inefficient routes, introducing additional transport distance and more negative environmental impact.

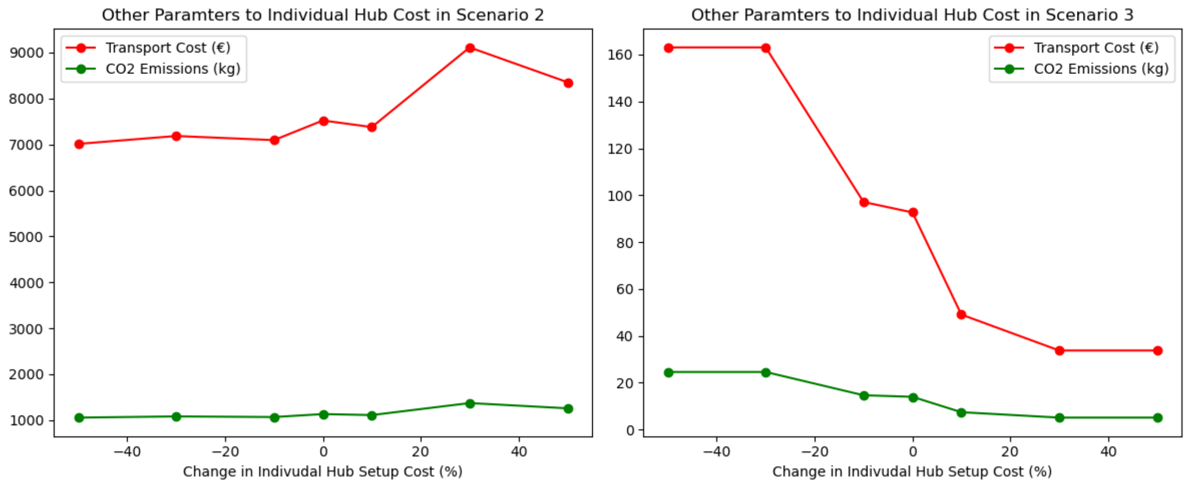
Figure 5.11 reveals that variations in the total budget are shown to directly impact the number of hubs used and parcels processed in scenarios 2 and 3. Similar to the above sensitivity analysis results, scenario 1 remains constant, confirming that primary hubs alone do not scale with additional budget in the case study (Table C.3). On the contrary, in scenario 2, as the budget increases, the proportion of parcels processed grows, alongside the number of secondary and local hubs used. The transport cost and CO_2 emissions exhibit a slight non-linear trend, implying an efficiency threshold in hub expansion. Similarly, in scenario 3, the parcel delivery rate improves with a higher budget, though only the number of local hubs also increases. A notable difference in scenarios 2 and 3 is that the transport cost and CO_2 emissions rise sharply in scenario 3, while those in scenario 2 remain relatively constant, suggesting an improved efficiency of allowing transfer hubs in the network. Nevertheless, the stable number of primary hubs used in both scenarios 2 and 3 indicates that the freight allocation to primary hubs could be overly strict, as even an unlimited budget does not increase the number of selected primary hubs.



(a) Proportion of Parcel Handled (%)

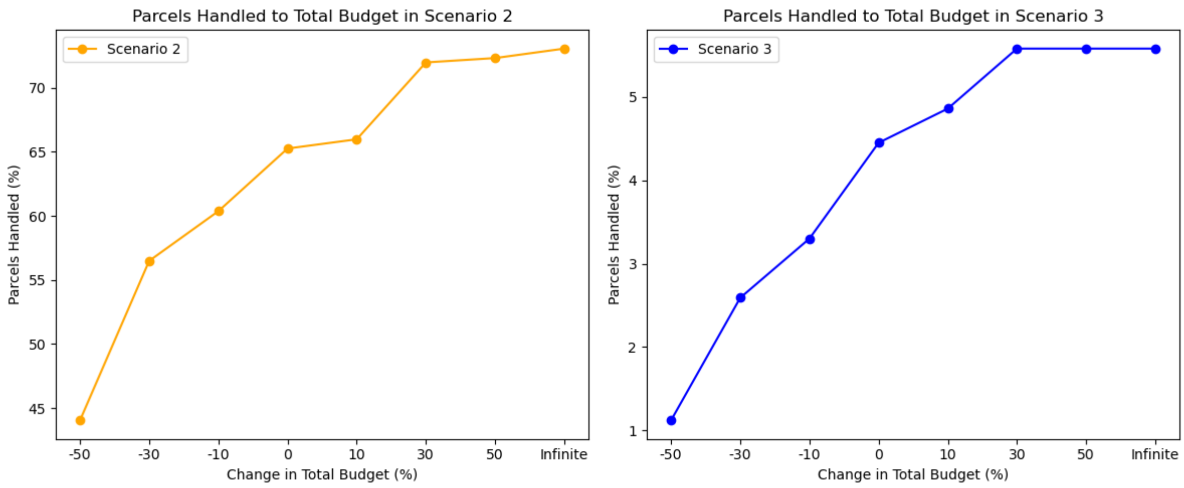


(b) Number of Hubs Used

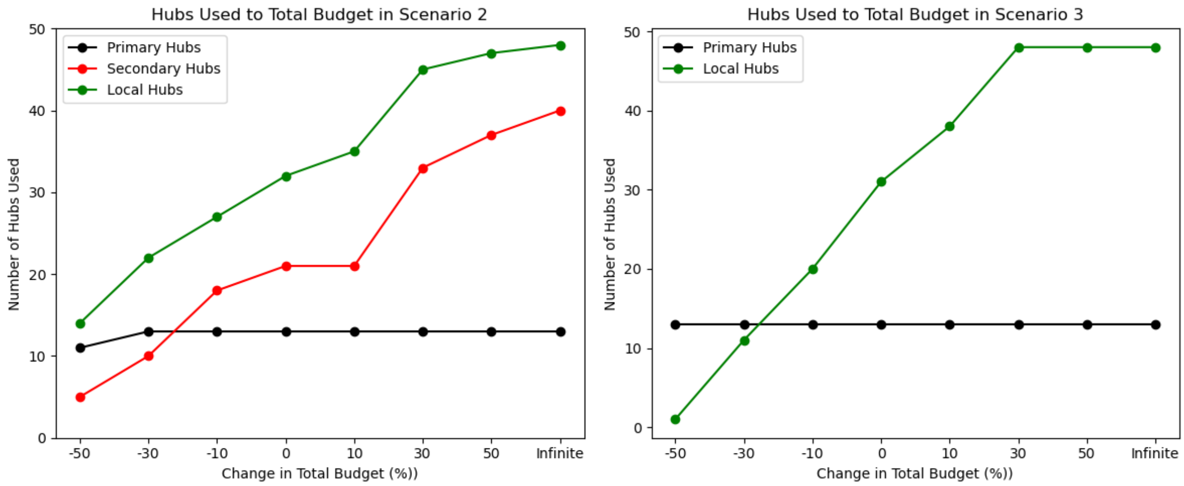


(c) Other Parameters

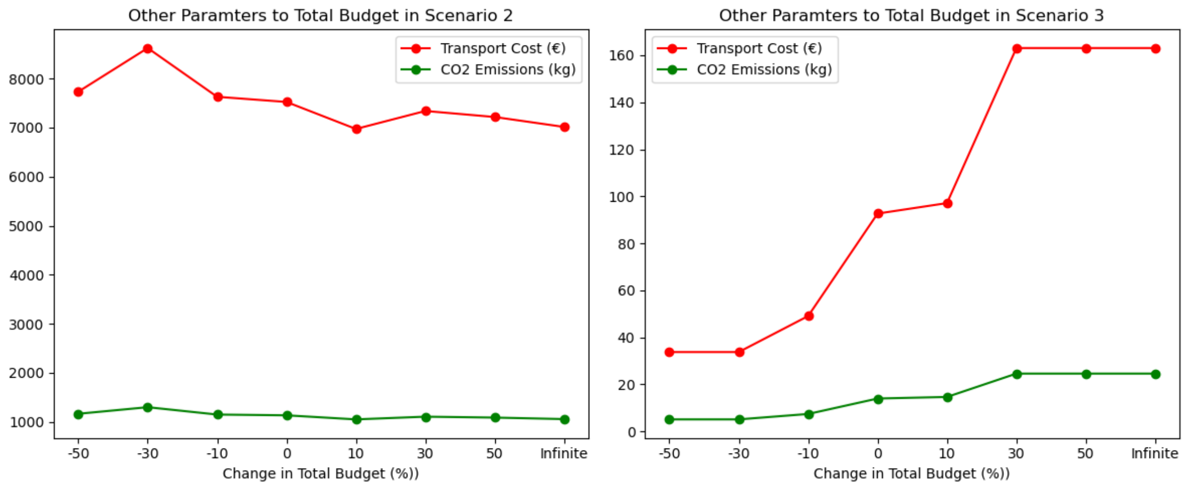
Figure 5.10: Sensitivity Analysis on Hub Setup Cost



(a) Proportion of Parcel Handled (%)



(b) Number of Hubs Used



(c) Other Parameters

Figure 5.11: Sensitivity Analysis on Total Budget

5.4.2. Network Performances

The simulation is conducted using baseline parameters and time-based transfer penalties to construct the network graph (Section 3.3). The baseline parameter values and the simulation results are listed in Tables 5.1 and 5.2. To further distinguish how freight flow and hub usage patterns vary in different scenarios, Figures 5.15, 5.12, and 5.14 illustrate the spread of used hubs, the intensity of parcels flown between hubs, and the quantity of parcels handled at each origin and destination hub, respectively.

Table 5.1: Simulation Parameters

Parameter	Notation	Value	Unit
Transport Mode Parameters			
Train speed	s_{train}	120	km/h
Metro speed	s_{metro}	80	km/h
Light rail speed	$s_{\text{light rail}}$	30	km/h
Train cost per km	c_{train}	0.30 [69]	€/km
Metro cost per km	c_{metro}	0.171 [1]	€/km
Light rail cost per km	$c_{\text{light rail}}$	0.193 [1]	€/km
Train emissions	e_{train}	0.02	kg CO_2/km
Metro emissions	e_{metro}	0.03	kg CO_2/km
Light rail emissions	$e_{\text{light rail}}$	0.05	kg CO_2/km
Transfer Penalties			
Transfer time penalty: train $\to$ metro	$p_t(\text{train}, \text{metro})$	5/60	hour
Transfer time penalty: train $\to$ light rail	$p_t(\text{train}, \text{light rail})$	7/60	hour
Transfer time penalty: metro $\to$ light rail	$p_t(\text{metro}, \text{light rail})$	4/60	hour
Transfer cost penalty: train $\to$ metro	$p_c(\text{train}, \text{metro})$	1.0	€
Transfer cost penalty: train $\to$ light rail	$p_c(\text{train}, \text{light rail})$	1.5	€
Transfer cost penalty: metro $\to$ light rail	$p_c(\text{metro}, \text{light rail})$	0.5	€
Hub Setup Costs			
Primary hub setup cost	c_{primary}	200,000	€
Local hub setup cost	c_{local}	50,000	€
Secondary hub setup cost	$c_{\text{secondary}}$	100,000	€
Hub Capacities			
Primary hub capacity	Q_{primary}	10,000	parcels/day
Secondary hub capacity	$Q_{\text{secondary}}$	5,000	parcels/day
Local hub capacity	Q_{local}	2,500	parcels/day

Table 5.2: Simulation Results

Metric	Scenario 1	Scenario 2	Scenario 3
Parcels Delivered	2,516 (1.04%)	158,505 (65.26%)	10,811 (4.45%)
Total Hub Setup Cost (€)	2,600,000	6,300,000	4,150,000
Transport Cost (€)	33.72	7,521.88	92.65
CO_2 emissions (kg)	5.08	1,132.82	9.96
Number of Hubs Used			
Primary Hubs	13	13	13
Secondary Hubs	0	21	0
Local Hubs	0	32	31

Table 5.1 displays that scenario 1 only processes 1.04% of total freight demand. The hub setup cost is relatively low (€2,600,000), with 13 primary hubs in operation. The transport cost and CO_2 emissions are also minimal (€33.72 and 5.08 kg). When secondary hubs and local hubs can be used, such as in scenario 2, the number of parcels processed increases to almost two-thirds of the total demand (65.26%), significantly increasing the network utilisation. As a result, the hub setup cost amounts to €6,300,000 due to the secondary hubs and additional local hubs enabled. The transport cost and CO_2 emissions also rise to €7,521.88 and 1,132.82 kg, respectively, reflecting longer transport distances and higher emissions. On the other hand, the parcel handling rate of 4.45% in scenario 3 is higher than in scenario 1 but significantly lower than that of scenario 2. The hub setup cost in this case is also in the middle between scenarios 1 and 2 (€4,300,000), as well as the transport cost and CO_2 emissions (€92.65 and 9.96 kg), which are higher than in scenario 1 but significantly lower than in scenario 2.

When visualising the freight flows, Figure 5.12 illustrates that scenario 1, where primary hubs handle all parcels, has a concentrated parcel movement pattern with a relatively simple network. In contrast, when secondary hubs are added to scenario 2, there are more diverse directions that parcels flow in, using additional network nodes to reach more destinations. The number of parcels handled at each hub is also more varied, as seen in Figure 5.12; a hub in scenario 2 may handle a low, medium, or high number of parcels. However, different from scenario 2, though local hubs are enabled in scenario 3, the quantity of allowed freight is still limited due to the absence of compulsory transfer hubs. Nevertheless, compared to scenario 1, there are more localised delivery routes in the last scenario.

One significant finding from Figure 5.12 is that in scenario 2, several secondary hubs appeared in close proximity to primary hubs, particularly in high-demand areas. This spatial clustering can be partly explained by the use of betweenness centrality scores. In this study, secondary hubs were originally intended to be selected based on betweenness centrality scores, a measure of a node's strategic importance for enabling transfers within a transport network; however, because the transport graph was constructed as a fully connected network using Euclidean distances (rather than actual public transit topology), every station was directly connected to every other station. As a result, no paths required an intermediate node, and all stations exhibited identical betweenness centrality scores of 1. Due to this issue, secondary hubs could not be meaningfully distinguished using centrality, as all nodes appeared equally unimportant in structural terms. To ensure that a hierarchy of hubs could still be established, the simulation adopted a fallback classification logic. Specifically, any selected station that was not among the top-ranked primary or local hubs was automatically classified as a secondary hub. The closest possible secondary hub to the destination (local hub) was selected. As a result, the classification of secondary hubs was implicitly shaped by spatial proximity and their eligibility to form valid parcel routes under budget and capacity constraints, rather than structural centrality. This likely explains why some secondary hubs appear spatially close to primary hubs, particularly in high-demand zones, where high demands prompted the reuse of nearby stations for intermediate transfer roles, even if not structurally justified. By visualising the secondary hub rankings, it is evident that all stations indeed have the same centrality score of 1, as shown in Figure 5.13 below.

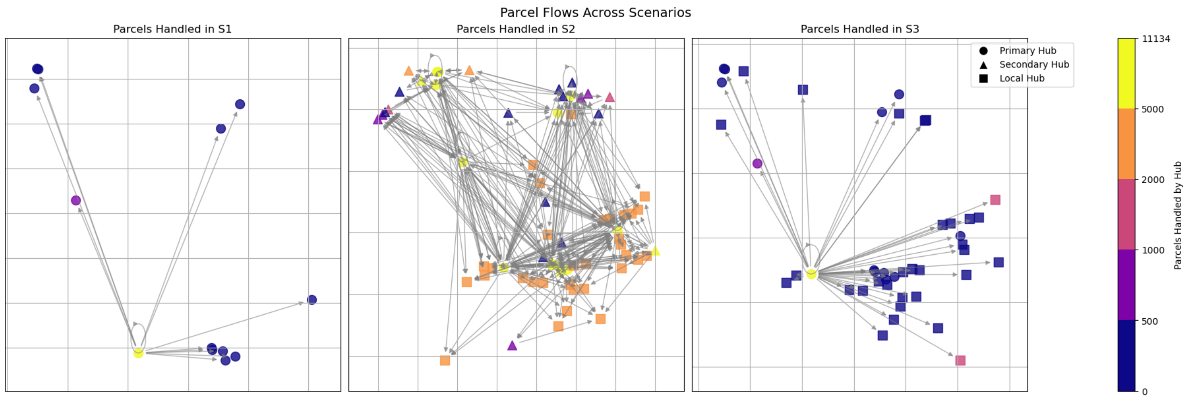


Figure 5.12: Parcel Flow Distributions

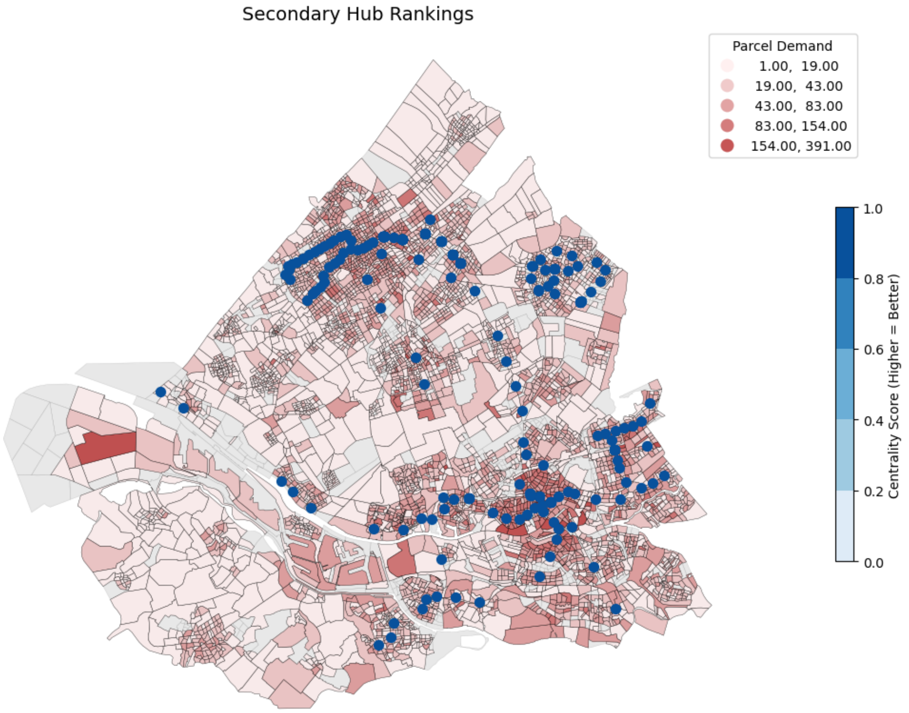


Figure 5.13: Secondary Hub Rankings

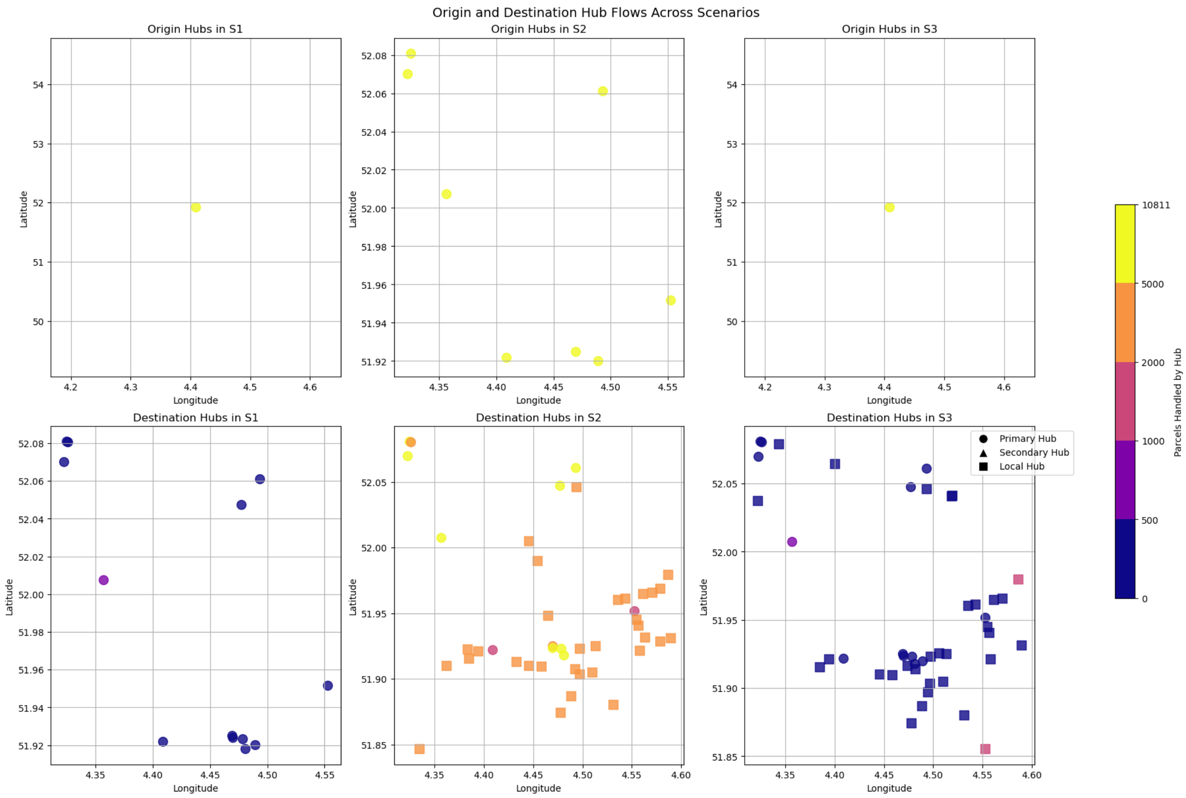
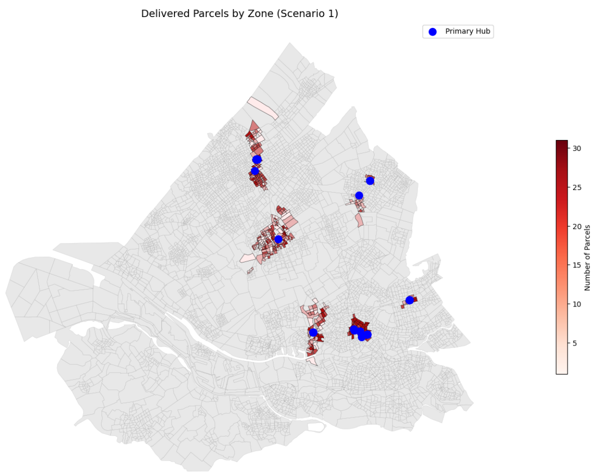


Figure 5.14: Origin and Destination Hub Distributions

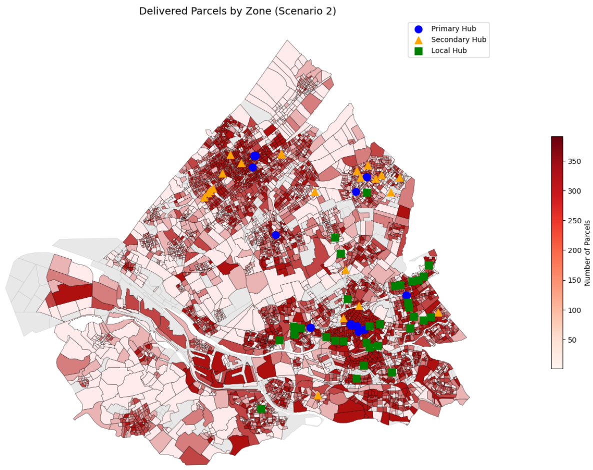
For origin and destination hubs, Figure 5.14 illustrates that only one origin hub is activated in scenarios 1 and 3. This could be due to the strict freight allocation mechanism (Section B.4). In scenario 1, for a freight trip to be assigned, both the origin and destination must have a primary hub within reach, limiting the number of hubs activated. The reach is determined by real-world travel distance and time constraints set in the freight allocation step (Section 3.3), enforced by computing Haversine distances and applying time-based weight (note that the cost transfer penalty was only analysed in the sensitivity analysis). Consequently, only one primary hub meets the reach in scenario 1, while the other potential primary hubs are beyond the threshold, preventing them from being activated and leading to very limited origin hub activation in scenario 1. However, while the incoming parcels are still clustered at one origin in scenario 3, the local hubs facilitate a wider distribution of deliveries, activating more destination hubs in this scenario. Contrarily, in scenario 2, the origin and destination hubs are spread out much more widely since secondary hubs allow more primary and local hubs to be connected.

Further, Figure 5.15b illustrates the distribution of delivered parcels and used hubs in each scenario. Scenario 1 has a limited concentration of deliveries since they could only occur between zones connected to these primary hubs; hence, many demand zones located farther from primary hubs remained unserved. In scenario 2, however, coverage is significantly wider due to the secondary hubs. This notably broad coverage of parcel deliveries arises from the allocation hierarchy and fallback hub classification approach. Since centrality-based metrics failed to differentiate secondary hubs due to the fully connected structure of the transport graph, secondary hubs were classified based on positional rank alone, resulting in a large number of them. Then, any secondary hub connected to a local hub was eligible to act as a transfer station in scenario 2. In a fully connected network, all hubs are technically linked, meaning nearly all secondary hubs qualify as valid transfer points. This, combined with the loose selection of local hubs using nearest-neighbour queries (KDTree), enabled the model to construct valid paths for a vast majority of parcels. Therefore, even zones located far from dense public transport corridors were able to receive deliveries, leading to the extensive spatial coverage observed in scenario 2. On the other hand, scenario 3 imposes stricter delivery logic, as only one intermediate hub is allowed and no broad classification of transfer points exists. Thus, while coverage improves over scenario 1 due to the inclusion of local hubs, it remains less extensive than scenario 2.

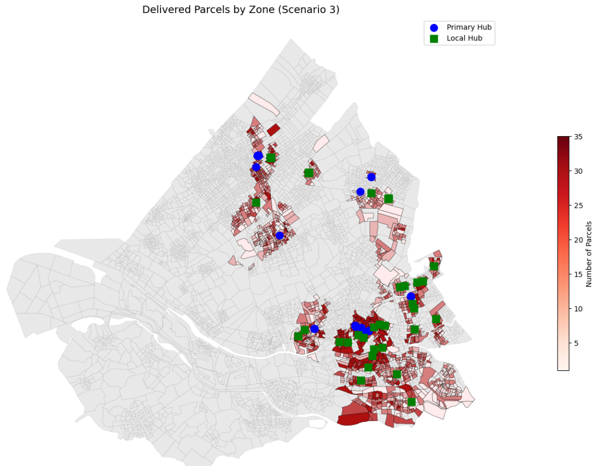
Relating Figure 5.12 to Figure 5.15, another reason for the excessive secondary hubs could be that stations near central areas of the city tend to be close to zones with high parcel volumes, often where primary hubs are also located. Although secondary hubs were not selected using meaningful centrality scores, the parcel allocation process activated them in high-demand areas to relieve capacity pressures on primary hubs. As shown in the darker red-shaded zones in Figure 5.15b, secondary hubs were needed in dense demand clusters to balance freight flow and maintain connectivity across the network. Therefore, additional transfer hubs, which were in close proximity to primary hubs, may have been activated to ensure capacity balancing and maintain network connectivity across all routes.



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

Figure 5.15: Delivered Parcels and Used Hubs

5.5. Discussions

This study presents an innovative approach to urban freight planning by investigating Public Transport-Based Freight Delivery (PTF), using public transport stations as freight delivery hubs. A multi-criteria decision analysis (MCDA) technique, the Best-Worst Method (BWM), was employed to weigh hub selection criteria and rank hubs, while simulation tested the implementation feasibility of proposed hub configurations. Prior tactical and operational research on PTF exists, but the strategic PTF hub planning remains largely unexplored. Thus, the study provides novel insights into hub performance, sensitivity to key parameters, and trade-offs in network design in combined passenger and freight transport systems.

Firstly, the results from the BWM (Section 4) revealed that accessibility and capacity were the most critical criteria for hub selection. The sensitivity analysis indicated that accessibility remained the dominant factor for primary hubs, while capacity played a greater role for local hubs. The relatively lower importance of cargo requirements suggests that public transport hubs can accommodate a wide range of freight types. Through the results of the sensitivity analysis, the BWM is robust and effective in determining hub selection criteria.

Secondly, simulation outcomes (Chapter 5) demonstrated different trade-offs between the three hub network scenarios. Scenario 1 (primary hub use) is efficient in cost and emissions but severely limited in handling demand. Scenario 2 (hierarchical network) allows for a much higher freight handling quantity but at a significantly higher transport cost and CO_2 emissions. Scenario 3 (decentralised network) represents a more balanced parcel handling and cost efficiency than scenario 1 but requires careful budget allocation to local hubs, and the network utilisation rate is still significantly lower than scenario 2. These comparisons imply that secondary hubs play a complex role in such networks, as they improve network connectivity but introduce additional hub setup and transport costs, the first of which could be significant, as well as higher emissions.

Further, the sensitivity analysis for the simulation shows that only scenario 2 was sensitive to hub capacity changes, which was also the most affected scenario by individual hub setup costs. This indicates that hub capacity and financial constraints play a major role in network scalability. While the total budget could have seemed to play a vital role, only scenarios 2 and 3 benefited from the increased available budget, as scenario 1 remained unchanged regardless of budget size. Furthermore, in scenario 3, while allocating more budget to local hubs initially leads to an increase in the number of parcels handled, beyond a certain threshold, the additional investment does not significantly increase network utilisation. This suggests that the network reaches an efficiency threshold where adding more local hubs no longer provides substantial benefits and may even introduce inefficiencies due to factors such as increased operational complexity and longer transport distances. Regarding the transfer penalties, time penalties had minimal impact on the network performance, while cost penalties significantly increased transport costs and emissions, implying that economic incentives are a stronger barrier than operational delays caused by public transport mode transfer.

For methodology, the approach of MCDA (the BWM) and simulation used in this study provided a structured way of evaluating both qualitative and quantitative aspects of PTF hubs. BWM identifies the most critical hub selection factors from multiple experts' perspectives, ensuring that the criteria are well-balanced and consistent. On the other hand, simulation provides real-world validation of the performance of identified hubs and reveals key trends in the performance of varying hub configurations. Despite the rarity of this combination of methods, the overall methodology ensures that the selected hubs are not only theoretically optimal based on the BWM rankings but also operationally viable based on simulation results under realistic conditions.

It is worth noting that in this study, a "good" network is not defined in an absolute sense through an optimisation model (e.g., minimising cost or maximising efficiency) but is assessed based on its ability to deliver parcels effectively and efficiently under practical constraints. Since this research is exploratory and aims to evaluate the feasibility of using public transport for urban freight, the three scenarios were manually designed to represent plausible and distinct operational strategies: minimal hub use (scenario 1), a hierarchical model (scenario 2), and a decentralised model (scenario 3). The evaluation framework is grounded in the use of multiple KPIs, such as parcel delivery rate (effectiveness), hub setup cost (infrastructure investment), transport cost (operational efficiency), and CO_2 emissions (environmental impact). Rather than benchmark these KPIs against a universal standard, the study compares how each configuration performs across these dimensions. The results reflect real-world trade-offs between cost, coverage, and sustainability (e.g., in Table 5.2). Thus, the performance of each network is not judged in isolation but interpreted in relation to the other scenarios. The framework recognises that what constitutes a "good" network may vary by stakeholder priorities, i.e., a city authority may prioritise emissions, while a logistics provider may focus on delivery coverage.

5.6. Limitations

Despite the above contributions, the study has several limitations. The first is data availability. Although the freight demand data used in the simulation is based on real urban freight flows, sources on the station information are limited, resulting in subjective judgments of some station conditions. Additionally, static demand and only one day of station data were employed, whereas real-world freight flows and public transport schedules fluctuate, though the latter is generally more stable. Thus, a longer duration of both freight and transit service statistics would represent more practical demand and network patterns, resulting in more realistic network performances. More importantly, due to the anonymity of the survey, a follow-up review of inconsistent answers was not possible, resulting in all survey results being excluded from the BWM analysis. The sample size for the BWM interviews was then limited to three experts (who participated in the interview). Nevertheless, though this may seem to have constrained the generalisability of the results, the method's strength lies in the structured elicitation of informed judgments and the selected participants' substantial domain knowledge to evaluate the criteria. Therefore, only using the BWM interview results was still valid.

Another limitation concerns the identification of secondary hubs. The method used, which was betweenness centrality, produced identical scores for all stations, making it impossible to distinguish between them meaningfully. This outcome is due to the design of the transport graph, which was fully connected using Euclidean distances rather than the actual topology of the public transport network. As a result, every station was equally central in the network, and the ranking system for secondary hubs failed to reflect their true centrality. While this did not impact the logic for parcel allocation or hub capacity, it signals the need for more delicate approaches in future work to better capture the functional role of transfer hubs within real-world transport systems.

Related to the second limitation is the use of Euclidean distances to estimate inter-station distances. Although computationally efficient, this approach oversimplifies how stations are connected in practice. Unlike straight-line distances, actual travel paths follow transit lines, which include directional constraints, transfers, and mode changes. Consequently, two stations that are geographically close might require a long or circuitous transit journey to connect. On the other hand, major interchange stations, such as those linking train, metro, and light rail, could appear less central in Euclidean terms but are, in fact, critical connectors in the network. These stations offer greater flexibility, directness, and routing options, thereby increasing their strategic value for freight allocation. In the future, using network-based distances derived from real transit routes would allow future models to better reflect operational realities, such as route directionality, line availability, and hub connectedness.

Fourth, operational details and any real-time system disruptions, such as traffic congestion and operational delays, are not considered in this study. Similarly, policy interventions on the system are also excluded, such as time-restricted freight access or incentive schemes for public transport freight use. Moreover, the study focuses on one metropolitan region; thus, its exact application to other urban contexts should be adapted based on the results of this research. To overcome these, incorporating a routing mechanism would introduce a significant methodological shift. This research determines the most appropriate hubs that freight should travel to but does not explicitly model their step-by-step movement along actual public transit lines. Routing algorithms could take into account the network-based distances and topologies to identify optimal paths, incorporating travel time, transfer penalties, and other real-time traffic constraints. For instance, transfer times at hubs may be adjusted based on live hub utilisation rates, as hubs with higher freight handling volumes could experience longer transfer delays due to congestion and higher processing time. Note that while Euclidean distances could still technically be used with a routing mechanism, they would be insufficient for capturing the full operational logic of route planning. Hence, to meaningfully implement routing, the simulation would need to switch from geometric to network-based distances.

Note that addressing the last limitation above would likely change multiple KPIs. First, parcel delivery rates may improve, particularly in scenarios where current allocations are constrained (e.g., scenario 1), benefitting from more efficient routing via well-connected hubs. Hub setup costs could increase slightly, as more strategic—but potentially more expensive—interchange stations are activated due to their network centrality. Transport costs may increase or decrease depending on the structure of the network. This is since, while routing might reduce detours and unnecessary hops, the reliance on longer yet feasible transit paths may increase travel distance overall. In this case, CO_2 emissions would likely follow a similar trend. If parcels are routed more efficiently but over longer network paths, emissions may rise slightly, depending on vehicle types and modal splits assumed in the model. However, if routing reduces the number of transfers or detours, emissions could also decrease due to improved flow efficiency.

6 Conclusions and Recommendations

6.1. Conclusions

This study explores the feasibility of integrating urban freight deliveries into public transport by employing a multi-criteria decision analysis (MCDA) approach combined with simulation. In this study, a public transport-based freight delivery (PTF) system is proposed, and the results provide insights into hub selection criteria, operational efficiency, and trade-offs within different network configurations. The sub-research questions are answered as follows:

RQ1: What are the criteria for selecting public transport stations to be hubs in a public transport-based freight delivery (PTF) system?

The critical freight hub selection criteria identified through the BWM approach include cargo requirements (freight properties), costs (capital, daily, and long-term), connectivity (service frequency and coverage), capacity (physical ability to handle freight), and accessibility (proximity to major transport networks and freight demand). Among them, accessibility, capacity, and costs emerged as the most significant criteria for both primary and local hubs. Accessibility reflects the importance of integrating freight flows seamlessly within the existing public transport infrastructure, capacity stresses the space and operational capability to manage freight, while costs imply that the financial burden could be a significant barrier to PTF projects.

RQ2: How can the identified criteria be used to rank public transport stations as different levels of freight hubs?

The identified criteria from the BWM are operationalised into a systematic hub classification framework, whereby:

- **Primary hubs** were predominantly ranked based on accessibility, which was the most influential criterion across all weight scenarios (baseline, upper bound, and lower bound), followed by capacity and costs. Cargo requirements and connectivity exhibited lower sensitivity to expert weighting adjustments, consistently ranking as the least influential criteria. There can be seen a strong expert consensus regarding the essential role of accessibility and capacity in selecting primary hubs.
- **Local hubs** were primarily ranked based on capacity, consistently weighted the highest across all scenarios. Accessibility was a close second, particularly sensitive to variations in expert weighting, notably approaching the importance of capacity in the lower-bound scenario. Compared to primary hubs, cargo requirements and connectivity were more influential for local hubs, demonstrating moderate importance and some variability. Costs maintained a moderate but stable criterion, ranking third or fourth in criteria weights.
- **Secondary hubs** were initially selected using betweenness centrality to measure network transfer potential. However, due to limitations in the fully connected transport network (Euclidean distances), all secondary hub candidates received identical centrality scores, highlighting a method-

ological limitation and an opportunity for refinement through alternative centrality measures or MCDA approaches in future research.

RQ3: What are the possible network configurations comprising different levels of hubs?

Three distinct network configurations were explored in this study:

- Scenario 1 (Minimal Network): Only primary hubs are utilised, offering cost efficiency and minimal emissions but severely limiting the parcel-handling capacity and coverage.
- Scenario 2 (Hierarchical Network): Combines primary, secondary, and local hubs to enhance parcel-handling capability and network coverage significantly, though incurring higher operational and environmental costs.
- Scenario 3 (Decentralised Network): Utilises primary and local hubs extensively without mandatory secondary hubs, balancing cost efficiency and improved parcel coverage compared to scenario 1, but requires careful budget allocation and operational planning.

RQ4: How can the performance of the proposed hubs be evaluated under realistic urban scenarios?

The outcome of the proposed hub networks was evaluated through a simulation that incorporates real-life parcel demand data and public transport information from the Rotterdam-The Hague Metropolitan Region (MRDH). The performance metrics used were comprehensive, including parcel delivery rate (effectiveness), hub setup and operational costs (economic viability), transport costs and network utilisation (operational efficiency), and CO_2 emissions (environmental sustainability). Results indicated clear trade-offs between these metrics.

However, limitations of the simulation, such as reliance on Euclidean distances, suggest that realistic performance evaluations could be further improved by incorporating actual transit routes, directional constraints, and routing algorithms. Future research could therefore include more refined, transit-network-based distance calculations to accurately reflect real-world operational conditions.

Based on the answers to the sub-questions, the main research question can be answered:

How can we optimally plan the hubs of a public transport-based freight delivery (PTF) system?

The BWM and simulation findings indicate that the design of PTF hub networks should 1) take multiple stakeholder perspectives into account and 2) strike a balance between network reach, hub handling capability, and practical financial constraints. On the one hand, the BWM results reflect the different opinions on the selection criteria of PTF hubs from different decision-makers. On the other hand, the evaluated scenarios reveal the advantages and disadvantages of varying hub compositions. Scenario 1 incurs minimal costs and emissions; however, it is significantly limited in its capacity to meet demand. In scenario 2, where each delivery must navigate through a hierarchical order of primary, secondary, and local hubs, the result is a much elevated freight-handling rate, but with significantly higher costs and emissions due to increased transfers. A network that facilitates primary and local hub connections without mandatory secondary hubs, such as in scenario 3, achieves a balance between cost efficiency and goods handling capacity, yet requires diligent budget allocation to local hubs and results in a much lower network utilisation than scenario 2. Therefore, secondary and local hubs play a dual role in the network: they improve network utilisation and coverage but also introduce additional costs. Their effectiveness depends on a combination of factors such as budget allocation, demand volume, origin-destination patterns, and time sensitivity of freight demand, as well as the structure of the hub network.

In terms of methodological contributions, the study presents a novel integration of the BWM and simulation so that a structured, comprehensive decision-support framework for policymakers and urban planners is developed. While the BWM ensures that expert-driven criteria guide hub selection, simulation validates the operational feasibility of these hubs under different network conditions. This combined approach enhances the robustness of PTF hub planning and serves as a replicable model for future research on integrated urban logistics.

6.2. Recommendations

6.2.1. Future Research

While this study offers a strategic framework for hub selection, additional research is necessary to refine operational aspects. Routing, scheduling, and fleet management should be planned based on the identified hub network configurations. The identified hubs, including primary, secondary, and local hubs established in this study, may function as infrastructure points in future optimisation models centred on vehicle routing, scheduling, and synchronisation.

Secondly, this study focuses on hub-based freight allocation rather than the routing of the actual paths that freight will travel to pass through their allocated hubs. While this is appropriate for high-level strategic planning, future research could incorporate a routing mechanism, which does not need to be overly complex, to optimise freight flows based on real-time conditions, congestion levels, and multimodal connections. Adding a routing mechanism can even incorporate factors such as congestion and transfer delays. For instance, if a parcel is assigned to hub A, routing can determine the exact path it travels from hub A to hub B. Alternative paths can also be modelled by a routing algorithm, including possible delays due to congestion and even adaptive rerouting in response to real-time conditions.

Even without a routing mechanism, future research could integrate real-time demand fluctuations and investigate network adaptability instead of using static demands. In addition to operational disruptions, such as real-time delays and congestion, the impact of policy interventions, such as freight access restrictions, pricing incentives, and regulatory measures, on network efficiency warrants further investigation. More importantly, the BWM interviews show that stakeholders possess differing views on the integration of public and freight transport. Consequently, assessing the acceptance of these initiatives among a wider range of stakeholders would enhance their practical implementation.

Fourth, due to time and scope limitations, the multi-criteria and simulation approach was applied to one metropolitan region only, the MRDH, which is economically vibrant and has a well-developed transport network ideal for public transit, road vehicles, and active modes. However, this framework should be adapted to account for variations in urban geography, transport infrastructure, local policies, economic prosperity, and social demographics, all of which potentially affect the outcomes. To mitigate this, comparative studies across different urban areas globally may help identify scalable best practices for integrating freight into public transport networks in a general sense. Also, for any similar PTF system, the network efficiency threshold should be investigated so as to avoid redundant additional investments that do not necessarily further improve system performance.

Furthermore, alternative LMD options could be explored in the future, such as crowdshipping and autonomous delivery, which can complement the public transport delivery. An increasing number of researchers are already examining the advantages and feasibility of innovative last-mile solutions, and this study's outcome could be incorporated into those studies.

Last but not least, future research should reconsider the use of centrality-based measures for selecting secondary hubs, especially when the transport network is constructed using Euclidean distances. As this study revealed, all stations in the fully connected graph received identical centrality scores due to the absence of topological variation, which is an inherent limitation when using betweenness centrality in geometrically connected networks where each node is equally reachable from all others. This limitation severely undermines the usefulness of centrality as a differentiator in identifying strategic transfer hubs. As a result, the selection of secondary hubs in this study defaulted to a fallback method based on spatial closeness to destination hubs rather than genuine topological importance. While this allowed for operational feasibility in the simulation, it limits the accuracy and replicability of the hub classification process. To address this, future studies could consider building the transport graph based on actual transit lines or use hybrid approaches that integrate MCDA-derived criteria with network-based indicators. This would ensure a more realistic and context-sensitive identification of secondary hubs, particularly in systems where highly central nodes may not be operationally suitable for freight activities. Testing different weighting schemes or applying adaptive selection logic could further align network design with local planning goals such as sustainability, equity, or multimodal integration.

6.2.2. Implementation

Regarding implementation, city governments and transit agencies can utilise the hub classifications and selection criteria from this study to evaluate the feasibility of implementing logistics delivery at existing transport stations. Transport nodes with high accessibility could be prioritised as freight hubs, given their potential demand resulting from proximity to origin and destination locations. The hub categories identified in this study may be modified to facilitate flexible hub configurations that more effectively respond to region-specific transport and demand conditions.

Conversely, irrespective of the implementation region, it is essential to consider the trade-offs among cost, efficiency, and sustainability. Financial constraints greatly impact hub selection; therefore, it is vital to pursue a balanced investment allocation across different hub types. Minimising transfer penalties is beneficial for reducing operational costs, which can be achieved through efficient scheduling and coordination of pre- and last-mile vehicles with public transport vehicles. A comprehensive cost-benefit analysis during the initial development phase could significantly aid in evaluating the financial feasibility of PTF systems, thereby mitigating the risk of unsuccessful implementations. Also, policymakers can consider providing subsidies or establishing financial incentives for the retrofitting of transport stations to accommodate freight services.

Since this study only conducted a simulation, a pilot project testing selected transport stations as freight hubs would provide real-world validation in the future. A phased approach may be implemented to evaluate various hub configurations prior to full-scale adoption. In the initial phase, freight deliveries at major transit hubs with existing infrastructure may be evaluated. Thereafter, the system could be expanded by strategically incorporating secondary hubs to enhance network utilisation and increase cost-effectiveness. In the final phase, full-scale implementation can proceed following a thorough co-ordination of all operations. This phased approach should involve initially testing minimal freight flows, such as parcels, followed by the gradual inclusion of other types of goods, such as waste, groceries, and bulk items. The pilot project could even consider assessing the viability of highly time-sensitive deliveries (e.g., same-day delivery).

Lastly, the successful implementation of PTF systems necessitates effective collaboration among public and private stakeholders, including public transport operators, freight companies, and city planners. The intrinsic public and private nature of PTF systems suggests that public-private partnerships (PPPs) could be formed to finance and manage the integration of public and freight transport. Through collaborative efforts, such partnerships can best minimise disruptions to passenger services and enhance the efficiency of freight movement overall. What is also necessary is that regulatory frameworks should be updated to facilitate the freight utilisation of public transport infrastructure while addressing potential conflicts with passenger traffic.

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A

The Best-Worst Method (BWM) Survey

Best-Worst Method Survey for Freight Hub Evaluation

This survey aims to gather expert opinions on the relative importance of criteria for evaluating freight hubs. Your inputs will help calculate weights for the criteria using the Best-Worst Method (BWM). The process involves selecting the most important (Best) and least important (Worst) criteria, followed by pairwise comparisons of other criteria relative to the Best and Worst criteria.

In **Parts I and II**, you will be asked to compare the relative importance of the criteria for primary (access) hubs and local (egress) hubs, respectively. In **Part III**, you will compare the relative importance of the sub-criteria for each main criterion. For each question, select the appropriate level of importance for comparisons. Please ensure your answers are consistent to improve accuracy.

* Indicates required question

1. Industry Sector/Organisation *

2. Role within the Industry Sector/Organisation *

Part I: Primary (Access) Hubs - Best Criterion

3. Among the five main criteria, which criterion do you consider the most important (Best) for evaluating access hubs? *

Mark only one oval.

- Cargo Requirements *Skip to question 4*
- Costs
- Connectivity
- Capacity
- Accessibility

I. Pairwise Comparisons Against the Best Criterion

For each criterion below, compare the importance of your chosen Best criterion relative to the criterion. Use the following scale:

1 = Equally Important: The Best Criterion is equally important as the other criterion.

2 = Slightly More Important: The Best Criterion is slightly more important than the other criterion.

3 = Moderately More Important: The Best Criterion is moderately more important than the other criterion.

4 = Moderately to Strongly More Important: The Best Criterion lies between moderate and strong importance compared to the other criterion.

5 = Strongly More Important: The Best Criterion is strongly more important than the other criterion.

6 = Strong to Very Strongly More Important: The Best Criterion lies between strong and very strong levels.

7 = Very Strongly More Important: The Best Criterion is very strongly more important than the other criterion.

8 = Very Strong to Absolutely More Important: The Best Criterion lies between very strong and extreme levels of more importance than the other criterion.

9 = Absolutely More Important: The Best Criterion is overwhelmingly more important than the other criterion.

Example:

Suppose you choose **"Costs"** as the Best Criterion, and you are comparing **"Capacity"** against it:

- If **"Costs"** is moderately more important than **"Capacity"**, it is likely to assign a **3** for "Costs to Capacity".
- If **"Costs"** is extremely more important than **"Capacity"**, it is likely to assign a **9** for "Costs to Capacity".

4. How much more important is the Best criterion compared to Costs? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

5. How much more important is the Best criterion compared to Connectivity? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

6. How much more important is the Best criterion compared to Capacity? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

7. How much more important is the Best criterion compared to Accessibility? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Skip to question 8

Part I: Primary (Access) Hubs - Worst Criterion

8. Among the five main criteria, which criterion do you consider the least important (Worst) for evaluating access hubs? *

Mark only one oval.

- ◯ Cargo Requirements *Skip to question 9*
- ◯ Costs
- ◯ Connectivity
- ◯ Capacity
- ◯ Accessibility

I. Pairwise Comparisons Against the Worst Criterion

9. How much more important is Costs compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

10. How much more important is Connectivity compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

11. How much more important is Capacity compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

12. How much more important is Accessibility compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part II: Local (Egress) Hubs - Best Criterion

13. Among the five main criteria, which criterion do you consider the most important (Best) for evaluating egress hubs? *

Mark only one oval.

- ◯ Cargo Requirements *Skip to question 14*
- ◯ Costs
- ◯ Connectivity
- ◯ Capacity
- ◯ Accessibility

II. Pairwise Comparisons Against the Best Criterion

14. How much more important is the Best criterion compared to Costs? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

15. How much more important is the Best criterion compared to Connectivity? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

16. How much more important is the Best criterion compared to Capacity? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

17. How much more important is the Best criterion compared to Accessibility? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part II: Local (Egress) Hubs - Worst Criterion

18. Among the five main criteria, which criterion do you consider the least important (Worst) for evaluating egress hubs? *

Mark only one oval.

- ◯ Cargo Requirements *Skip to question 19*
- ◯ Costs
- ◯ Connectivity
- ◯ Capacity
- ◯ Accessibility

II. Pairwise Comparisons Against the Worst Criterion

19. How much more important is Costs compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

20. How much more important is Connectivity compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

21. How much more important is Capacity compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

22. How much more important is Accessibility compared to the Worst criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

End of Parts I & II: Main Criteria Weight Determination

After deciding the weight for the main criteria for all types of hubs, you will determine the weights of the sub-criteria for each main criterion. The weights of sub-criteria will remain consistent for all hub types.

Part III: Best Sub-Criterion Selection: Cargo Requirements

23. Among the sub-criteria of "**Cargo Requirements**", which sub-criterion do you consider the most important for evaluating "**Cargo Requirements**"? *

Mark only one oval.

- Vulnerability
- Demand Volatility
- Security

24. How much more important is your chosen Best Sub-Criterion compared to Vulnerability? *

(Assign 1 if they are the same sub-criterion)

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

25. How much more important is your chosen Best Sub-Criterion compared to Demand Volatility? *

(Assign 1 if they are the same sub-criterion)

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

26. How much more important is your chosen Best Sub-Criterion compared to Security? *

(Assign 1 if they are the same sub-criterion)

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Worst Sub-Criterion Selection: Cargo Requirements

27. Among the sub-criteria of "**Cargo Requirements**", which sub-criterion do you consider the least important for evaluating "**Cargo Requirements**"? *

Mark only one oval.

- Vulnerability
- Demand Volatility
- Security

28. How much more important is Vulnerability compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

29. How much more important is Demand Volatility compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

30. How much more important is Security compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Best Sub-Criterion Selection: Costs

31. Among the sub-criteria of "**Costs**", which sub-criterion do you consider the most important for evaluating "**Costs**"? *

Mark only one oval.

- Investment Costs
- Operational Costs
- Maintenance & Upgrade Costs

32. How much more important is your chosen Best Sub-Criterion compared to Investment Costs? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

33. How much more important is your chosen Best Sub-Criterion compared to Operational Costs? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

34. How much more important is your chosen Best Sub-Criterion compared to Maintenance & Upgrade Costs? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Worst Sub-Criterion Selection: Costs

35. Among the sub-criteria of "**Costs**", which sub-criterion do you consider the least important for evaluating "**Costs**"? *

Mark only one oval.

- Investment Costs
- Operational Costs
- Maintenance & Upgrade Costs

36. How much more important is Investment Costs compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

37. How much more important is Operational Costs compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

38. How much more important is Maintenance & Upgrade Costs compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Best Sub-Criterion Selection: Connectivity

39. Among the sub-criteria of "**Connectivity**", which sub-criterion do you consider the most important for evaluating "**Connectivity**"? *

Mark only one oval.

- ◯ Service Frequency
- ◯ Service Coverage
- ◯ Proximity to Other Transit Modes

40. How much more important is your chosen Best Sub-Criterion compared to Service Frequency? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

41. How much more important is your chosen Best Sub-Criterion compared to Service Coverage? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

42. How much more important is your chosen Best Sub-Criterion compared to Proximity to Other Transit Modes? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Worst Sub-Criterion Selection: Connectivity

43. Among the sub-criteria of "**Connectivity**", which sub-criterion do you consider the least important for evaluating "**Connectivity**"? *

Mark only one oval.

- Service Frequency
- Service Coverage
- Proximity to Other Transit Modes

44. How much more important is Service Frequency compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

45. How much more important is Service Coverage compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

46. How much more important is Proximity to Other Transit Modes compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Best Sub-Criterion Selection: Capacity

47. Among the sub-criteria of "**Capacity**", which sub-criterion do you consider the most important for evaluating "**Capacity**"? *

Mark only one oval.

- Physical Space
- Equipment & Labour
- Expansion Potential

48. How much more important is your chosen Best Sub-Criterion compared to Physical Space? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

49. How much more important is your chosen Best Sub-Criterion compared to Equipment & Labour? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

50. How much more important is your chosen Best Sub-Criterion compared to Expansion Potential? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Worst Sub-Criterion Selection: Capacity

51. Among the sub-criteria of "**Capacity**", which sub-criterion do you consider the least important for evaluating "**Capacity**"? *

Mark only one oval.

- Physical Space
- Equipment and Labour
- Expansion Potential

52. How much more important is Physical Space compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

53. How much more important is Equipment & Labour compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

54. How much more important is Expansion Potential compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Best Sub-Criterion Selection: Accessibility

55. Among the sub-criteria of "**Accessibility**", which sub-criterion do you consider the most important for evaluating "**Accessibility**"? *

Mark only one oval.

- ( ) Proximity to Demand Locations
- ( ) Proximity to Supply Locations
- ( ) Access to Road Network
- ( ) Access to Active Modes
- ( ) Digital Accessibility

56. How much more important is your chosen Best Sub-Criterion compared to Proximity to Demand Locations? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

57. How much more important is your chosen Best Sub-Criterion compared to Proximity to Supply Locations? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

58. How much more important is your chosen Best Sub-Criterion compared to Access to Road Network? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

59. How much more important is your chosen Best Sub-Criterion compared to Access to Active Modes? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

60. How much more important is your chosen Best Sub-Criterion compared to Digital Accessibility? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

Part III: Worst Sub-Criterion Selection: Accessibility

61. Among the sub-criteria of "**Accessibility**", which sub-criterion do you consider the least important for evaluating "**Accessibility**"? *

Mark only one oval.

- Proximity to Demand Locations
- Proximity to Supply Locations
- Access to Road Network
- Access to Active Modes
- Digital Accessibility

62. How much more important is Proximity to Demand Locations compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

63. How much more important is Proximity to Supply Locations compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

64. How much more important is Access to Road Network compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

65. How much more important is Access to Active Modes compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

66. How much more important is Digital Accessibility compared to your chosen Worst Sub-Criterion? *

1	2	3	4	5	6	7	8	9
☆	☆	☆	☆	☆	☆	☆	☆	☆

End of Survey

Thank you for your valuable input! Your responses will be analysed for consistency, and the results will be used to calculate weights for the criteria.

B

Simulation Code

B.1. Data Preprocessing

```python
# Import necessary libraries
import pandas as pd
import geopandas as gpd
import networkx as nx
import numpy as np
from haversine import haversine, Unit
from scipy.spatial import KDTree
import matplotlib.pyplot as plt
from shapely.geometry import Point
```

Listing B.1: Importing Required Libraries

```python
# Load station and parcel datasets
stations = pd.read_csv('MRDH Stations.csv')
access_hubs = pd.read_csv('Stations_Classifications_Access.csv')
egress_hubs = pd.read_csv('Stations_Classifications_Egress.csv')
parcels = pd.read_csv('ParcelDemand_REF.csv')

# Ensure latitude and longitude are numeric
stations['lat'] = stations['lat'].astype(float)
stations['lon'] = stations['lon'].astype(float)

# Read shapefile of the zones in the study area
zones = gpd.read_file('Zones_v6.shp')

# Set CRS and convert to EPSG 4326
zones.set_crs(epsg=28992, inplace=True)
zones = zones.to_crs(epsg=4326)

# Compute centroids of each zone
zones["centroid"] = zones.geometry.to_crs(epsg=3857).centroid  # Ensure projection before
    computing centroid
zones["lat"] = zones["centroid"].y
zones["lon"] = zones["centroid"].x

# Match the OD-pair of each parcel with the latitudes and longitudes of corresponding zones
# Merge to assign latitudes and longitudes for origin zones
parcels = parcels.merge(zones[['AREANR', 'lat', 'lon']], left_on='O_zone', right_on='AREANR',
     how='left') # AREANR = Area Number
parcels.rename(columns={'lat': 'O_lat', 'lon': 'O_lon'}, inplace=True)
parcels.drop(columns=['AREANR'], inplace=True)

# Merge to assign latitudes and longitudes for destination zones
parcels = parcels.merge(zones[['AREANR', 'lat', 'lon']], left_on='D_zone', right_on='AREANR',
     how='left')
parcels.rename(columns={'lat': 'D_lat', 'lon': 'D_lon'}, inplace=True)
parcels.drop(columns=['AREANR'], inplace=True)
```

```python

# Rename columns
access_hubs.rename(columns={'Station': 'name'}, inplace=True)
egress_hubs.rename(columns={'Station': 'name'}, inplace=True)

# Merge access and egress hub rankings to the station data
stations = stations.merge(access_hubs[['name', 'Access_Rank']], on='name', how='left')
stations = stations.merge(egress_hubs[['name', 'Egress_Rank']], on='name', how='left')

# Build a spatial index for nearest station lookup
station_coords = stations[['lat', 'lon']].values
station_tree = KDTree(station_coords)
station_id_map = {i: station_id for i, station_id in enumerate(stations['id'].values)}

# Baseline transport mode parameters (speed in km/h, cost per km in €, emissions in kg CO2/km)
mode_params = {
    'train': {'speed': 120, 'cost_per_km': 0.30, 'emission': 0.02},
    'subway': {'speed': 80, 'cost_per_km': 0.171, 'emission': 0.03},
    'light_rail': {'speed': 30, 'cost_per_km': 0.193, 'emission': 0.05}
}

# Baseline transfer penalties (extra time in hours, cost in €)
transfer_penalty_time = {('train', 'subway'): 5/60, ('train', 'light_rail'): 7/60, ('subway', 'light_rail'): 4/60}
transfer_penalty_cost = {('train', 'subway'): 1, ('train', 'light_rail'): 1.5, ('subway', 'light_rail'): 0.5}
```

Listing B.2: Loading and Processing Data

B.2. Transport Graph Construction

```python
def build_graph(stations, weight_type='time'):
    """
    Constructs a graph based on transport stations and their connections.

    Parameters:
    - stations: DataFrame containing station details.
    - weight_type: Determines edge weights ('time', 'cost').

    Returns:
    - NetworkX graph representation of the transport network.
    """
    G = nx.Graph()

    for i, station_a in stations.iterrows():
        for j, station_b in stations.iterrows():
            if i != j:
                # Compute real-world distance using Haversine formula
                distance = haversine(
                    (station_a['lat'], station_a['lon']),
                    (station_b['lat'], station_b['lon'])
                )

                # Retrieve transport mode for each station
                mode_a = station_a['mode']
                mode_b = station_b['mode']

                # Extract speed, cost per km, and emission factor based on mode
                speed = mode_params[mode_a]['speed']
                cost_per_km = mode_params[mode_a]['cost_per_km']

                # Apply transfer penalties if switching modes
                transfer_time = transfer_penalty_time.get((mode_a, mode_b), 0)
                transfer_cost = transfer_penalty_cost.get((mode_a, mode_b), 0)

                # Compute weight based on selected criteria
                if weight_type == 'time':
                    weight = (distance / speed) + transfer_time
                elif weight_type == 'cost':
```

```
                weight = (distance * cost_per_km) + transfer_cost
            else:
                raise ValueError("Invalid weight type.")

            # Add edge to the graph with computed weight
            G.add_edge(station_a['id'], station_b['id'], weight=weight)

    return G
```

Listing B.3: Transport Graph Construction

B.3. Hub Selection

```
def calculate_betweenness_centrality(G):
    """
    Computes betweenness centrality for all nodes in the transport network graph G.
    Returns a pandas Series with node IDs as index and centrality values as values.
    """
    centrality = nx.betweenness_centrality(G)  # Compute betweenness centrality
    return pd.Series(centrality).sort_values(ascending=False)
```

Listing B.4: Centrality Calculation

```
# Set total hub setup budget
HUB_SETUP_BUDGET = 10000000  # Baseline budget: €10 million

def select_hubs_within_budget(stations, budget, strategy, G):
    """
    Selects hubs within the allocated budget based on the given strategy while ensuring no
    hub type overlaps.

    Parameters:
    - stations: DataFrame containing station information.
    - budget: Total budget available for hub setup.
    - strategy: Freight transport strategy (minimal, hierarchical, or decentralised).
    - G: NetworkX graph representing the transport network.

    Returns:
    - selected_hubs: List of hubs selected within the budget.
    """

    selected_hubs = []  # Store selected hubs
    current_cost = 0  # Track total hub setup cost

    # Define hub setup costs per type
    hub_setup_costs = {
        "Primary Hub": 200000,  # Baseline € per primary hub
        "Local Hub": 50000,     # Baseline € per local hub
        "Secondary Hub": 100000 # Baseline € per secondary hub
    }

    # Determine max number of hubs within budget
    max_primary_hubs = budget // hub_setup_costs["Primary Hub"]
    max_local_hubs = 149  # Local hubs limited to total stations
    max_secondary_hubs = budget // hub_setup_costs["Secondary Hub"]

    # STEP 1: Select Primary Hubs FIRST
    primary_hubs = set(stations.nsmallest(max_primary_hubs, 'Access_Rank')['id'].values)

    # STEP 2: Select Secondary Hubs (Only for Scenario 2)
    if strategy == 'hierarchical':
        centrality_scores = calculate_betweenness_centrality(G)
        secondary_hubs = set(centrality_scores.nlargest(max_secondary_hubs).index)
        secondary_hubs -= primary_hubs  # Prevent primary-secondary overlap
    else:
        secondary_hubs = set()  # No secondary hubs for Scenario 1 & 3

    # STEP 3: Select Local Hubs (Avoiding Primary & Secondary)
    if strategy == 'decentralised':  # Scenario 3 (Decentralised)
```

```python
        num_local_hubs = min(int(0.6 * (budget // hub_setup_costs["Local Hub"])), max_local_hubs) # Baseline allocation rate: 60%
        num_primary_hubs = min((budget - num_local_hubs * hub_setup_costs["Local Hub"]) // hub_setup_costs["Primary Hub"], max_primary_hubs)

        primary_hubs = set(stations.nsmallest(num_primary_hubs, 'Access_Rank')['id'].values)
        local_hubs = set(stations.nsmallest(num_local_hubs, 'Egress_Rank')['id'].values)

    else:
        local_hubs = set(stations.nsmallest(max_local_hubs, 'Egress_Rank')['id'].values)

    # Ensureno hub appears in multiple categories
    local_hubs -= (primary_hubs | secondary_hubs)

    # STEP 4: Combine candidate hubs
    candidate_hubs = list(primary_hubs) + list(secondary_hubs) + list(local_hubs)

    # STEP 5: Select hubs while staying within budget
    for hub in candidate_hubs:
        hub_type = (
            "Primary Hub" if hub in primary_hubs else
            "Secondary Hub" if hub in secondary_hubs else
            "Local Hub"
        )
        hub_cost = hub_setup_costs[hub_type]  # Get hub cost

        if current_cost + hub_cost <= budget:
            selected_hubs.append(hub)
            current_cost += hub_cost

    return selected_hubs
```

Listing B.5: Budget-Constrained Hub Selection

B.4. Freight Allocation

```python
def allocate_freight(G, parcels, stations, selected_hubs, strategy):
    """
    Allocates freight flows between hubs based on scenario.
    Implements capacity constraints for Primary, Secondary, and Local hubs.

    Parameters:
    - G: NetworkX graph representing the transport network.
    - parcels: DataFrame containing parcel origin-destination information.
    - stations: DataFrame of station information (potential hubs).
    - selected_hubs: Set of hubs chosen within the budget for a given strategy.
    - strategy: The freight transport strategy (minimal, hierarchical, or decentralised).

    Returns:
    - allocated_flows: List of tuples (Parcel_ID, route_nodes) representing freight routes.
    """

    allocated_flows = []  # Store allocated parcel routes
    station_lookup = {row['id']: (row['lat'], row['lon']) for _, row in stations.iterrows()}  # Map station ID to coordinates

    # Identify hub types from the selected hubs based on ranking
    primary_hubs = {hub for hub in selected_hubs if hub in stations.nsmallest(50, 'Access_Rank')['id'].values}
    local_hubs = {hub for hub in selected_hubs if hub in stations.nsmallest(149, 'Egress_Rank')['id'].values}
    secondary_hubs = {hub for hub in selected_hubs if hub not in primary_hubs and hub not in local_hubs}

    # Assign capacity limits to hubs:
    hub_capacity = {
        hub: 10000 if hub in primary_hubs else
             5000 if hub in secondary_hubs else
             2500
        for hub in selected_hubs
```

```python
    } # Baseline capacity values

    # Remove parcels with missing origin or destination coordinates
    parcels = parcels.dropna(subset=['O_lat', 'O_lon', 'D_lat', 'D_lon'])

    # Iterate through each parcel to allocate a freight route
    for _, parcel in parcels.iterrows():
        origin_coord = (parcel['O_lat'], parcel['O_lon'])  # Origin coordinates
        destination_coord = (parcel['D_lat'], parcel['D_lon'])  # Destination coordinates

        # Find the closest station (hub) to the origin and destination using KDTree
        _, origin_idx = station_tree.query(origin_coord)
        _, destination_idx = station_tree.query(destination_coord)
        origin_station = station_id_map.get(origin_idx)  # Get nearest hub to the origin
        destination_station = station_id_map.get(destination_idx)  # Get nearest hub to the destination

        # Scenario 1: Minimal (Primary hubs only)
        if strategy == 'minimal':
            # Ensure both origin and destination are primary hubs
            if origin_station not in primary_hubs or destination_station not in primary_hubs:
                continue  # Skip parcels that cannot be routed
            route_nodes = [origin_station, destination_station]  # Direct connection

        # Scenario 2: Hierarchical (Primary → Secondary → Local)
        elif strategy == 'hierarchical':
            # Ensure that all required hub types exist
            if not primary_hubs or not secondary_hubs or not local_hubs:
                continue  # Skip if not enough hubs

            # Select closest primary hub for origin
            origin_station = min(primary_hubs, key=lambda h: haversine(station_lookup[h], origin_coord))

            # Select closest local hub for destination
            destination_station = min(local_hubs, key=lambda h: haversine(station_lookup[h], destination_coord))

            # Select a valid secondary hub that connects to a local hub
            possible_secondary_hubs = [h for h in secondary_hubs if G.has_edge(h, destination_station)]
            if not possible_secondary_hubs:  # If no valid secondary hub exists, skip allocation
                continue
            transfer_hub = min(possible_secondary_hubs, key=lambda h: haversine(station_lookup[h], destination_coord))

            # Ensure the transfer hub is not creating a loop (e.g., revisiting origin or destination)
            if transfer_hub == origin_station or transfer_hub == destination_station:
                continue  # Skip invalid allocations

            route_nodes = [origin_station, transfer_hub, destination_station]  # Three-hub path

        # Scenario 3: Decentralised (Primary & Local)
        elif strategy == 'decentralised':

            # Ensure the origin is always a Primary hub
            if origin_station not in primary_hubs:
                continue  # Skip parcels that do not start at a Primary hub

            # Case 1: Primary → Primary (Direct)
            if destination_station in primary_hubs:
                route_nodes = [origin_station, destination_station]

            # Case 2: Primary → Local (Direct)
            elif destination_station in local_hubs:
                route_nodes = [origin_station, destination_station]

            # Case 3: Primary → Transfer Hub (Primary or Local) → Local
```

```
            elif destination_station in local_hubs:
                possible_transfer_hubs = [
                    h for h in (primary_hubs | local_hubs)  # Allow both primary & local as transfer hubs
                    if any(G.has_edge(h, destination_station)) and h != origin_station
                ]
                if not possible_transfer_hubs:
                    continue  # No valid transfer hub, skip parcel
                transfer_hub = min(possible_transfer_hubs, key=lambda h: haversine(station_lookup[h], destination_coord))

                # Ensure transfer hub is not revisiting the origin
                if transfer_hub != origin_station:
                    route_nodes = [origin_station, transfer_hub, destination_station]

            else:
                continue  # Skip parcels that do not fit the valid cases in this scenario

        # Enforce capacity constraints before confirming the route
        full_hub = next((hub for hub in route_nodes if hub in hub_capacity and hub_capacity[hub] <= 0), None)
        if full_hub:
            # Attempt to reassign to an alternative local hub with remaining capacity
            alternative_hubs = [h for h in local_hubs if h in hub_capacity and hub_capacity[h] > 0]
            if alternative_hubs:
                destination_station = min(alternative_hubs, key=lambda h: haversine(station_lookup[h], destination_coord))
                route_nodes = [origin_station, destination_station]
            else:
                continue  # If no alternative hub is available, skip the parcel

        # Store the allocated route for the parcel
        allocated_flows.append((parcel['Parcel_ID'], route_nodes))

        # Reduce hub capacities for each hub used in the route
        for hub in route_nodes:
            if hub in hub_capacity:
                hub_capacity[hub] -= 1  # Reduce capacity after usage

    return allocated_flows
```

Listing B.6: Freight Allocation

```
def classify_hubs(stations, used_hubs, G, strategy):
    """
    Classifies the hubs that were actually used in freight allocation stage into Primary,
    Secondary, or Local categories.

    Parameters:
    - stations: DataFrame containing station details.
    - used_hubs: Set of hubs that were actually used in the freight allocation.
    - G: NetworkX graph representing the transport network.
    - strategy: Scenarios (minimal, hierarchical, or integrated).

    Returns:
    - hub_classification: Dictionary categorizing hubs into "Primary", "Secondary", and "
    Local".
    """

    # Initialise classification dictionary with empty lists
    hub_classification = {"Primary": [], "Secondary": [], "Local": []}

    # Identify Primary hubs based on the lowest 50 "Access Rank" values among used hubs
    primary_hubs = {hub for hub in used_hubs if hub in stations.nsmallest(50, 'Access_Rank')['id'].values}

    # Identify Local hubs based on the lowest 149 "Egress Rank" values among used hubs
    local_hubs = {hub for hub in used_hubs if hub in stations.nsmallest(149, 'Egress_Rank')['id'].values}

```

```
    if strategy == "hierarchical":
        """
        Hierarchical Scenario:
        - Secondary hubs are used in this scenario, selected based on high betweenness
    centrality values.
        """
        centrality_scores = calculate_betweenness_centrality(G)  # Compute betweenness
    centrality
        secondary_hubs = {hub for hub in used_hubs if hub in centrality_scores.nlargest(100).
    index}  # Top 100 central hubs

        # Ensure no hub is assigned as both Primary and Secondary or Local and Secondary
        secondary_hubs -= (primary_hubs | local_hubs)  # Remove any overlap

    else:
        """
        Decentralised & Minimal Scenarios:
        - These scenarios do not preselect or use secondary hubs, thus the secondary hubs
    list remains empty.
        """
        secondary_hubs = set()

    # Classify hubs into respective categories
    for hub in used_hubs:
        if hub in primary_hubs:
            hub_classification["Primary"].append(hub)  # Assign to Primary category
        elif hub in local_hubs:
            hub_classification["Local"].append(hub)  # Assign to Local category
        elif hub in secondary_hubs:
            hub_classification["Secondary"].append(hub)  # Assign to Secondary category

    return hub_classification
```

Listing B.7: Used Hub Classification

```
def verify_budget_constraint(selected_hubs, stations, G, strategy):
    """
    Verifies whether the used hubs comply with the predefined budget constraint.

    Parameters:
    - used_hubs: Set of hubs used.
    - stations: DataFrame containing station details.
    - G: NetworkX graph representing the transport network.
    - strategy: The freight transport strategy (minimal, hierarchical, or integrated).

    Returns:
    - Prints the total hub setup cost and whether the budget constraint is satisfied.
    """

    # Classify the selected hubs into Primary, Secondary, and Local categories
    classified_hubs = classify_hubs(stations, selected_hubs, G, strategy)

    # Define the cost of setting up each type of hub
    hub_setup_costs = {
        "Primary": 200000,   # Cost per primary hub (Originally: €200,000)
        "Local": 50000,      # Cost per local hub (Originally: €50,000)
        "Secondary": 100000  # Cost per secondary hub (Originally: €100,000)
    }

    # Compute the total setup cost based on the number of hubs in each category
    total_cost = sum(len(classified_hubs[category]) * hub_setup_costs[category]
                     for category in ["Primary", "Secondary", "Local"])
    remaining_cost = HUB_SETUP_BUDGET - total_cost  # Calculate remaining budget

    # Display the computed total hub setup cost
    print(f"Total hub setup cost: €{total_cost:,}")
    print(f"Remaining budget: €{remaining_cost:,}")

    # Check if the total cost exceeds the predefined budget limit
    if total_cost > HUB_SETUP_BUDGET:
        print("Warning: Budget exceeded!")  # Alert the user if budget is exceeded
```

```
    else:
        print("Budget constraint satisfied.")  # Confirm that the budget is within limits
```

Listing B.8: Budget Verification

B.5. Simulation Execution

```
# Define different scenarios
scenarios = {
    'S1': 'minimal',        # Only Primary Hubs
    'S2': 'hierarchical',   # Primary → Secondary → Local
    'S3': 'decentralised'   # Primary & Local
}

scenario_results = {} # Store results for each scenario
hub_counts = {}  # Store hub type counts for each scenario

# Run simulation for each scenario
for scenario, strategy in scenarios.items():
    print(f"\nRunning simulation for scenario: {scenario} ({strategy})")

    # Step 1: Construct the transport graph first to allow network-based hub selection
    G = build_graph(stations, weight_type='time') # Default weight type: time

    # Step 2: Select candidate hubs within budget
    selected_hubs = select_hubs_within_budget(stations, HUB_SETUP_BUDGET, strategy, G)

    # Step 3: Classify the selected hubs into Primary, Secondary, and Local
    classified_hubs = classify_hubs(stations, selected_hubs, G, strategy)

    # Step 4: Allocate freight based on selected hubs
    allocated_freight = allocate_freight(G, parcels, stations, selected_hubs, strategy)

    # Step 5: Identify which hubs were actually used in freight allocation
    used_hubs = set(hub for _, route in allocated_freight for hub in route)

    # Ensure scenario_results entry exists before assignment
    if scenario not in scenario_results:
        scenario_results[scenario] = {}  # Initialise the dictionary first
    scenario_results[scenario]['hubs'] = used_hubs  # Ensure only used hubs are stored

    # Step 6: Verify budget constraint using only the hubs that were actually used
    verify_budget_constraint(used_hubs, stations, G, strategy)

    # Step 7: Store hub classification for analysis based on used hubs
    classified_hubs = classify_hubs(stations, used_hubs, G, strategy)
    hub_counts[scenario] = {
        "Primary": len(classified_hubs["Primary"]),
        "Secondary": len(classified_hubs["Secondary"]),
        "Local": len(classified_hubs["Local"])
    }

    # Step 8: Store results
    scenario_results[scenario] = {
        'hubs': used_hubs,  # Store only used hubs
        'allocated_freight': allocated_freight,  # Store allocated freight
        'primary_hubs': classified_hubs.get("Primary", set()),
        'secondary_hubs': classified_hubs.get("Secondary", set()),
        'local_hubs': classified_hubs.get("Local", set()),
        'selected_hubs': selected_hubs  # Store all selected hubs for reference
    }

# Ensure that only actually used hubs are stored in scenario results
for scenario, results in scenario_results.items():
    used_hubs = set(hub for _, route in results['allocated_freight'] for hub in route)
    results['hubs'] = used_hubs
```

Listing B.9: Simulation Execution

B.6. KPI Evaluations

```python
# Count the total number of parcels in the demand data
total_parcels = len(parcels)

# Evaluate parcel delivery rate (%) and hubs used for each scenario
for scenario, results in scenario_results.items():
    allocated_parcels = 0
    used_stations = set()

    # Retrieve only hubs that were actually used
    used_hubs = results['hubs']

    # Get the strategy for the scenario
    strategy = scenarios[scenario]

    # Classify hubs based on the actual used hubs
    classified_hubs = classify_hubs(stations, used_hubs, G, strategy)
    all_hubs = set(classified_hubs["Primary"] + classified_hubs["Secondary"] + classified_hubs["Local"])

    # Iterate through parcel routes
    for _, route in results['allocated_freight']:
        # Only count deliveries that passed through classified hubs
        if all(hub in all_hubs for hub in route):
            allocated_parcels += 1
            used_stations.update(route)

    # Calculate the proportion of parcels delivered
    proportion_delivered = (allocated_parcels / total_parcels) * 100

    print(f"Scenario {scenario}: {allocated_parcels} parcels delivered ({proportion_delivered:.2f}%)")
    print(f"Scenario {scenario}: {len(used_stations)} classified hubs used")

# Evaluate KPIs
def evaluate_kpis(allocated_flows, distances, mode):
    total_cost = 0
    total_emissions = 0

    for _, route in allocated_flows:  # Extract Parcel_ID and its route
        for i in range(len(route) - 1):  # Iterate through route pairs
            edge = (route[i], route[i + 1])  # Get edge (station-to-station)
            edge_distance = distances.get(edge, 0)  # Get distance, default to 0 if not found

            total_cost += edge_distance * mode_params[mode]['cost_per_km'] # Calculate transport cost
            total_emissions += edge_distance * mode_params[mode]['emission'] # Calculate emissions

    return {'Total Cost €()': total_cost, 'Total Emissions (kg CO2)': total_emissions}

# Retrieve distance attributes from the graph
distances = nx.get_edge_attributes(G, 'weight')

# Run KPI evaluation for each scenario
for scenario, results in scenario_results.items():
    print(f"Scenario {scenario} KPIs:")

    # Calculate KPIs per mode
    kpis_train = evaluate_kpis(results['allocated_freight'], distances, 'train')
    kpis_subway = evaluate_kpis(results['allocated_freight'], distances, 'subway')
    kpis_lr = evaluate_kpis(results['allocated_freight'], distances, 'light_rail')

    # Sum total KPIs
    kpis_total = kpis_train['Total Cost €()'] + kpis_subway['Total Cost €()'] + kpis_lr['Total Cost €()']
    emissions_total = kpis_train['Total Emissions (kg CO2)'] + kpis_subway['Total Emissions (kg CO2)'] + kpis_lr['Total Emissions (kg CO2)']
```

Listing B.10: KPI Evaluations

B.7. Verification

```python
# Verify if the shortest hub-based path is followed
def verify_hub_based_paths(G, scenario_results, hub_structure):
    """
    Verifies whether allocated freight routes in each scenario follow the expected shortest paths between hubs, and ensures they comply with the predefined hub structure.

    Parameters:
    - G: NetworkX graph representing the transport network.
    - scenario_results: Dictionary containing freight allocation results for each scenario.
    - hub_structure: Dictionary mapping each scenario to the set of hubs allowed for routing.

    For each scenario, the function checks:
    1. Whether each route consists only of allowed hubs;
    2. Whether the actual route taken is equivalent in cost (distance/time) to the computed shortest path based on the graph.
    """
    for scenario, data in scenario_results.items():
        errors = 0  # Track number of violations or anomalies

        for _, route in data['allocated_freight']:
            if len(route) < 2:
                continue  # Skip invalid or incomplete routes

            source, target = route[0], route[-1]  # Identify origin and destination hubs

            try:
                # Compute the expected shortest path between origin and destination
                expected_path = nx.shortest_path(G, source=source, target=target, weight='weight')

                # If all hubs in the route are within the allowed hub set, assume valid and continue
                if set(route).issubset(hub_structure[scenario]):
                    continue

                # Compute total distance of the actual route
                actual_distance = sum(
                    G[u][v]['weight'] for u, v in zip(route[:-1], route[1:])
                    if G.has_edge(u, v)
                )

                # Compute total distance of the expected shortest path
                expected_distance = sum(
                    G[u][v]['weight'] for u, v in zip(expected_path[:-1], expected_path[1:])
                )

                # Check if the actual distance deviates significantly from the expected one
                if not np.isclose(expected_distance, actual_distance, atol=1e-5):
                    errors += 1  # Flag as error if distances do not match

            except nx.NetworkXNoPath:
                errors += 1  # Increment error count if no valid path exists

        print(f"Scenario {scenario}: {errors} errors in hub-based path validation")

# Run verification using selected hubs per scenario
verify_hub_based_paths(
    G,
    scenario_results,
    {
        "S1": scenario_results["S1"]["primary_hubs"],      # Scenario 1: Only Primary hubs
        "S2": scenario_results["S2"]["selected_hubs"],     # Scenario 2: Primary + Secondary
        "S3": scenario_results["S3"]["selected_hubs"]      # Scenario 3: Primary + Local
    }
)
```

Listing B.11: Path Verification

C
Sensitivity Analysis

Table C.1: Sensitivity Analysis Results: Hub Capacity

Capacity (parcels/day)							
Experiment	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
Primary	5,000	7,000	9,000	**10,000**	11,000	13,000	15,000
Transfer	2,500	3,500	4,500	**5,000**	5,500	6,500	7,500
Local	1,250	1,750	2,250	**2,500**	2,750	3,250	3,750

Scenario 1							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	2,516	2,516	2,516	**2,516**	2,516	2,516	2,516
% of Parcels	1.04	1.04	1.04	**1.04**	1.04	1.04	1.04
Hubs Used (P, S, L)	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)	**(13, 0, 0)**	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)
Hub Cost (€)	2,600,000	2,600,000	2,600,000	**2,600,000**	2,600,000	2,600,000	2,600,000
Transport Cost (€)	33.72	33.72	33.72	**33.72**	33.72	33.72	33.72
CO_2 Emission (kg)	5.08	5.08	5.08	**5.08**	5.08	5.08	5.08

Scenario 2							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	89,303	113,108	143,425	**158,505**	171,875	204,406	231,013
% of Parcels	36.77	46.57	59.06	**65.26**	70.77	84.16	95.12
Hubs Used (P, S, L)	(13, 3, 32)	(13, 9, 32)	(13, 19, 32)	**(13, 21, 32)**	(13, 27, 32)	(13, 33, 32)	(13, 36, 32)
Hub Cost (€)	4,500,000	5,100,000	6,100,000	**6,300,000**	6,900,000	7,500,000	7,800,000
Transport Cost (€)	6,188.28	7,289.50	7,791.76	**7,521.88**	7,773.45	8,148.79	9,172.60
CO_2 Emission (kg)	931.97	1097.82	1173.46	**1131.81**	1□170.70	1,227.23	1,381.42

Scenario 3							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	10,811	10,811	10,811	**10,811**	10,811	10,811	10,811
% of Parcels	4.45	4.45	4.45	**4.45**	4.45	4.45	4.45
Hubs Used (P, S, L)	(13, 0, 31)	(13, 0, 31)	(13, 0, 31)	**(13, 0, 31)**	(13, 0, 31)	(13, 0, 31)	(13, 0, 31)
Hub Cost (€)	4,150,000	4,150,000	4,150,000	**4,150,000**	4,150,000	4,150,000	4,150,000
Transport Cost (€)	96.32	95.39	89.94	**92.65**	92.65	92.65	92.65
CO_2 Emission (kg)	14.51	14.37	13.55	**13.95**	13.95	13.95	13.95

Table C.2: Sensitivity Analysis Results: Hub Setup Cost

Hub Setup Cost (€)							
Experiment	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
Primary	100,000	140,000	180,000	**200,000**	220,000	260,000	300,000
Transfer	50,000	70,000	90,000	**100,000**	110,000	130,000	150,000
Local	25,000	35,000	45,000	**50,000**	55,000	65,000	75,000

Scenario 1							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	2,516	2,516	2,516	**2,516**	2,516	2,516	2,516
% of Parcels	1.04	1.04	1.04	**1.04**	1.04	1.04	1.04
Hubs Used (P, S, L)	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)	**(13, 0, 0)**	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)
Hub Cost (€)	2,600,000	2,600,000	2,600,000	**2,600,000**	2,600,000	2,600,000	2,600,000
Transport Cost (€)	33.72	33.72	33.72	**33.72**	33.72	33.72	33.72
CO_2 Emission (kg)	5.08	5.08	5.08	**5.08**	5.08	5.08	5.08

Scenario 2							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	177,430	175,404	162,697	**158,505**	146,899	144,037	131,060
% of Parcels	73.06	72.22	66.29	**65.26**	60.49	59.31	53.96
Hubs Used (P, S, L)	(13, 40, 48)	(13, 35, 47)	(13, 21, 36)	**(13, 21, 32)**	(13, 17, 28)	(13, 26, 12)	(13, 22, 20)
Hub Cost (€)	9,000,000	8,450,000	6,500,000	**6,300,000**	5,700,000	5,100,000	4,500,000
Transport Cost (€)	7,012.36	7,184.21	7,094.37	**7,521.88**	7,378.16	9,112.53	8,335.09
CO_2 Emission (kg)	1,056.08	1,081.96	1,068.43	**1,132.81**	1,111.17	1,372.37	1,285.30

Scenario 3							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	13,553	13,553	11,803	**10,811**	8,019	6,851	6,180
% of Parcels	5.58	5.58	4.86	**4.45**	3.30	2.82	2.54
Hubs Used (P, S, L)	(13, 0, 48)	(13, 0, 48)	(13, 0, 38)	**(13, 0, 31)**	(13, 0, 20)	(13, 0, 14)	(13, 0, 9)
Hub Cost (€)	5,000,000	5,000,000	4,500,000	**4,150,000**	3,600,000	3,300,000	3,050,000
Transport Cost (€)	163.07	163.07	97.10	**92.65**	49.05	33.72	33.72
CO_2 Emission (kg)	24.56	24.56	14.62	**13.95**	7.39	5.08	5.08

Table C.3: Sensitivity Analysis Results: Total Budget

Total Budget (€)								
Experiment	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)	8 (Unlimited)
Value	5,000,000	7,000,000	9,000,000	**10,000,000**	11,000,000	13,000,000	15,000,000	Infinite
Scenario 1								
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)	8 (Unlimited)
No. of Parcels	2,516	2,516	2,516	**2,516**	2,516	2,516	2,516	2,516
% of Parcels	1.04	1.04	1.04	**1.04**	1.04	1.04	1.04	1.04
Hubs Used (P, S, L)	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)	**(13, 0, 0)**	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)
Hub Cost (€)	2,600,000	2,600,000	2,600,000	**2,600,000**	2,600,000	2,600,000	2,600,000	2,600,000
Transport Cost (€)	33.72	33.72	33.72	**33.72**	33.72	33.72	33.72	33.72
CO_2 Emission (kg)	5.08	5.08	5.08	**5.08**	5.08	5.08	5.08	5.08
Scenario 2								
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)	8 (Unlimited)
No. of Parcels	106,961	137,189	146,608	**158,505**	160,254	174,817	175,633	177,430
% of Parcels	44.04	56.49	60.37	**65.26**	65.98	71.98	72.32	73.06
Hubs Used (P, S, L)	(11, 5, 14)	(13, 10, 22)	(13, 18, 27)	**(13, 21, 32)**	(13, 21, 35)	(13, 33, 45)	(13, 37, 47)	(13, 40, 48)
Hub Cost (€)	3,400,000	4,700,000	5,750,000	**6,300,000**	6,450,000	8,150,000	8,650,000	9,000,000
Transport Cost (€)	7,731.09	8,621.10	7,627.68	**7,521.88**	6,971.31	7,338.26	7,214.96	7,012.36
CO_2 Emission (kg)	1,164.32	1,298.36	1,148.75	**1,132.81**	1,049.90	1,105.16	1,086.59	1,056.08
Scenario 3								
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)	8 (Unlimited)
No. of Parcels	2,729	6,294	8,019	**10,811**	11,803	13,553	13,553	13,553
% of Parcels	1.12	2.59	3.30	**4.45**	4.86	5.58	5.58	5.58
Hubs Used (P, S, L)	(13, 0, 1)	(13, 0, 11)	(13, 0, 20)	**(13, 0, 31)**	(13, 0, 38)	(13, 0, 48)	(13, 0, 48)	(13, 0, 48)
Hub Cost (€)	2,650,000	3,150,000	3,600,000	**4,150,000**	4,500,000	5,000,000	5,000,000	5,000,000
Transport Cost (€)	33.72	33.72	49.05	**92.65**	97.10	163.07	163.07	163.07
CO_2 Emission (kg)	5.08	5.08	7.39	**13.96**	14.62	24.56	24.56	24.56

Table C.4: Sensitivity Analysis Results: Local Budget Allocation

% Budget Allocated to Local Hubs									
Experiment	0.1	0.2	0.3	0.4	0.5	**0.6**	0.7	0.8	0.9
Scenario 3									
Metric	1	2	3	4	5	**6**	7	8	9
No. of Parcels	2,516	2,516	2,729	6,203	8,019	**10,811**	11,983	13,553	13,553
% of Parcels	1.04	1.04	1.12	2.55	3.30	**4.45**	4.93	5.58	5.58
Hubs Used (P, S, L)	(13, 0, 0)	(13, 0, 0)	(13, 0, 1)	(13, 0, 10)	(13, 0, 20)	**(13, 0, 31)**	(13, 0, 39)	(13, 0, 48)	(13, 0, 48)
Hub Cost (€)	2,600,000	2,600,000	2,650,000	3,100,000	3600000	**4,150,000**	4,550,000	5,000,000	5,000,000
Transport Cost (€)	33.72	33.72	33.72	33.72	49.05	**92.65**	111.77	163.07	163.07
CO_2 Emission (kg)	5.08	5.08	5.08	5.08	7.49	**13.95**	16.83	24.56	24.56

Table C.5: Sensitivity Analysis Results: Transfer Penalty (Time)

Transfer Penalty (Time) (hours)							
Experiment	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
Train-Metro	2.5/60	3.5/60	4.5/60	**5.0/60**	5.5/60	6.5/60	7.5/60
Train-Light Rail	3.5/60	4.9/60	6.3/60	**7.0/60**	7.7/60	9.1/60	10.5/60
Metro-Light Rail	2.0/60	2.8/60	3.6/60	**4.0/60**	4.4/60	5.2/60	6.0/60

Scenario 1							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	2,516	2,516	2,516	**2,516**	2,516	2,516	2,516
% of Parcels	1.04	1.04	1.04	**1.04**	1.04	1.04	1.04
Hubs Used (P, S, L)	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)	**(13, 0, 0)**	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)
Hub Cost (€)	2,600,000	2,600,000	2,600,000	**2,600,000**	2,600,000	2,600,000	2,600,000
Transport Cost (€)	33.72	33.72	33.72	**33.72**	33.72	33.72	33.72
CO_2 Emission (kg)	5.08	5.08	5.08	**5.08**	5.08	5.08	5.08

Scenario 2							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	158,505	158,505	158,505	**158,505**	158,505	158,505	158,505
% of Parcels	65.26	65.26	65.26	**65.26**	65.26	65.26	65.26
Hubs Used (P, S, L)	(13, 21, 32)	(13, 21, 32)	(13, 21, 32)	**(13, 21, 32)**	(13, 21, 32)	(13, 21, 32)	(13, 21, 32)
Hub Cost (€)	6,300,000	6,300,000	6,300,000	**6,300,000**	6,300,000	6,300,000	6,300,000
Transport Cost (€)	6,877.11	7,135.02	7,392.92	**7,521.88**	7,650.83	7,908.74	8,166.64
CO_2 Emission (kg)	1,035.71	1,074.55	1,113.39	1,132.81	**1,152.23**	1,191.07	1,229,92

Scenario 3							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	10,811	10,811	10,811	**10,811**	10,811	10,811	10,811
% of Parcels	4.45	4.45	4.45	**4.45**	4.45	4.45	4.45
Hubs Used (P, S, L)	(13, 0, 31)	(13, 0, 31)	(13, 0, 31)	**(13, 0, 31)**	(13, 0, 31)	(13, 0, 31)	(13, 0, 31)
Hub Cost (€)	4,150,000	4,150,000	4,150,000	**4,150,000**	4,150,000	4,150,000	4,150,000
Transport Cost (€)	92.65	92.65	92.65	**92.65**	92.65	92.65	92.65
CO_2 Emission (kg)	13.95	13.95	13.95	**13.95**	13.95	13.95	13.95

Table C.6: Sensitivity Analysis Results: Transfer Penalty (Cost)

Transfer Penalty (Cost) (€)							
Experiment	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
Train-Metro	0.5	0.9	1.1	**1.0**	1.1	1.3	1.5
Train-Light Rail	0.7	1.15	1.35	**1.5**	1.65	1.95	2.25
Metro-Light Rail	0.25	0.35	0.45	**0.50**	0.55	0.65	0.75

Scenario 1							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	2,516	2,516	2,516	**2,516**	2,516	2,516	2,516
% of Parcels	1.04	1.04	1.04	**1.04**	1.04	1.04	1.04
Hubs Used (P, S, L)	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)	**(13, 0, 0)**	(13, 0, 0)	(13, 0, 0)	(13, 0, 0)
Hub Cost (€)	2,600,000	2,600,000	2,600,000	**2,600,000**	2,600,000	2,600,000	2,600,000
Transport Cost (€)	449.42	449.42	449.42	**449.42**	449.42	449.42	449.42
CO_2 Emission (kg)	67.68	67.68	67.68	**67.68**	67.68	67.68	67.68

Scenario 2							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	158,505	158,505	158,505	**158,505**	158,505	158,505	158,505
% of Parcels	65.26	65.26	65.26	**65.26**	65.26	65.26	65.26
Hubs Used (P, S, L)	(13, 21, 32)	(13, 21, 32)	(13, 21, 32)	**(13, 21, 32)**	(13, 21, 32)	(13, 21, 32)	(13, 21, 32)
Hub Cost (€)	6,300,000	6,300,000	6,300,000	**6,300,000**	6,300,000	6,300,000	6,300,000
Transport Cost (€)	101,822.48	105,919.09	108,163.94	**109,749.30**	111,334.67	114,505.41	117,676.14
CO_2 Emission (kg)	15,334.71	15,951.67	16,289.75	16,528.51	**16,767.27**	17,244.79	17,722.31

Scenario 3							
Metric	1 (-50%)	2 (-30%)	3 (-10%)	**4 (+0%)**	5 (+10%)	6 (+30%)	7 (+50%)
No. of Parcels	10,811	10,811	10,811	**10,811**	10,811	10,811	10,811
% of Parcels	4.45	4.45	4.45	**4.45**	4.45	4.45	4.45
Hubs Used (P, S, L)	(13, 0, 31)	(13, 0, 31)	(13, 0, 31)	**(13, 0, 31)**	(13, 0, 31)	(13, 0, 31)	(13, 0, 31)
Hub Cost (€)	4,150,000	4,150,000	4,150,000	**4,150,000**	4,150,000	4,150,000	4,150,000
Transport Cost (€)	1,453.55	1,453.55	1,453.55	**1,453.55**	1,453.55	1,453.55	1,453.55
CO_2 Emission (kg)	218.91	218.91	218.91	**218.91**	218.91	218.91	218.91

D

Scientific Paper

Hub Location Selection for Public Transport-Based Urban Freight Delivery

A Multi-Criteria and Simulation Approach

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***Abstract*— Freight transport is vital for urban economic growth, yet its increasing demand exacerbates congestion and emissions. The integration of freight delivery within public transport networks presents a sustainable alternative, leveraging underutilized transit capacity. While prior studies focus on operational aspects, limited research addresses strategic hub locations within public transit networks. This study introduces a novel framework for selecting public transport stations as freight hubs using a Multi-Criteria Decision Analysis (MCDA) approach with the Best-Worst Method (BWM). The framework evaluates key factors, such as accessibility, capacity, and costs, to determine optimal hub locations. A simulation is subsequently conducted to assess real-world viability, demonstrating the trade-offs between network reach, handling efficiency, and financial constraints. The results indicate that strategic hub placement significantly impacts network scalability and efficiency. Future research can expand upon this framework to refine urban freight delivery models tailored to specific implementation areas.**

***Index Terms*—Freight Transport, Urban Logistics, Public Transport, Hub Location Problem, Multi-criteria Decision Analysis, Multi-criteria Decision Making, Simulation**

I. INTRODUCTION

Freight transport is crucial for urban economic sustainability [35]; however, it contributes significantly to congestion and greenhouse gas emissions. The demand for time-sensitive last-mile deliveries (LMDs) has surged along with e-commerce expansion, intensifying environmental and logistical challenges [7] [4]. Traditional freight solutions, such as trucks and vans, increase energy consumption and pollution, necessitating alternative models for urban logistics [18] [35].

Public Transport-Based Freight Delivery (PTF) presents a promising solution by utilizing existing transit infrastructure for freight movement in urban areas. Various public transport modes, including trains, light rail, metro, and trams, can accommodate freight transport, reducing road congestion and emissions [6] [24] [32]. However, existing research primarily focuses on the operational feasibility of the system rather than the strategic planning of freight hubs [27] [31] [41]. Hubs are crucial as they serve as central nodes for consolidating, transferring, and managing freight flows, allowing goods to be processed, sorted, and directed efficiently across an urban network [23]. In dense metropolitan areas, properly retrofitted public transport stations have the potential to serve as freight hubs without the need to build extensive new infrastructure. The effectiveness of a PTF system hinges on the optimal placement of hubs, namely the hub structure and locations, to ensure efficient freight consolidation and distribution.

This study aims to develop a framework for selecting public transport stations as freight hubs within a PTF system. The specific objectives include the following:

- Identifying key criteria for selecting transit stations as freight hubs.
- Exploring possible network configurations that integrate passenger and freight transport.
- Analyzing the efficiency and sustainability impacts of different hub configurations.

Under the overarching main research question, ***"How can we optimally plan the hubs of a public transport-based freight delivery (PTF) system?"***, the study seeks to answer the following sub-research questions:

1) What are the criteria for selecting public transport stations to be hubs in a public transport-based freight delivery (PTF) system?
2) How can the identified criteria be used to rank public transport stations as different levels of freight hubs?
3) What are the possible network configurations comprising different levels of hubs?
4) How can the performance of the proposed hubs be evaluated under realistic urban scenarios?

A mixed-methods approach is employed, combining literature review, MCDA (the BWM), and simulation. The BWM is utilized to derive criteria weights, with inputs from relevant stakeholders. A simulation of a real case study evaluates the framework's practical application, comparing various hub configurations under realistic constraints.

The remainder of the paper is organized as follows. Section 2 presents the findings from the literature, explaining the concept of the PTF system and determining factors for its hub locations. Section 3 discusses the methods used in the study, including MCDA (the BWM) and the simulation. Section 4 outlines the developed criteria, followed by Section 5, where the outputs of the simulation-based case study are illustrated. Finally, Section 6 discusses the findings, research limitations, and recommendations.

II. Literature Review

A. Public Transport-Based Freight Delivery (PTF)

Public transport-based freight delivery (PTF) leverages existing passenger transit networks to facilitate freight movement in urban areas. By repurposing underutilized transport capacity, these systems aim to reduce congestion, emissions, and costs associated with LMDs [22]. PTF has been explored as an alternative to conventional urban logistics solutions, particularly in cities facing traffic bottlenecks and strict environmental regulations. The benefits of PTF systems include increased efficiency in freight distribution, reduced reliance on road transport, and potential financial gains for transit operators who utilize excess capacity [4] [16] [19].

1) Successful and Failed Implementations: Several case studies illustrate the viability of PTF systems, as well as the challenges they face. The CarGoTram in Dresden, Germany, successfully reduced emissions and traffic congestion by integrating freight transport into the city's tram network, demonstrating that rail-based freight can be a feasible solution in urban environments [38]. Similarly, Zurich's Cargo Tram has been used for waste collection, repurposing public transport infrastructure for decreased road traffic and emissions at a relatively low price in Switzerland [38] [54]. In contrast, CityCargo Tram in Amsterdam, The Netherlands, faced operational difficulties and financial constraints that led to its discontinuation, highlighting the importance of stakeholder collaboration and economic viability in PTF adoption [38]. Monoprix, a French supermarket chain, has implemented a system using rail and natural gas-fueled vehicles to distribute non-perishable products to their stores in Paris, France, leading to significant positive impacts on the environment [55]. Nevertheless, this project implies the challenge of limited logistics facilities in cities [38]. Overall, these cases demonstrate the potential of PTF models to reduce environmental impacts and improve urban logistics efficiency; however, the success of such systems depends on well-structured networks, policy support, and financial feasibility.

2) Modelling Techniques: PTF research predominantly focuses on operational and tactical planning rather than strategic network design. Optimization models such as the Pickup and Delivery Problem with Time Windows (PDPTW-SL) and variants of the dial-a-ride problem (DARP) have been explored to improve scheduling and routing within PTF systems [2] [17] [26] [27] [28] [25] [34] [40]. However, these models often lack realistic reflections on public transit networks by using simplified or synthetic routes. While operational and tactical decisions are crucial for daily operations, PTF planning centers around strategic choices. Considering long-term factors such as station selection and storage area design is crucial before evaluating public transit vehicle dimensions, service frequency, scheduling, and last-mile delivery [5]. Oliveira et al. [45] found a significant gap in research on site selection for shared facilities. Additionally, many integrated systems are small-scale prototypes, making it difficult to assess their actual benefits due to the use of artificial data in quantitative studies [44].

Multi-agent modelling can serve as a quantitative approach for evaluating freight transport networks, incorporating shippers, logistics service providers (LSPs), and regulatory authorities [20] [56]. These models facilitate the simulation of complex networks, incorporating the expectations and constraints of all stakeholders. Most studies, however, focus solely on multi-agent models for either passenger or freight transport, rather than integrating both aspects [37]. In one study, a combined optimization and simulation approach was employed to schedule shared passenger and freight transport on fixed infrastructure, though it only investigated the tactical planning of the integrated transport system [31].

B. Hub Location Problem (HLP)

PTF systems are complex multi-tier systems that transport commodities from a depot to an intermediate point before reaching the customers' destination; thus, they should utilize hubs as points of consolidation, connecting and switching for flows between origin-destination station pairs [23]. These hubs streamline freight flows by minimizing the number of required transfers, enhancing network efficiency. Hub location problem (HLP) is a subtype of Facility Location Problem (FLP) that is specifically tailored to strategically placing central points for goods transfer [29] [47]. In PTF systems, HLP models face unique challenges as they must integrate freight within a system optimized for passengers. Determining hub locations in PTF systems remains challenging due to the divergent needs of passenger and freight flows [3]. Defining optimal hub locations for freight within a public transit system requires sophisticated modelling techniques capable of incorporating multi-dimensional constraints, such as accessibility [36], land-use limitations [52], and the integration of freight-specific requirements within the existing passenger transit systems [23].

C. Multi-Criteria Decision Analysis (MCDA): The Best-Worst Method (BWM)

Multi-Criteria Decision Analysis (MCDA) has been widely applied in research to determine facility locations based on quantitative and qualitative criteria [39]. The Best-Worst Method (BWM), in particular, has gained traction for its ability to derive consistent and reliable weight assignments for multiple selection factors. Compared to traditional MCDA techniques such as the Analytic Hierarchy Process (AHP), the BWM effectively reduces computational complexity while maintaining high decision-making accuracy and adaptability to varying scenarios while maintaining reliability and consistency [50] [51].

D. Factors Impacting Freight Hubs

The suitability of transit stations as freight hubs depends on various factors, including infrastructure capacity [44], cost (investment and operational) [16] [21] [55], and cargo properties [38]. Research highlights that high-value, low-volume goods are best suited for PTF systems [38], whereas bulky freight requires dedicated handling facilities [14]. Additionally, integrating sustainable LMD solutions such as self-collection points or parcel lockers at transit stations can enhance efficiency and customer convenience [14] [45] [55]. This also leads to the necessity of good station accessibility to facilitate the provision of convenient LMD, supported by other studies that explored influencing factors on logistics facility locations. These studies emphasized the importance of proximity to demand, production, and major transport networks [46] [57].

E. Summary

Designing a freight transit network for urban areas requires considering both long-term and short-term operations. Public transport such as trams, metros, and trains is capable of transporting freight. Existing stations can serve as locations for transfer or LMD pickup while accommodating diverse freight based on the goods and stations' characteristics. Although tactical and operational studies are notable, research on the strategic planning of combined public and freight transport is limited. Certain studies construct a synthetic network or utilize one existing route to ascertain demand, supply, and transfer nodes, optimizing scheduling and routing decisions without evaluating network suitability. In addition, current research does not provide guidance on the selection of PTF hubs and products. Moreover, as many studies concentrate on small-scale prototype projects using one or a few routes, analyzing full-scale freight-passenger transport projects presents a significant research opportunity.

The hub location design of a PTF system could be regarded as a Hub Location Problem (HLP). Using existing transit stations as freight hubs can lead to a reduction in infrastructure construction costs; however, this necessitates meticulous planning due to various factors impacting hub locations. Multi-Criteria Decision Analysis (MCDA) can aid in identifying PTF hubs by evaluating both quantitative and qualitative attributes, including station capability, goods properties, accessibility for stakeholders, and associated investment and operational costs. The MCDA tool, the Best-Worst Method (BWM), can effectively assign weights to all (sub-)criteria, ranking candidate public transport stations and categorizing them into appropriate hub levels. The results of MCDA, encompassing detailed criteria with assigned weights and prioritized lists of station-based hubs, can be simulated via multi-agent modelling to assess specific hub configurations in real-world scenarios.

III. METHODS

This section discusses the methodology utilized in this study, including the BWM for criteria determination and simulation for a case study. Figure 1 provides an overview of the methods.

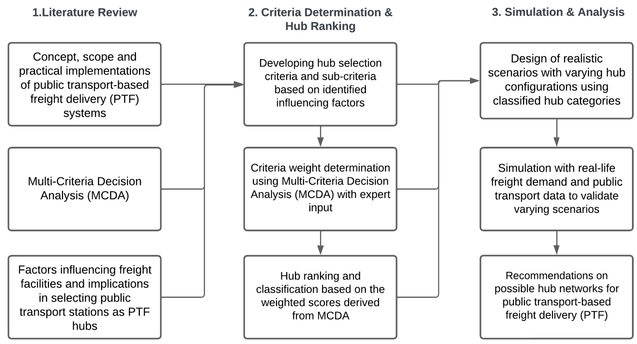


Fig. 1: Methodology

A. Criteria Determination and Weight Derivation

The criteria are determined based on the literature and consultation with selected experts in relevant fields to ensure their comprehensiveness. After the criteria are finalized, the BWM is undertaken to obtain the weights of each criterion and sub-criterion. The process is as follows:

1. Define the Criteria

Based on the factors identified from the literature and opinions from selected experts, the selection criteria of freight hubs were finalized.

2. Identify the Best and Worst Criteria

A panel of experts from both public and freight transport fields evaluated the criteria. The experts identified the *Best criterion* that they viewed as the most important and the *Worst criterion*, which they regarded as the least important in the selection of PTF freight hubs. Both a BWM survey and an interview were initially used to elicit criteria weights, but the anonymous survey responses were excluded due to unverifiable inconsistencies that exceeded acceptable thresholds. Instead, only the interview data gathered from several domain experts in freight transport, urban logistics, and public transport were used, with all responses demonstrating acceptable consistency levels (calculated in Step 5).

3. Formulate Pairwise Comparisons

Pairwise comparisons were conducted to establish other criteria's relative importance compared to the best and worst ones:

1) **Best-to-Others (B-to-O) Comparison**: Experts rated the importance of the best criterion relative to all other criteria on a scale of 1 to 9, where 1 represents equal importance and 9 refers to being absolutely more important than.
2) **Others-to-Worst (O-to-W) Comparison**: Experts rated the importance of all other criteria relative to the worst criterion, using the same scale in the B-to-O comparisons.

4. Calculate Criteria Weights

The pairwise comparisons from Step 3 resulted in two vectors, including a_{Bj}, the Best-to-Others comparisons and

a_{jW}, the Others-to-Worst comparisons. Using these pairwise comparisons, the relative weight (w_j) of each criterion was calculated. A set $J = 1, 2, ...j, ..., J$ was defined to be the set of criteria. The maximum absolute deviation (ξ) between the pairwise comparisons and the derived weights was minimized:

$$\min \xi \tag{1}$$

Subject to:

$$|\frac{w_B}{w_j} - a_{Bj}| \leq \xi, \qquad \forall j \in J \tag{2}$$

$$|\frac{w_j}{w_W} - a_{jW}| \leq \xi, \qquad \forall j \in J \tag{3}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{4}$$

$$w_j \geq 0, \qquad \forall j \in J \tag{5}$$

Where:

- w_B: Weight of the best criterion.
- w_W: Weight of the worst criterion.
- a_{Bj}: Best-to-Others comparison values.
- a_{jW}: Others-to-Worst comparison values.

5. Evaluate Input-Based Consistency Ratio

The reliability of all answers was checked by the input-based consistency ratio (CR_j), representing the consistency level of the pairwise comparisons for a criterion j [33].

$$CR = \max_j CR_j \tag{6}$$

Where:

$$CR_j = \begin{cases} \left| \frac{a_{Bj} \cdot a_{jW} - a_{BW}}{a_{BW} \cdot a_{BW} - a_{BW}} \right|, & a_{BW} > 1 \\ 0, & a_{BW} = 1 \end{cases} \tag{7}$$

CR is the global input-based consistency ratio for all criteria, which could be compared with the threshold values [33].

6. Derive Final Weights and Hub Rankings

Lastly, the weights (w_j) derived from the BWM process were applied to score and rank candidate hub locations. Each hub was evaluated against the criteria using performance scores obtained from transit data and qualitative assessments. The weighted sum of scores for each hub determined its final ranking:

$$\text{Score}_{\text{Hub}} = \sum_{j=1}^{n} w_j \cdot \text{Criterion Performance}_{\text{Hub},j} \tag{8}$$

Steps 4 and 5 were carried out using the BWM's Excel solver [49]. For primary and local hubs, the BWM was carried out individually to determine the criteria weights for each hub type. The reason is that while the criteria are suitable for selecting freight hubs in general, hubs with varying functions emphasize the importance of each criterion differently. The outputs of the MCDA process were then lists of hubs per category. Unlike primary and local hubs, secondary hubs were selected using the stations' betweenness centrality scores (Section III-B). The rationale for this approach stemmed from the concern that including secondary hubs in the BWM would significantly increase the complexity and length of the survey or interview, making it impractical for participants with limited availability. Also, in real life, transfer facilities are mostly selected based on the network composition and freight patterns rather than pre-defined locations.

B. Simulation

Using the BWM results as inputs, the simulation of the case study was then undertaken (Figure 2). The duration of the simulation was a day.

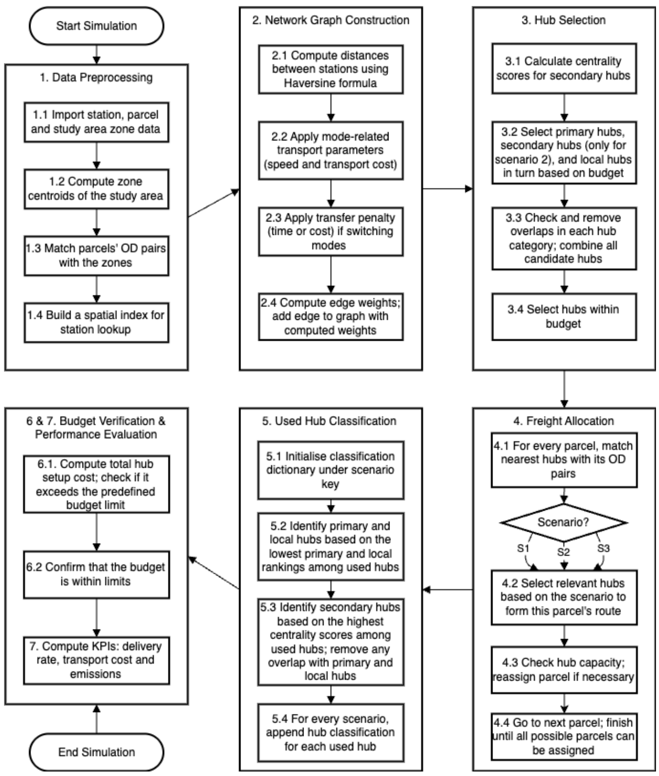


Fig. 2: Simulation

1. Data Preprocessing

The first step involved importing and preparing the datasets. Station data, including latitudes, longitudes, transport modes, and hub classification, were loaded. Real-world parcel demand data specifying the origin and destination zones was integrated. The pairwise distances between stations were computed using the Haversine formula [15]:

$$d_{ij} = 2R \arcsin \left(\sqrt{\sin^2\left(\frac{\phi_j - \phi_i}{2}\right) + \cos(\phi_i)\cos(\phi_j)\sin^2\left(\frac{\lambda_j - \lambda_i}{2}\right)} \right) \tag{9}$$

Where:

- d_{ij} is the great-circle distance between two stations i and j,

- R is the Earth's radius (6371 km),
- ϕ_i, ϕ_j are the latitudes of stations i and j,
- λ_i, λ_j are the longitudes of stations i and j.

2. Network Construction

The distances between stations computed in Step 1 were used to construct the network. Each station operates a transport mode (e.g., train, metro, or light rail), using predefined speed, cost per kilometer, and emission parameters. The calculations of travel weight were influenced by the delivery focus, specifically whether it was time- or cost-efficient. The case study mainly used the time penalty to construct the network graph. In this way, the total travel weight was computed as distance divided by transport speed, with an additional transfer time penalty when switching between transport modes:

$$w_{ij} = \frac{d_{ij}}{s_m} + p_t \tag{10}$$

Where:

- w_{ij} is the travel weight between stations i and j.
- d_{ij} is the computed great-circle distance using the Haversine formula.
- s_m is the speed of the transport mode m at a station i.
- p_t represents any transfer penalty time when switching between transport modes.

As explained above, the weight calculations could also incorporate cost considerations, which are the distance multiplied by cost per kilometer, plus any transfer cost penalty if changing transport modes. The cost-type weight could be evaluated as below:

$$w_{ij} = (d_{ij} \times \text{cost\_per\_km}) + \text{transfer\_cost} \tag{11}$$

Due to the limited scale of the study, the simulation used the network graph constructed with time penalties; however, the sensitivity analysis included experimenting with varying values of cost penalties to identify the trade-off between cost efficiency and network performance.

3. Hub Selection

The final number of hubs was budget-constrained to ensure the total hub setup cost did not exceed a predefined limit. The budget constraint was defined as follows:

$$\sum_{h \in H} c_h \leq B_H \tag{12}$$

Where:

- c_h is the setup cost of hub h,
- H is the selected set of hubs,
- B_H is the total hub setup budget.

The freight was allocated to different hubs based on the scenario, as explained in Step 4. Particularly, in scenario 2, betweenness centrality was used to identify potential secondary hubs [12]:

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{13}$$

Where:

- σ_{st} is the total number of shortest paths from node s to t
- $\sigma_{st}(v)$ is the number of those paths that pass through node v

4. Freight Allocation

Once the network was constructed, freight was allocated to hubs based on predefined scenarios. For every scenario, the allocation process adhered to hub capacity constraints so that the number of parcels a hub could handle did not exceed its capacity limit. For each hub, this number varied:

- **Primary Hubs:** High capacity (e.g., 10,000 parcels/day)
- **Secondary Hubs:** Medium capacity (e.g., 5,000 parcels/day)
- **Local Hubs:** Low capacity (e.g., 2,500 parcels/day)

Parcel allocation followed one of the three strategies, according to the scenario:

- **Minimal Hub Use (Scenario 1)**: Only primary hubs were used. An allocated parcel's origin and destination should have a nearby primary hub. The route was determined as a direct path between the selected primary hubs.
- **Hierarchical Network (Scenario 2)**: A structured hub sequence was enforced:
  - The **origin** station was assigned to the closest primary hub to the origin.
  - The **destination** station was assigned to the nearest local hub to the destination.
  - A **secondary hub** was selected to be a transfer station between the origin and destination hubs, which was from the candidate hubs with top centrality scores that had a connection to the local hub.
- **Decentralized Network (Scenario 3)**: Parcels moved through primary and local hubs (primary to primary or primary to local). If no direct path existed between the selected primary and local hubs, another primary hub was used as an intermediate transfer point.

If a hub reached full capacity, parcels were either rerouted to an alternative hub or excluded from allocation if no feasible path existed at all. The final output consisted of a list of allocated parcels and their respective routes, namely the hubs they will depart from, transfer at (if required), and arrive at.

5. Used Hub Classification

This step categorized the used stations in Step 4 (freight allocation) into primary, secondary, and local hubs based on scenario and precomputed station rankings. In each scenario, primary hubs were chosen from the utilised hubs by examining which ones are in the top 50 stations with the lowest primary hub rank values (a lower value refers to a higher ranking). The number 50 represents the maximum number of primary hubs possible, calculated by dividing the total budget by a primary hub's setup cost. Similarly, local hubs were identified as the used hubs that fell within the top stations with the lowest local hub rank values. On the other hand, secondary hubs were selected from the top 100 most central stations based on betweenness centrality scores, where the number

100 was randomly determined to ensure sufficient candidate secondary stations. Overlaps between hub types were resolved by removing stations already classified as primary or local hubs from the secondary hub set.

6. Budget Verification

Before calculating KPIs, the actual total expense was checked to ensure that it was below the assumed budget limit. Primary hubs had the highest unit cost, followed by secondary and local hubs. The total budget was calculated by summing the number of hubs multiplied by their corresponding unit costs, which was compared with the fixed total budget used in the simulation. If the budget was exceeded in a scenario, that scenario was then impractical under the current financial constraints, and the simulation setting should be adjusted.

7. Performance Evaluation

To evaluate the network performance, the delivery rate was computed as the number of freight delivered divided by the total demand. Other key performance indicators (KPIs), the transport cost and CO_2 emissions, were calculated as follows:

$$C_{total} = \sum_{(i,j)\in R} d_{ij} \times c_m + p_c \tag{14}$$

$$E_{total} = \sum_{(i,j)\in R} d_{ij} \times e_m \tag{15}$$

Where:

- C_{total} is the total transport cost,
- E_{total} is the total emissions (kg CO_2),
- c_m is the cost per km of mode m,
- e_m is the emission per km of mode m,
- p_c is the transfer cost penalty.

IV. Hub Selection Criteria

A. Hub Categories

As discussed in Section I, this study utilizes a multi-tiered hub network to efficiently distribute freight within the metropolitan public transport system. Namely, three types of hubs are defined. *Primary hubs*, or access hubs, manage multi-modal handling, long-term storage, and freight aggregation for long-haul transport, consolidating freight inflows from LSPs and directing them to secondary and local hubs. *Secondary hubs*, or transfer hubs, connect primary hubs to local hubs by handling mid-level transfers between primary and local network layers. *Local hubs*, or egress hubs, are positioned near demand clusters to support end-point delivery operations, minimizing last-mile costs and road congestion. While primary hubs receive (large) incoming flows, local hubs are more likely to handle smaller freight volumes since goods have been redistributed via primary and secondary hubs already.

B. Selection Criteria

Based on the extensive literature review, comprehensive selection criteria for freight hubs in the PTF system are developed. In total, there are five main criteria defined, each with supporting sub-criteria:

- **Cargo Requirements:**
  1) Vulnerability: Handling of fragile goods;
  2) Demand Volatility: If the station can deliver goods needed on a regular basis or irregularly/urgently;
  3) Security: Capability to provide additional security measures for high-value or sensitive goods.
- **Costs:**
  1) Investment Costs: Costs of initial investment of the stations and modification of vehicles;
  2) Operational Costs: Day-to-day operational costs of additional equipment and labour;
  3) Maintenance & Upgrade Costs: Long-term costs, including maintenance and eventual upgrades or replacements of infrastructure.
- **Connectivity**
  1) Service Frequency: Number of services in a certain time period (e.g., during peak hours or per day);
  2) Service Coverage: Number of routes possible and how many destinations can be reached;
  3) Proximity to Other Transit Modes: If it is a multi-modal transit station itself or close to other types of stations.
- **Capacity:**
  1) Physical Space: Space available at the station for microconsolidation, storage and transfer;
  2) Equipment & Labour: Capability to install logistics-related facilities and available staff;
  3) Expansion Potential: Potential for growth in freight operations.
- **Accessibility:**
  1) Proximity to Demand Locations: Closeness to demands (e.g., customer homes, locations of business receivers);
  2) Proximity to Supply Locations: Closeness to supplies (e.g., warehouses and distribution centres);
  3) Access to Road Network: Ease of access for pre- and last-mile operators travelling with road vehicles;
  4) Access to Active Modes: Ease of access for pre- and last-mile operators travelling with active modes (e.g., biking and walking);
  5) Digital Accessibility: Presence of smart systems and digital platforms for the staff to manage freight flows and passengers to co-exist with freight activities in the station.

Through the BWM, the weights of the (sub-)criteria are determined (Tables I and II). From Table I, it can be seen that accessibility is the most significant criterion for primary hubs (0.3259), whereas capacity is the key factor for local hubs (0.2954). This signifies the various operational roles that these hubs fulfill. Primary hubs function as key access points within the network, emphasizing convenient access to essential infrastructure and financial viability. Local hubs, integrated into urban environments for LMD, prioritize capacity over accessibility, reflecting a heightened focus on efficient package handling in constrained urban areas.

TABLE I: Main Criteria Weights

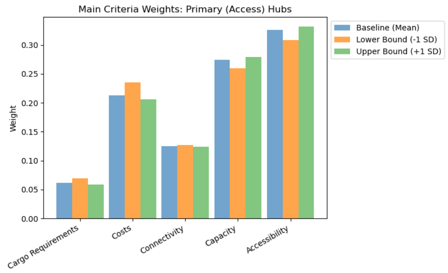
Criteria	Primary (Access) Hubs	Local (Egress) Hubs
Cargo Requirements	0.0612	0.1137
Costs	0.2132	0.2076
Connectivity	0.1250	0.1514
Capacity	0.2746	0.2954
Accessibility	0.3259	0.2320

TABLE II: Sub-Criteria Weights

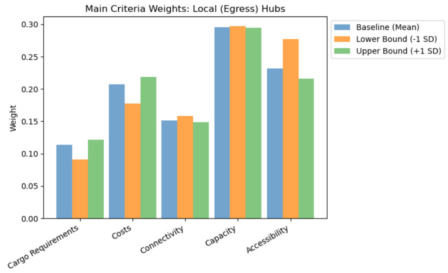
Cargo Requirements	**Weight**
Vulnerability	0.2972
Demand Volatility	0.5118
Safety	0.1910
Costs	**Weight**
Investment Costs	0.4759
Operational Costs	0.2417
Maintenance & Upgrade Costs	0.2824
Connectivity	**Weight**
Service Frequency	0.175
Service Coverage	0.65
Proximity to Other Transit Modes	0.175
Capacity	**Weight**
Physical Space	0.6066
Equipment & Labour	0.2374
Expansion Potential	0.1560
Accessibility	**Weight**
Proximity to Demand Locations	0.1487
Proximity to Supply Locations	0.177
Access to Road Network	0.4794
Access to Active Modes	0.0818
Digital Accessibility	0.1135

For accessibility, access to the road network (0.4794) plays the most crucial role (Table II). Costs consistently rank as an essential criterion, among which investment costs (0.4759) hold considerable significance, indicating that initial infrastructure expenses are an essential element in PTF hub selection, while operational costs (0.2417) are deemed of moderate significance for the overall hub expenses. On the other hand, for capacity, equipment & labour and expansion potential are of minor importance (0.2374 and 0.1560), indicating that automation and scalability are not the main capacity factors, whereas physical space plays the most crucial role (0.6066). Connectivity has a greater impact on local hubs as a main criterion (0.1514 and 0.1250 for local and primary hubs). Among connectivity, service coverage (0.65) is paramount, suggesting a preference for extensive delivery service availability. The low weight of proximity to other transit modes (0.175) indicates that present-day urban freight transport predominantly depends on road-based delivery rather than intermodal alternatives.

1) Sensitivity Analysis: Sensitivity analysis was undertaken for the criteria weights (Figures 3). The most important criteria for primary hubs are accessibility and costs, while cargo requirements hold minimal influence, and almost all criteria weights are relatively stable in primary hubs. However, the criteria for local hubs exhibit heightened sensitivity to variations among experts, though capacity is the absolutely dominant criterion. Nevertheless, it can be seen that the BWM maintains robustness overall, as the observed ranking shifts are moderate and not extreme, regardless of the hub type.



(a) Primary (Access) Hubs

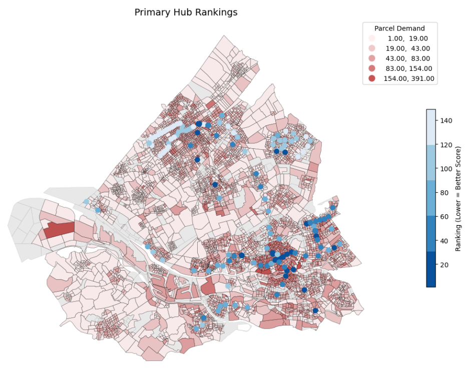


(b) Local (Egress) Hubs

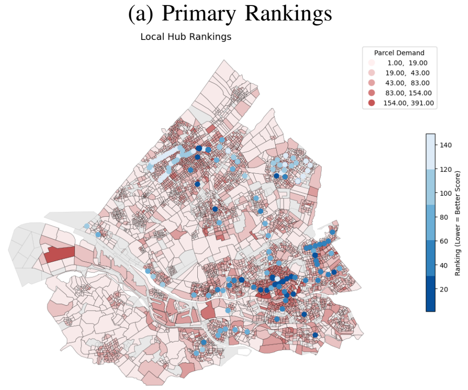
Fig. 3: Sensitivity Analysis on Main Criteria Weights

C. Hub Rankings

The rankings of the primary and local hubs, obtained using the BWM, are shown in Figure 4.



(a) Primary Rankings



(b) Local Rankings

Fig. 4: Primary and Local Hub Rankings

It can be observed that many stations rank similarly for both hubs, which could be due to the insignificant differences in the criteria weights for primary and local hubs, resulting in similar station scores. Another reason could be that transit stations in the study area have, in general, 1) good access to parcel origins and destinations and 2) sufficient capability to operate freight.

V. Simulation

A. Study Area

The study focuses on the Rotterdam-The Hague Metropolitan Area (MRDH), in South Holland, The Netherlands. South Holland is among the most economically developed provinces in the Netherlands, hosting various international institutions and corporations. The MRDH encompasses the urban regions within this province, housing approximately 2.4 million residents and 1.3 million employment opportunities, representing 13.5% of the Dutch population [43]. Covering an area of 1213 km^2, the MRDH contributes 15% to the gross national product (GNP) collectively. South Holland possesses a comprehensive transport network comprising roads, rail, waterways, and public transit [13], including the MRDH. Figure 5 illustrates the study area of the MRDH (colored regions), with South Holland serving as the base map (grey region).

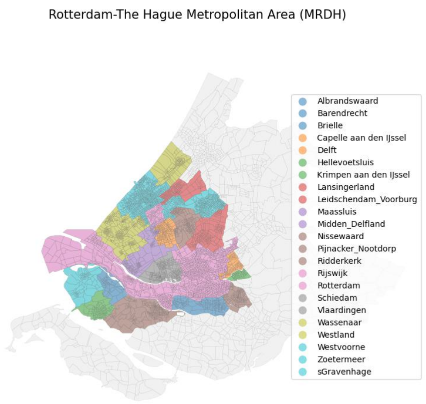


Fig. 5: Study Area: Rotterdam-The Hague Metropolitan Area (MRDH)

B. Data

The Multi-Agent Simulation System for Goods Transport (MASS-GT), an agent-based freight transport simulation model, is used to obtain freight movements in the MRDH [9]. The MASS-GT parcel demand module, which simulates the parcel demands in South Holland, including the MRDH, is used. This module generates parcel demands using real-world sociodemographic and empirical logistics data, including household information, average parcel demand volumes, and LSPs' market share. The resultant parcel demand data contains the origins and destinations, LSPs, and depots (LSP distribution centers). As MASS-GT solely includes parcel information, the case study simulates parcels. One of the major advantages of using MASS-GT is the high level of realism due to real-life logistics data. Also, the model has been applied in various applications [11] [8] [10], proving its effectiveness and reliability in modelling urban freight.

The study involves a total of 149 train, light rail, and metro stations within the MRDH. The train stations comprise all NS stations in this region. The metro services consist of lines A to D operated in Rotterdam, in addition to RandstadRail's line E that connects The Hague and Rotterdam. The light rail stations include RandstadRail lines 3, 4, and 34, which differ from the local tram lines in the region. Including an excessive number of local tram lines in this study would render the simulation overly complex and unrealistic to conduct within a limited timeframe; hence, trams are not considered. The station locations are sourced from the OpenStreetMap API, represented by colord circles in Figure 6.

For sub-criteria that required quantitative data, static GTFS data serves to assess the sub-criterion service frequency for train stations [1], while that of light rail stations is determined by the schedules of RandstadRail lines 3, 4, and 34 [30], due to GTFS data's limited availability. The fixed timetable for the metro routes is utilized to determine the frequencies of metro stations [48]. A single day's timetable for both the light rail and metro is used (0:00 to 24:00 on 17/01/2025).

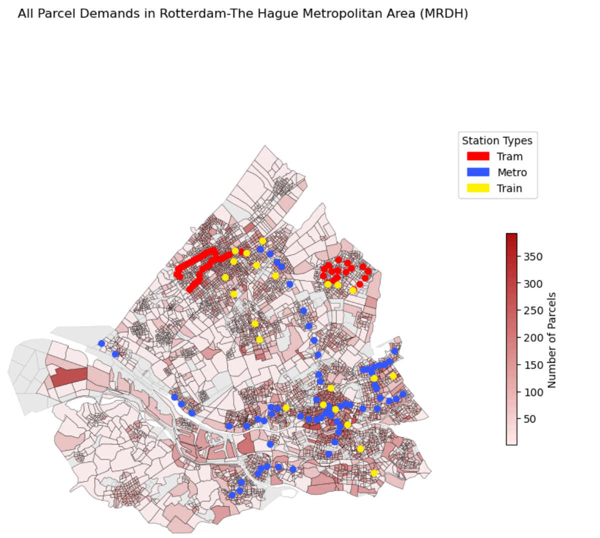


Fig. 6: Parcel Demands and Rail Stations in Rotterdam-The Hague Metropolitan Area (MRDH)

C. Assumptions

As explained previously, this study is centered on the strategic hub location planning of PFT systems; therefore, operational details of the proposed network need to be assumed. The assumptions are as follows:

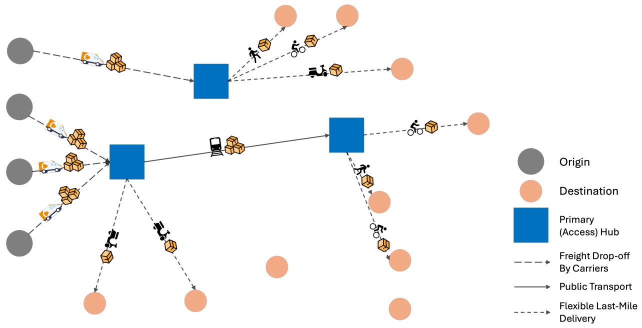
- Pre-Operations by LSPs:
  Prior to entering the PTF system, parcels are transported

from LSPs' distribution centers (e.g., PostNL, DHL, DPD, FedEx) to public transport stations. Each LSP collects parcels, stores them in standardized containers based on destinations, and delivers them to the nearest public transport station. For simplicity, the simulation excludes LSP warehouse-to-transit station transport.
- Operations at Public Transport Stations:
Parcels will be loaded onto public transit at stations. LSPs are expected to deliver parcels to stations on a predetermined schedule or ad hoc, depending on the station's capability. Station staff can possibly perform the (un)loading of goods onto transit vehicles.
- Middle-leg Transport by Public Transport Vehicles:
A delivery trip commences when a vehicle leaves the designated station. Generally, trains, metros, and light rail systems typically operate with regular frequency that adheres to a fixed schedule. Consequently, the schedule of individual vehicles is not considered in the simulation, minimizing additional complexity for the analysis.
- Exclusion of Last-Mile Operations:
Transit vehicles deliver goods to stations near demand, which may or may not be different from departure points. Unloaded goods are removed from vehicles and containers and transshipped to LMD operators or stored at the station before LMD collection. Container unloading from transit vehicles is assumed to be timed. Similar to other operational decisions, the LMD operations are excluded.

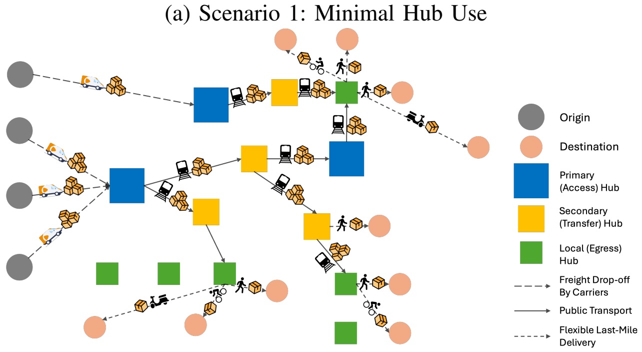
D. Scenarios

Three scenarios are designed to evaluate varying hub configurations of the integrated freight network, as shown in Figure 7. The scenarios are:

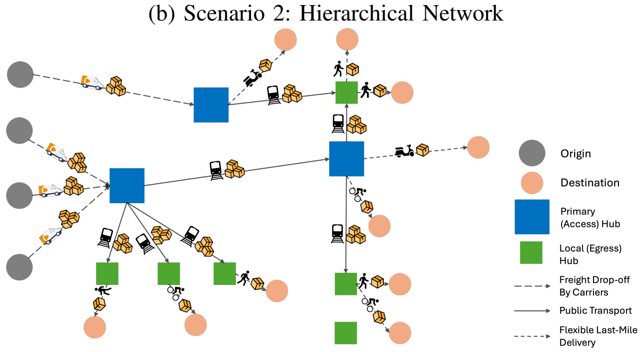
- **Scenario 1: Primary Hub Use**
Only primary hubs handle freight. Avoiding secondary and local hubs, goods are routed between primary hubs near their origins and destinations.
- **Scenario 2: Hierarchical Routing**
Freight traverses primary, secondary, and local hubs, adhering to a strict hierarchy. Hub rankings and centrality scores are utilized to identify each primary and local hub, along with the optimal secondary hub for this primary and local hub pair.
- **Scenario 3: Decentralized Hub Network**
Primary and local hubs handle freight delivery, though a proportion of the budget is allocated to local hubs to promote the use of cost-effective, decentralized egress stations and reduce dependence on primary hubs.
  - Case 1: Direct route primary $\rightarrow$ primary;
  - Case 2: Direct route primary $\rightarrow$ local;
  - Case 3: Primary $\rightarrow$ primary $\rightarrow$ local; when no direct primary $\rightarrow$ local route exists, another primary hub is used as a transfer point.



(a) Scenario 1: Minimal Hub Use



(b) Scenario 2: Hierarchical Network



(c) Scenario 3: Decentralised Network

Fig. 7: Scenarios

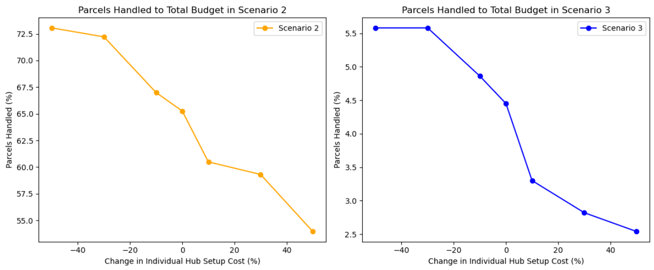
E. Sensitivity Analysis

A sensitivity analysis was conducted for key parameters utilized in the simulation (Figures 11 to 12). Firstly, the results indicate that variations in hub capacity substantially impact scenario 2, whereas scenarios 1 and 3 are predominantly unaffected. In scenario 2, the proportion of parcels handled, total hub cost, and the number of secondary hubs used increase, indicating a higher network utilization rate (Figure 9).

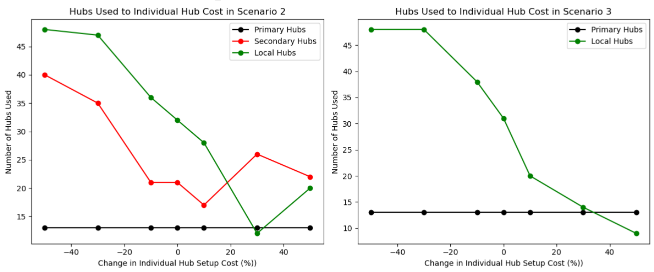
Secondly, modifying hub setup costs influences scenarios 2 and 3, resulting in a decrease in parcel processing, the number of hubs utilized (excluding primary hubs), and fluctuations in transport costs and CO_2 emissions (Figure 8). Changes in the total budget also influence the number of hubs utilized and parcels delivered in scenarios 2 and 3, whereas scenario 1 remains unaffected (Figure 10).

Scenario 3 specifically encourages the utilization of local hubs; thus, this scenario is impacted by local budget allocation (Figure 11). When less than 30% of the budget is designated for local hubs, almost no parcels are delivered, and no local hubs are operational. Increased budget allocation to local hubs significantly increases parcels handled, concurrently raising the overall hub cost; however, the proportion of processed parcels reaches saturation once more than 70% of the budget is allocated to local hubs.

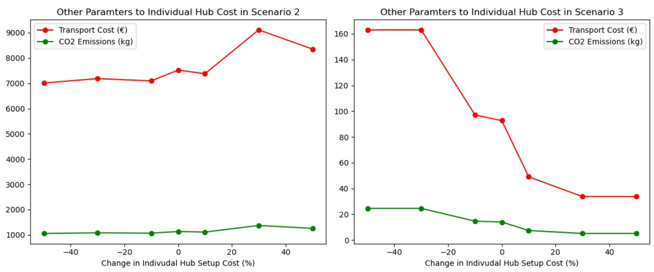
The network's sensitivity to the transfer time penalty is largely minimal across all scenarios. Scenarios 1 and 3 exhibit relative stability, whereas scenario 2 shows slight increases in transport costs and CO_2 emissions (Figure 12a). Similarly, elevated transfer cost penalties also result in slightly increased transport costs and CO_2 emissions in scenario 2 (Figure 12b). As scenarios 1 and 3 remain relatively stable, the primary and local hub uses are hence not substantially influenced by the transfer cost penalty.



(a) Proportion of Parcel Handled (%)



(b) Number of Hubs Used



(c) Other Parameters

Fig. 8: Sensitivity Analysis on Hub Setup Cost

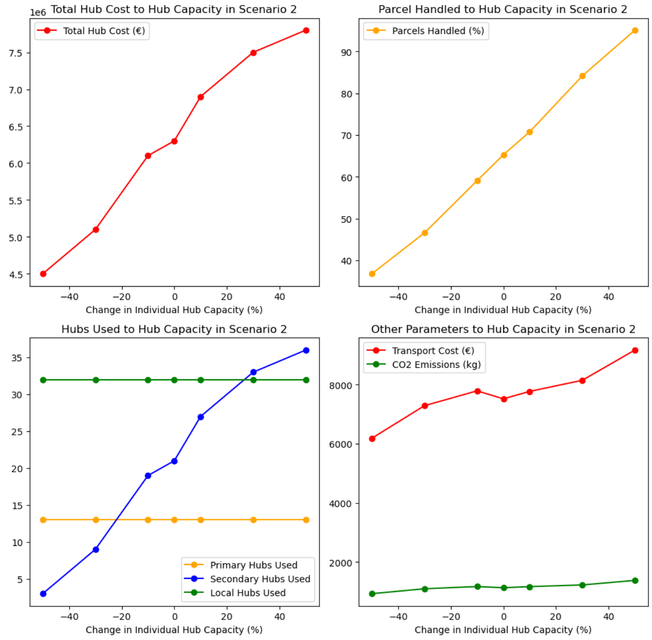
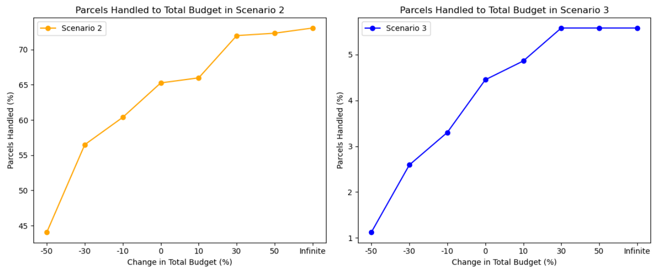
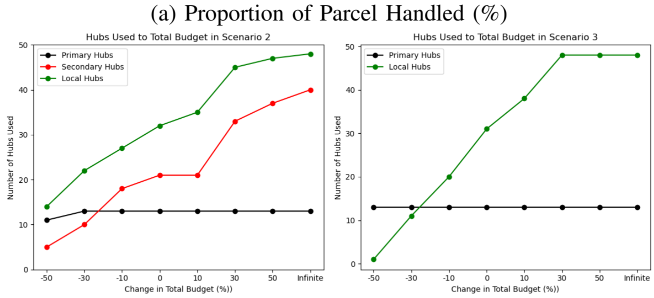


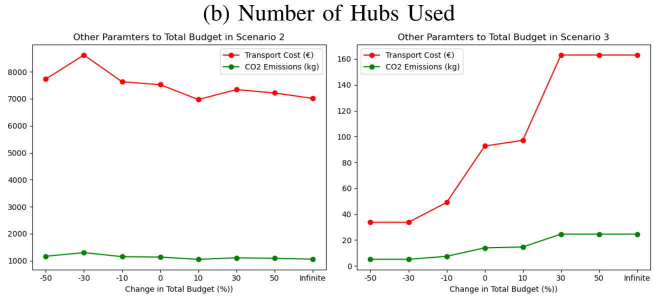
Fig. 9: Sensitivity Analysis on Hub Capacity



(a) Proportion of Parcel Handled (%)

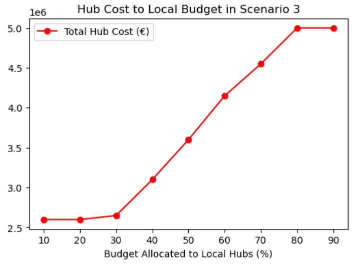


(b) Number of Hubs Used

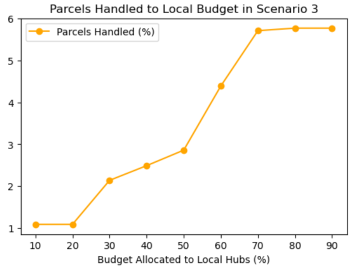


(c) Other Parameters

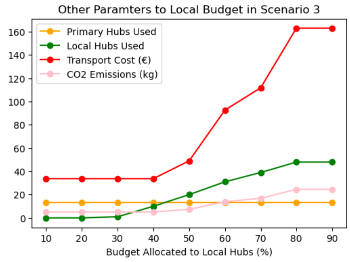
Fig. 10: Sensitivity Analysis on Total Budget



(a) Total Hub Cost

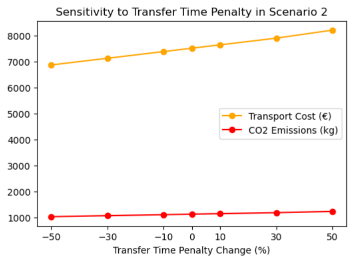


(b) Proportion of Parcel Handled (%)

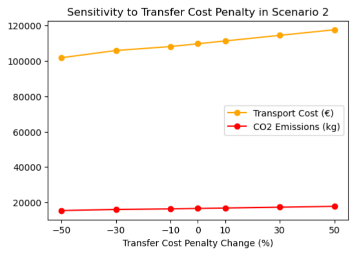


(c) Other Parameters

Fig. 11: Sensitivity Analysis on Local Budget Allocation



(a) Transfer Time Penalty



(b) Transfer Cost Penalty

Fig. 12: Sensitivity Analysis on Transfer Penalties

F. Results

Baseline parameter values and time-based transfer penalties are used to simulate the network. The parameter values are listed in Table III, while the simulation results are shown in Table IV. To distinguish how freight flow and hub usage patterns vary in different scenarios, Figures 13 to 16 illustrate the spread of used hubs, the intensity of parcels flown between hubs, and the quantity of parcels handled at each origin and destination hub, respectively, in each scenario.

TABLE III: Parameter Values

Parameter	Notation	Value
Transport Speeds (km/h)		
Train speed (km/h)	s_{train}	120
Metro speed (km/h)	s_{metro}	80
Light rail speed (km/h)	$s_{\text{light rail}}$	30
Transport Costs (€/km)		
Train	c_{train}	0.30 [53]
Metro	c_{metro}	0.171 [42]
Light rail	$c_{\text{light rail}}$	0.193 [42]
Emissions (kg CO_2/km)		
Train	e_{train}	0.02
Metro	e_{metro}	0.03
Light rail	$e_{\text{light rail}}$	0.05
Transfer Penalties (Time, h)		
Train → Metro	$p_t(\text{train}, \text{metro})$	5/60
Train → Light rail	$p_t(\text{train}, \text{light rail})$	7/60
Metro → Light rail	$p_t(\text{metro}, \text{light rail})$	4/60
Transfer Penalties (Cost, €)		
Train → Metro	$p_c(\text{train}, \text{metro})$	1.0
Train → Light rail	$p_c(\text{train}, \text{light rail})$	1.5
Tetro → Light rail	$p_c(\text{metro}, \text{light rail})$	0.5
Hub Setup Costs (€)		
Primary hub	c_{primary}	200,000
Local hub	c_{local}	50,000
Secondary hub	$c_{\text{secondary}}$	100,000
Hub Capacities (parcels/day)		
Primary hub	Q_{primary}	10,000
Secondary hub	$Q_{\text{secondary}}$	5,000
Local hub	Q_{local}	2,500

TABLE IV: Simulation Results

Metric	Scenario 1	Scenario 2	Scenario 3
Parcels Delivered	2,516 (1.04%)	158,505 (65.26%)	10,811 (4.45%)
Total Hub Setup Cost (€)	2,600,000	6,300,000	4,150,000
Transport Cost (€)	33.72	7,521.88	92.65
CO_2 emissions (kg)	5.08	1,132.82	9.96
Number of Hubs Used			
Primary Hubs	13	13	13
Secondary Hubs	0	21	0
Local Hubs	0	32	31

From Table IV, it can be seen that scenario 1 handles slightly more than 1% of the overall demand with only primary hubs. The overall cost for hub setup is approximately €2,600,000, with 13 primary hubs being operational. The transport cost and CO_2 emissions are negligible, amounting to €33.72 and 5.08 kg, respectively. In scenario 3, however, the combination of primary and local hubs results in a marginally higher parcel volume compared to scenario 1 (4.45%), though the hub setup cost drastically increases to €4,150,000. Nonetheless, transport costs and CO_2 emissions are comparatively low, recorded at €92.65 and 9.96 kg, respectively. On the other hand, the activation of secondary hubs and the utilization of local hubs in scenario 2, along with primary and local hubs, result in an increase in processed parcels to almost two-thirds of total freight (65.26%) and significantly enhance network utilization. The total cost for the hub setup in this case is €6,300,000, including expenses related to secondary hubs and additional primary and local hub pairs enabled by the secondary hubs.

Regarding parcel flow patterns (Figure 13), scenario 1 exhibits centralized flows with limited flexibility. Scenario 2 shows dense, interconnected flows via intermediate hubs, while scenario 3 features fragmented, localized flows enabled by local hubs. Furthermore, in scenario 1, only 1 origin hub is activated (Figure 14). This could be due to the strict freight allocation mechanism in scenario 1 that requires both the origin and destination to have a primary hub within reach for a freight trip to be assigned, determined by real-world travel distance and time constraints (Equations 9 and 10), hence limiting the number of hubs activated. Nevertheless, while the incoming parcels are still clustered at one origin in scenario 3, the local hubs facilitate a wider distribution of deliveries, activating more destination hubs. On the contrary, in scenario 2, the spatial distribution of origin and destination hubs is broader due to secondary hubs facilitating increased connections between primary and local hubs.

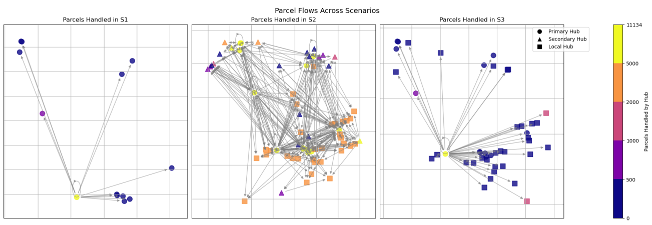


Fig. 13: Parcel Flow Distributions

Figure 15 presents the ranking of secondary hubs based on betweenness centrality. Interestingly, due to the construction of the transport graph as a fully connected network (based on Euclidean distances), all nodes received an identical centrality score of 1. This made it impossible to rank secondary hubs meaningfully using standard network topology metrics. Consequently, the simulation adopted a fallback approach in which nodes not qualifying as primary or local were designated as secondary hubs. This highlights a key methodological limitation, which is discussed in Section VI.

Last but not least, the number of delivered parcels can be visualised by zone, as defined in MASS-GT (Figure 16). Scenario 1 restricts coverage to zones near primary hubs. Scenario 2 achieves widespread coverage across zones, while scenario 3 expands beyond scenario 1 but remains less extensive than scenario 2. The reason that scenario 2 dramatically

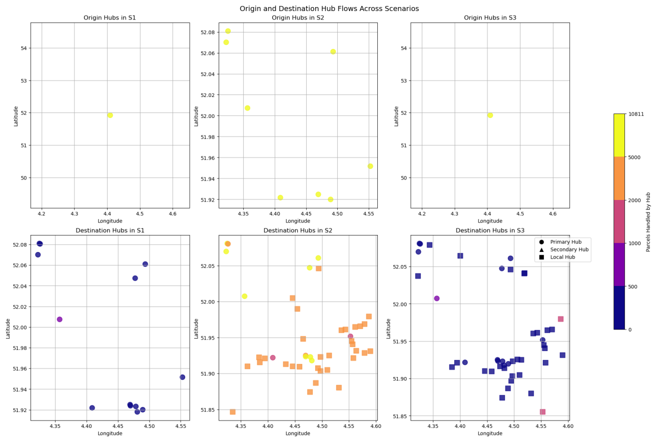


Fig. 14: Origin and Destination Hub Distributions

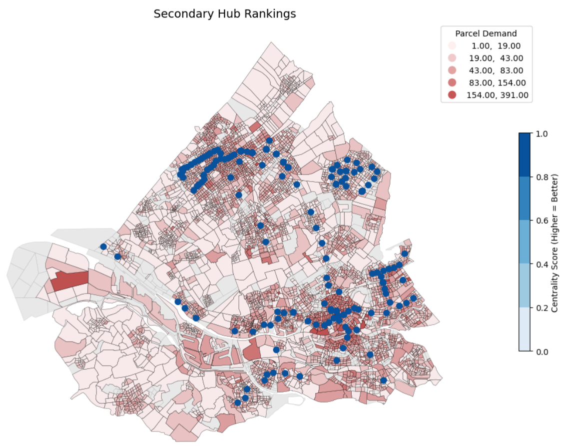
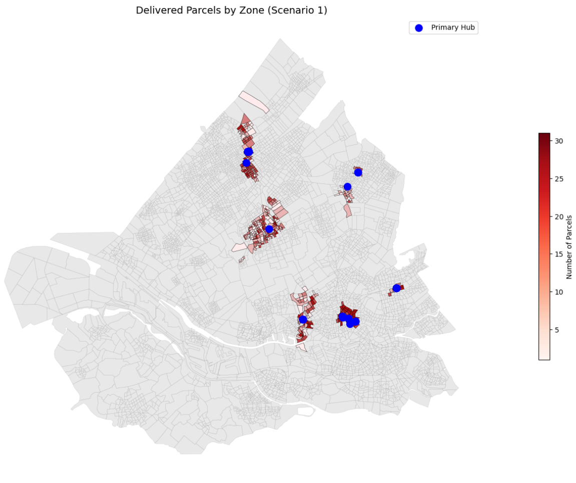


Fig. 15: Secondary Hub Rankings

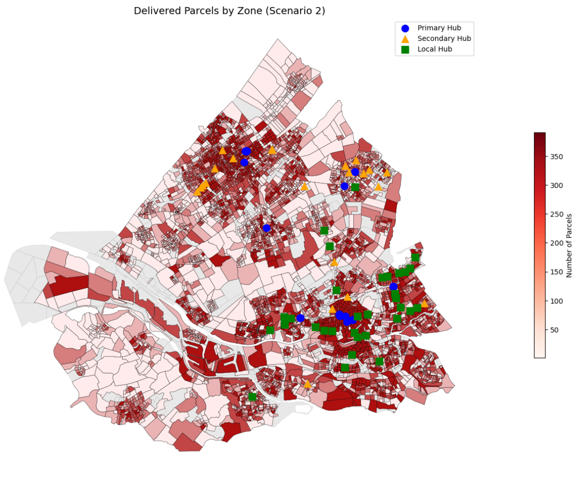
improves coverage could be due to the fact that centrality scores failed to differentiate nodes, allowing many stations to serve as secondary hubs if they were not ranked as primary or local and had connections with local hubs. Thus, deliveries could be routed through these intermediate hubs, increasing the geographic breadth of service. As is evident in Figure 16b, secondary hubs cluster around high-demand zones and primary hubs, suggesting that their selection was implicitly influenced by spatial proximity and whether they fulfill budget and capacity constraints rather than true centrality in the network. Meanwhile, scenario 3 exhibits improved coverage relative to scenario 1 by enabling deliveries via local hubs, though its performance remains less comprehensive than scenario 2.

VI. Discussions

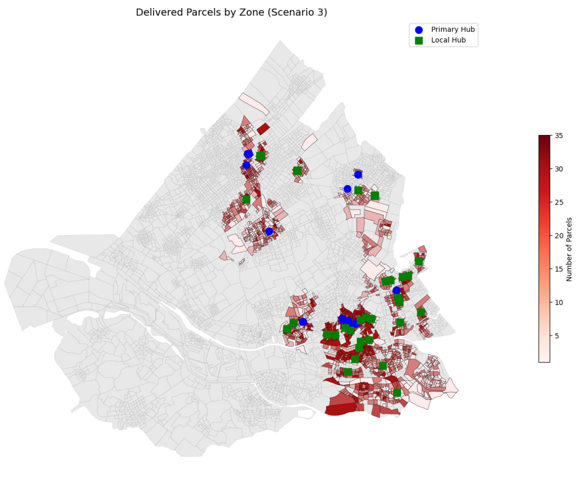
This study introduces an innovative framework for leveraging public transport stations as freight hubs in urban regions. The results provide insights into hub selection criteria, operational efficiency, and trade-offs within different network configurations of PTF systems. First, the literature review identified key factors influencing hub locations and formed



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

Fig. 16: Hub Location Distributions

corresponding selection criteria. Through expert consultation, the BWM then assessed the formulated criteria and identified accessibility as the most critical for primary hubs (entry points) and capacity for local hubs (egress points). This finding aligns with the shared nature of public transport hubs, where passenger and freight flows interact. The selection of public transport-based freight hubs hinges on their location within the network for the convenient use of all stakeholders, including LSPs, customers, and LMD carriers.

The simulation results further highlight trade-offs across different network configurations. A network relying solely on primary hubs (Scenario 1) is cost-effective and environmentally friendly but struggles to accommodate demand. In contrast, a hierarchical network (Scenario 2) ensures a relatively high freight handling rate but incurs additional costs and emissions due to frequent transfers. A primary and local hub network (Scenario 3) balances cost efficiency and handling capacity better than sole primary hub use but requires careful budget allocation and processes for much less freight than the hierarchical network. It can be seen that secondary and local hubs play a dual role in the network: they enhance coverage and utilization but also introduce additional costs. Their effectiveness is contingent on factors such as hub costs, budget allocation, and freight demand patterns.

The sensitivity analysis of the simulation underscores the network sensitivity. Hub setup costs significantly impact the PTF system's scalability, particularly in hierarchical networks where additional secondary hubs increase expenditure. Budget constraints also affect network performance, with excessive resource allocation to local hubs yielding insignificant parcel handling improvement beyond a certain threshold. Regarding transfer penalties, cost-related penalties exhibit a more substantial impact than time-based penalties, implying that economic factors pose greater constraints on freight integration than operational barriers.

One limitation of this study is the absence of an explicit routing mechanism. The simulation model determines the most suitable hubs for freight handling but does not explicitly model the movement of parcels along specific transport links. In reality, routing decisions consider congestion levels, path optimization, and transfer dependencies. Incorporating a routing algorithm in future research could enhance the realism of freight allocation, particularly by accounting for real-time network conditions and hub utilization rates. Additionally, the model assumes static demand and infrastructure, whereas real-world logistics fluctuate dynamically. Future studies should consider integrating dynamic freight demand patterns, time-sensitive adjustments, and policy interventions, such as regulatory incentives for freight access at transit hubs. Another limitation to improve is that non-anonymous surveys or only interviews should be done for the BWM to avoid loss of valuable expert-inputted data.

Moreover, using Euclidean distances to construct the network should be reconsidered. Utilising Euclidean distances to model network topology results in a fully connected network, leading to equal centrality scores and selection of secondary hubs solely based on spatial proximity to demand destinations. In effect, actual network-based distances may better reflect the real network, where stations are partially connected to each other and display varying centrality scores. It could also be useful to use the BWM or combined multi-criteria and network-based measures to rank secondary hubs if experts had sufficient time to participate in the study.

VII. Conclusions

This study explores the feasibility of urban Public Transport Freight Delivery (PFT), providing a strategic framework for freight hub selection in existing public transit networks. By combining multi-criteria decision analysis (MCDA) with simulation, the study proposes a structured decision support tool for combined passenger and freight planning, offering insights into hub performance and network trade-offs.

The MCDA tool, the Best-Worst Method (BWM), reveals that accessibility is the dominant criterion for selecting PTF hubs, particularly for primary hubs (access hubs), while capacity plays a more significant role in local hubs (egress hubs). Unlike traditional logistics facilities, where cargo-specific handling infrastructure is paramount, shared passenger-freight hubs must prioritize network integration to enhance urban mobility. More importantly, secondary hubs (transfer hubs) and local hubs have a complex role, as they improve network utilization at additional costs. Their effectiveness depends on a balance between budget allocation, the volume and spatial distribution of freight demand, and time sensitivity.

Furthermore, the simulation demonstrates that relying solely on primary hubs is highly insufficient for handling significant freight volumes. Hierarchical networks provide high freight capacity but at increased costs and emissions, whereas decentralized networks are more cost-effective but process a low amount of freight and require careful budget distribution to local hubs. Sensitivity analysis highlights that financial constraints, such as budget size and hub setup costs, impact system performance more than operational constraints, such as hub capacity and transfer penalties.

Despite its contributions, this study has several limitations. The model assumes static demand, while real-world freight flows fluctuate dynamically. Additionally, operational details such as routing, vehicle scheduling, and congestion mitigation are not explicitly considered. The simulation determines suitable hubs for freight handling but does not model the exact movement of parcels along the available transport routes between the hubs. Therefore, future studies are recommended to incorporate a routing algorithm, for instance, to optimize travel paths and adapt to network disruptions dynamically. Policy interventions such as freight access regulations or pricing incentives may also be incorporated. In addition, network-based distances should be used to better represent a realistic transport network. Also, the use of centrality-based measures for selecting secondary hubs could be improved, i.e., combining MCDA with approaches that generate network indicators. Further, comparative studies across different urban regions could validate the scalability of the PTF solution offered in this study, ensuring that the proposed methodology is adaptable to varying transport infrastructures and demographic landscapes.

For implementation, governments and transit agencies can leverage the hub classifications and selection criteria identified in this study to evaluate the feasibility of using public transit services for freight purposes. High-accessibility transport nodes could be prioritized, and flexible hub configurations should be explored to accommodate regional demand variations. Starting with pilot projects at selected hubs, followed by gradual expansion in the implemented area, can improve implementation viability. Moreover, public and private stakeholders should collaborate to finance and manage the retrofitting of transport stations for freight handling for maximum efficiency and implementation success. Additionally, regulatory frameworks should be updated to promote PTF delivery while mitigating potential conflicts with passenger traffic.

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