Crowdshipping as a delivery solution for outlier parcels

A case study in The Hague

Master Thesis

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Crowdshipping as a delivery solution for outlier parcels

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by

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Preface

With the completion of this thesis, it marks the end of my master's studies at Technical University of Delft. At the time I am typing down these words, it still feels so unreal that I will be graduating very soon. I've been working on this thesis for the past several months, and at this point, I am so proud of myself for the successful completion of this project.

The project would not be finished without the support and guidance from my supervision committee. Therefore I would like to first express my gratitude to my supervisors. To Gonçalo Correia, I still remember the time when I was having difficulty finding a suitable master thesis topic, your kind welcome and advice on the topic and potential committee members helped me a lot. During the project process, your critical and constructive feedback helped me to scope down to the most relevant parts and make progress efficiently. To Michiel de Bok, I feel so lucky to have you as one of my daily supervisors. This is not only because your constructive feedback at our weekly meetings has been helping me to move in the right direction with my project, but also because the positive and enthusiastic attitude you share with me has been inspiring me to keep going. To Merve Cebeci, as we are in similar ages, your understanding and support have been very helpful to me. Whenever I encounter a problem, whether it's a small technical problem or conceptual confusion, you are always there and willing to help me, I feel very warm to have you in my committee. To Ron van Duin, you've been very considerate of me during the project duration, whether it's coming up with new ideas to open up my mind or providing useful tips on the thesis. Your encouragement and affirmation of my work helped me to stay motivated in the final stage.

Then I would like to extend my gratitude to my parents and friends. Thanks to my parents for your unconditional support for me since always. Especially thanks for providing me the opportunity of studying abroad, seeing the larger world and living in a more free environment. To my friends, thanks for always being there and listening to my thoughts and for the care you keep sharing with me. To my roommates, thanks for your companion, whether it's a small kitchen talk of "how are you" or a random discussion of our similar and different cultural backgrounds, I've found it very interesting. The gratitude is also extended to all the people who have kindly offered me understanding and help in my master study's journey.

Finally, I would like to thank myself for not giving up and keeping going. The past 2.5 years in The Netherlands has been both wonderful and tough, and I am glad I kept growing through the obstacles and exploring myself. The most important lesson I learnt from the whole thesis progress is to accept the reality as it is and embrace the ordinariness we all share. I hope I can keep this lesson with me in my future life.

Keying Tang
Delft, March 2024

Summary

Purpose and Scope

With the steady growth of the e-commerce industry, more and more people are opting for online shopping than in-store shopping. In The Netherlands, the number of parcels delivered increased from 399 million in 2019 to 654 million in 2021 (ACM, 2023). Last mile delivery (LMD) refers to the last leg of the logistics chain where goods are transported from local distribution centres to end customers in urban areas, which consumes the most energy and generates the most emission of the whole supply chain (Gevaers, Van de Voorde, & Vanelslander, 2011). The increasing parcel demand results in increasing urban freight transport brought by LMD, which adds to the traffic congestion and emission problems. To address these problems, innovative logistics solutions for LMD are needed.

Crowdshipping is an innovative logistics initiative that aims at utilising the excess capacity in existing traveller trips to perform the delivery tasks, which could potentially reduce the traffic externalities and the volume of urban freight trips in LMD. However, similar to other shared mobility services such as ride-sharing, crowdshipping service may bring extra vehicle kilometres travelled due to detours and new trips generated such as drivers being motivated by monetary compensation (Pourrahmani & Jaller, 2021). To address the possible traffic externalises brought by crowdshipping service and better navigate it to achieve its potential sustainability benefits, various studies have been conducted to design and evaluate the operation strategies, while one study points out that prioritising outlier parcels, such as the parcels in geographically remote or low-demand areas, for crowdshipping service could achieve more transport and environmental benefits (Zhang & Cheah, 2023).

Therefore, this study aims to continue investigating the transport impacts of crowdshipping services for outlier parcels, which are defined as the parcels with high environmental impacts, in the context of LMD. The main research question is formulated as: **To what extent does crowdshipping service for outlier parcel delivery affect the transport performance of last-mile deliveries?**. The Hague is chosen as the study area, which is one of the most urbanized cities in The Netherlands.

Methodology

This study uses an agent-based modelling and simulation approach that takes into account the decision-making of train travellers and LSPs. This approach is taken as it could provide a more realistic performance evaluation of this decentralised logistics concept (Tapia, Kourounioti, Thoen, de Bok, & Tavasszy, 2023).

The methodology of this study consists of three main modules: outlier parcel segregation, crowdshipping supply system, and crowdshipping demand and supply matching. To begin with, the outlier parcel segregation module applies a delivery effort-based carbon footprint measurement method and segregates the parcels with a high carbon footprint as outlier parcels. The measurement method quantifies the carbon footprint by allocating the total tour delivery effort fairly to each parcel. In a delivery tour, the farther away the parcel is the more capacity it takes up, and the greater carbon footprint is allocated to the parcel.

Next to the outlier parcel demand for crowdshipping service, the crowdshipping delivery scenario is proposed as a public transport(PT)-based crowdshipping service with parcel lockers (PL) as the transfer

points between logistics service providers (LSPs) and occasional couriers (OCs), as shown in Figure 1. PT is selected as the main transport mode considering its sustainable characteristics and PL is employed for a smooth and consolidated operation. Train travellers with destinations or origins at the train stations are considered potential OCs.

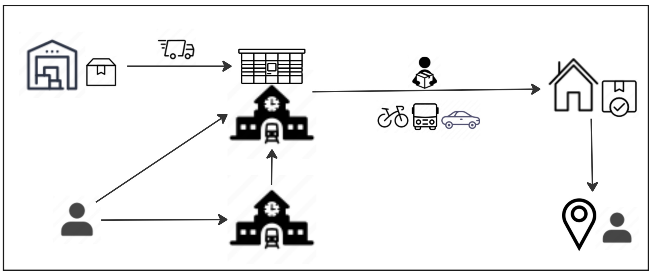

Figure 1: Visualisation of crowdshipping delivery scenario

For train travellers, the behavioural decision-making of each traveller is considered when selecting potential OCs and determining which traveller is matched with each parcel. Value of time (VoT) is used to refer to traveller's travel utility. For each individual, the provided VoT by the crowdshipping service is compared with travellers' preferred VoT, and the travellers with gains in VoT are selected as potential OCs. For each parcel, considering its final destination and the detour effort, the traveller with maximum VoT gains is matched with it.

With crowdshipping demand and supply available, the matching of them is based on the combination of (1) the availability of potential OCs, (2) the capacity of PL, and (3) the proximity of depots to PL at train stations. The third matching criterion ensures that the maximum benefits of saving van kilometres travelled in LMD can be examined in this study.

Finally, the three modules are synthesized in simulation. Different settings in both crowdshipping demand and supply modules are examined to assess their impacts on the transport performance of crowdshipping service for outlier parcel delivery.

Results

First the implementation results of the delivery effort-based carbon footprint measurement methods are shown, then the simulation results of different crowdshipping operation strategies are presented.

Figure 2 shows the parcel carbon footprint distribution for each LSP. As can be seen, large variations exist among different LSPs. The large variations can be explained as the different market shares of LSPs, as shown in Figure 3. Large LSPs (PostNL and DHL) have a low parcel carbon footprint, as the high parcel demand leads to gains in economies of scale, which facilitates a highly efficient operation in LMD and low delivery effort. While for small LSPs such as FedEx, the low parcel demand results in an inefficient operation and thus a significantly high parcel carbon footprint distribution. Because of the large variations of carbon footprint distribution among different LSPs, the segregation is performed for each LSP. Parcels with high carbon footprint are considered as outlier parcels. 1751 (3.1%) out of a total of 56801 parcels are segregated, with varying outlier percentages for each LSP.

Table 1 shows the results of key simulation scenarios. The key performance indicators (KPI) look at the transport performance in LMD as well as the crowdshipping service efficiency. A reference scenario and two simulation experiments are presented, with one focusing on the demand side and the other on the supply side. The first scenario R1 works as the reference scenario where all parcels are eligible

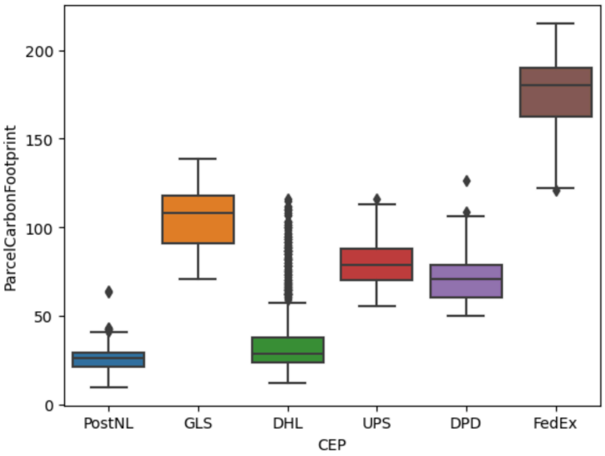

Figure 2: Box plot of parcel carbon footprint for each LSP

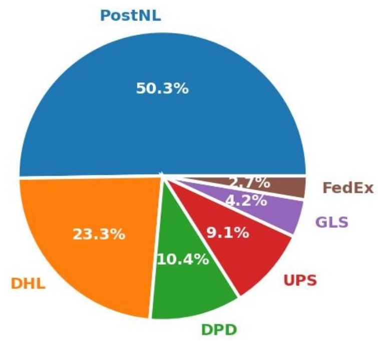

Figure 3: Market share of couriers based on parcel volumes (ACM, 2023)

Table 1: Simulation results of different LSP demand of outlier parcels and different PL configurations (green colours indicate relatively good performance)

Scenario label	R1	D1	D3	D4	P2:	P3	P4
Scenario specification	All parcels	All outliers	Exclude PostNL	Only FedEx, GLS	5 stations + 3 stops	4 main stations	5 high-demand
LSP outlier parcel demand (% of total demand)	Random 9050 (15.9)	1751 (3.08)	1377 (2.42)	361 (0.64)	1377 (2.42)		
KPI							
Match rate (%)	58.67	64.19	73.86	94.46	85.33	71.39	76.47
Total VKT reduction (%)	1.6	3.03	3.76	1.57	3.54	2.78	3.04
VKT reduction per matched parcel (km)	0.041	0.369	0.506	0.633	0.413	0.387	0.396
Compensation per VKT reduction (euro/km)	145.29	16.26	11.82	9.48	14.53	15.48	15.15

for crowdshipping, and a random 9050 parcels are selected to be in line with the total number of train travellers. The results show that compared to the current LMD performance without crowdshipping service, the proposed PT-based crowdshipping service can achieve a reduction in van kilometres travelled (VKT) with randomly selected parcel demand, and the car detour distance generated is quite small as most travellers opt for PT or active modes for the last leg of their train trips. This proves the sustainable benefits of the proposed crowdshipping service. But these benefits are very little compared to the high compensation paid, making the service very inefficient.

The three following scenarios (D1, D3, D4) focus on testing the impacts of crowdshipping for outlier parcels of different LSPs. All three scenarios achieve a much larger VKT reduction than the reference scenario, which proves the effectiveness of the crowdshipping service for outlier parcels. Compared to scenario D1 where all outlier parcels are eligible for crowdshipping, the better overall performance in scenario D3 indicates that the crowdshipping service might bring negative transport impacts to LSPs with large market share, as its current operation is efficient enough. Comparing scenario D4 to D1 and D3, the higher efficiency in reducing VKT indicates that crowdshipping could be more beneficial to LSPs with low market shares. A percentage of only 0.64% outlier parcels from the two smallest LSPs can reduce 1.57% of VKT, and a maximum of 0.633km reduction in VKT can be achieved by a single outlier parcel. This is because for the LSPs with less efficient operation in last-mile delivery, outsourcing the parcels with high carbon footprint from their total parcel demand to the crowdshipping service can maximize the savings in VKT and service inefficiency, thus the crowdshipping service could achieve its largest sustainability potential.

The second experiment (scenario D3, P2, P4) focuses on testing the impacts of the crowdshipping supply system with different PL network configurations, which consists of two parts: PL network size and PL locations. The results of scenarios D3 and P2 show that expanding the PL network size does not help achieve more VKT reduction. This is because a larger PL network requires the delivery vans to visit more PLs, and the benefits of more matched outlier parcels do not make up for the increased VKT this results in. This indicates that a small-sized PL network with a certain level of consolidation could work better for the proposed crowdshipping service. As for PL location, similar to PL network size, 5 high traveller demand stations and stops in scenario P4 can result in a higher match rate compared to scenario D3, but the increase in the distance from depots to PLs/train stations outweighs the benefits brought by more matched parcels. These two experiments emphasize the importance of carefully balancing the trade-off between traveller demand and the distance from depots to PLs/train stations when determining PL network size and PL locations.

Conclusion

In conclusion, this study proposes an integral method for designing and evaluating a PT-based crowdshipping service for outlier parcels in the last-mile delivery. This method defines the outlier parcels as the parcels with high environmental impacts and employs an agent-based modelling approach which considers the decision-making of individual travellers.

The implementation of delivery effort-based carbon footprint measurement method shows that large variations exist in the carbon footprint distribution of LSPs with different market shares. LSPs with small market shares have a higher carbon footprint distribution as a result of their less efficient operations in LMD compared to large LSPs.

The simulation results show that the proposed crowdshipping service could bring potential sustainable benefits and this benefit is much larger when prioritizing outlier parcels with high environmental impacts for crowdshipping. In addition, outsourcing the outlier parcels of LSPs with less market share to crowdshipping could bring considerably higher gains in VKT reduction and service efficiency.

From the supply side, a small-sized PL network fits well with the PT-based crowdshipping service for its consolidation benefits, and the trade-off between traveller demand and the distance from depots to stations should be carefully considered when determining PL network size, choosing PL locations and allocating PL capacity.

To better understand the impacts of crowdshipping service for outlier parcels in last-mile delivery, there are some recommendations for future research directions. First, it is recommended to test the proposed methods and scenarios on a larger geographical scale, which could lead to a larger part of LMD being outsourced to cross-city train trips and the larger potential of crowdshipping service could be examined. Second, it would be interesting to investigate the definition rules of outlier parcels from different perspectives and provide a more systematic evaluation of crowdshipping services for outlier parcels by comparing the performance under different definition rules. Third, more research could be done on the efficient design of a PT-based crowdshipping system. As this study shows the sustainable potential of such a system, more extensive studies such as those on the PT-based PL network design could provide more insights into the potential of PT-based crowdshipping service.

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Nomenclature

Abbreviations

Abbreviation	Definition
LMD	Last-mile delivery
WtW	Willingness to work
ABM	Agent-based modelling
GCD	Great-circle distance
ZWF	Zonal weighting factor
PT	Public transport
PL	Parcel locker
OC	Occasional courier
VoT	Value of Time
VKT	Van kilometres travelled
LSP	Logistics service providers

1 Introduction

In this chapter, first the problem that this study tries to address is explained. Following that, the goal and research questions are proposed. To answer the research questions, the approach and main methods of this study are briefly introduced. Lastly, the scope of this study is briefly described.

1.1. Problem definition

With the steady growth of the e-commerce industry and as a result of the lockdown measures taken during the COVID-19 pandemic period, more and more people are opting for online shopping than in-store shopping. In The Netherlands, the number of parcels delivered increased from 399 million in 2019 to 654 million in 2021 (ACM, 2023). Besides the increase in parcel demand, customers are expecting an increase in the quality of delivery. The e-commerce customers in The Netherlands constantly report late or missed delivery problems (ACM, 2023). Moreover, customers are becoming more aware of the environmental issues of logistics. They are expecting parcel delivery to be fast, reliable, cheap, have the option for on-demand and personalized service and environmentally friendly (Gevaers et al., 2011).

The increasing parcel demand and increasing customer expectations are posing challenges to the logistics service providers (LSPs) and urban freight system. Last mile delivery (LMD) refers to the last leg of the logistics chain where goods are transported from local distribution centres to end customers in urban areas, which is the most inefficient and expensive segment of the total logistics chain. It accounts for from 13% up to 75% of the total supply chain costs, consumes the most energy and generates the most emission of the whole supply chain (Gevaers et al., 2011). The increasing demand results in increasing urban freight transport, which adds to the traffic congestion and emission problems. To address the efficiency and environmental problems facing last-mile delivery, innovative logistics solutions are needed.

Crowdshipping is an innovative logistics initiative that relates to the idea of the Physical Internet, which envisions interconnected logistics based on distributed multi-segment intermodal transportation (Rougès & Montreuil, 2014). The concept of crowdshipping aims at utilising excess capacity in existing passenger trips to perform delivery tasks to improve transport system efficiency. Crowdshipping service mainly involves service providers/crowdshipping platforms, senders, and occasional couriers (OCs). The senders post-delivery requests on the platform and individuals who are willing to carry the packages with them during their journeys act as occasional couriers and get compensation for completing the delivery tasks. The services crowdshipping could offer to include but are not limited to on-demand delivery, community-based delivery, shopping and shipping delivery and first/last-mile delivery to/from local carriers (Pourrahmani & Jaller, 2021).

Crowdshipping has the potential benefits of reducing the traffic externalities brought by LMD, reducing delivery costs, increasing flexibility and accessibility to new products and promoting community engagement. However, similar to other shared mobility services such as ride-sharing, crowdshipping service may bring extra vehicle kilometres travelled due to detours and new trips generated such as drivers being motivated by monetary compensation (Pourrahmani & Jaller, 2021).

To address the possible traffic externalises brought by crowdshipping service and better navigate its potential impacts under different situations, various studies have been conducted to design and optimize the operation strategy and evaluate the corresponding impacts of crowdshipping service. Some studies focus on behavioural aspects to better understand different shareholders' acceptance towards crowdshipping, while others focus on optimizing the operations with proposed delivery scenarios and advanced allocation algorithms. However, few studies focus on integrating the modelling approach with the behavioural aspect, which could provide a more realistic performance evaluation of this decentralised logistics concept (Tapia et al., 2023). Also, most studies consider all parcel demand as potential crowdshipping demand, while prioritising outlier parcels, which are defined as the spatial outlier parcels in low-demand areas, for crowdshipping service could be more beneficial to LMD (Zhang & Cheah, 2023).

Therefore, this study aims at investigating the transport performance of crowdshipping services for outlier parcels in the context of last-mile delivery. The outlier parcels are defined as the ones with high environmental impacts and outsourcing them has the potential to save more van kilometres travelled and emissions in LMD than crowdshipping for regular parcel delivery.

This study starts with the definition rule for outlier parcels, following that, a crowdshipping delivery scenario regarding the supply strategies from the traveller and infrastructure aspects is proposed. An existing freight transport simulator is used and developed to simulate the delivery scenario and the matching process in an agent-based modelling approach. Different scenario settings are tested to see their impacts on the performance of crowdshipping service for outlier parcel delivery. Finally, the potential impacts of crowdshipping for outlier parcels with high environmental impacts in the context of last-mile delivery are discussed.

1.2. Research questions

This study focuses on crowdshipping service as an innovative solution that has the potential to solve the traffic problems in last-mile delivery, and prioritizes the high-environmental-impact parcels as the potential demand of this service to test its potential. Thus the main research question is formulated as below:

To what extent does crowdshipping service for outlier parcel delivery affect the transport performance of last-mile deliveries?

To answer the main research question sequentially and systematically, four sub-research questions are formulated as below:

1. *What definition rule(s) can be formulated for identifying outlier parcels?*
2. *What possible scenario(s) can be proposed to test the impacts of crowdshipping services for outlier parcel delivery?*
3. *How can the delivery scenarios of crowdshipping service for outlier parcels be simulated?*
4. *How do different crowdshipping service settings affect its performance in last-mile delivery?*

As the sequence of the sub-research questions shows, this project starts from the parcel demand side and then moves on to the crowdshipping supply side. With the analysis of both crowdshipping demand and supply sides, this project then focuses on the matching process of them. With the simulation of different crowdshipping service settings and assessing the performance of the simulation experiments, the main research question can therefore be answered.

1.3. Thesis approach

To answer the sub-research questions well, relevant methods are chosen for each of them, as shown in Table 1.1.

Table 1.1: Thesis approach corresponding to sub-research questions

Sub-research question	Methods	Chapter
1. What decision rules can be formulated for identifying outlier parcels?	Literature review, conceptualizing	Methodology
2. What are the possible scenarios to test the impact of crowdshipping service for outlier parcel delivery?		Methodology
3. How can the delivery scenarios of crowdshipping service for outlier parcels be simulated?	Agent-based modelling	Implementation
4. How do different crowdshipping service settings affect its performance in last-mile delivery?	Simulation	Simulation & analysis

For the first sub-research question, a combination of literature review and conceptualizing is used to formulate the definition rule for identifying outlier parcels. The second sub-research question is answered mainly based on conceptualizing the possible and sustainable delivery scenario of crowdshipping service, with regard to the specific contexts in the study area. The third sub-research question is answered by using and developing an existing agent-based model, which simulates the logistical decision-making of both LSPs and OCs, as well as the matching process of parcel demand and OCs. The final sub-research question is answered by running simulation experiments and analysing the simulation results with regard to the transport performance indicators.

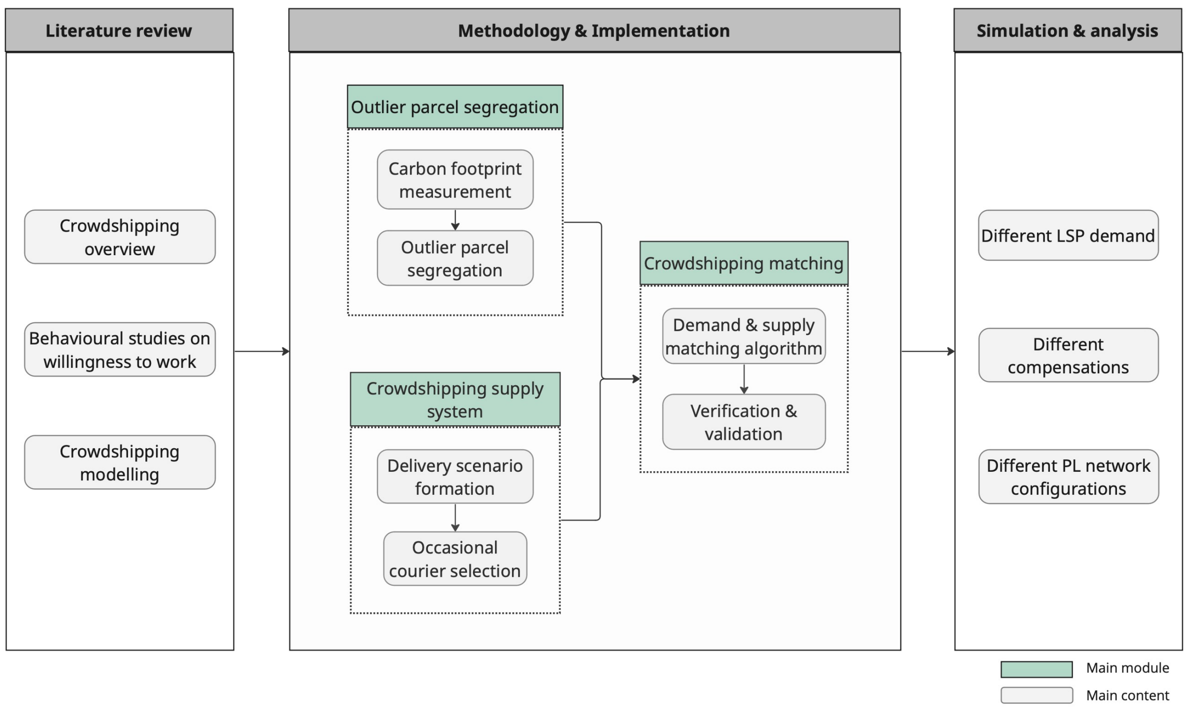


Figure 1.1: Thesis approach

Figure 1.1 shows an overview of the structure and methodology of this study. To begin with, the overview of the crowdshipping services, the behavioural studies on the traveller's willingness to work as occasional couriers for the service, and the scenarios and corresponding modelling methods proposed in the literature are reviewed.

In the methodology and implementation parts, three modules together form the overall methodology of this study, namely outlier parcel segregation, crowdshipping supply system, and crowdshipping matching. These three main modules focus respectively on the demand side, the supply side and the matching of demand and supply. The Outlier parcel segregation module focuses on the definition and the segregation process of outlier parcels, and it also distinguishes different LSPs in the segregation to align with real-life operations.

The Crowdshipping supply system module is mainly about proposing the delivery scenario from the service supply side. This module starts with a selection of suitable occasional courier transport mode and suitable alternative infrastructure solution to facilitate the sustainable operation of the crowdshipping service. Following that, the detailed design and implementation of the infrastructure network are elaborated concerning the possible crowdshipping service settings.

The crowdshipping supply system also includes the selection of potential OCs. Each individual's travel utility incorporating crowdshipping service is calculated, and the compensation level plays a key role in determining whether an individual is willing to work as an OC or not.

The third module is about the matching process of outlier parcels with OCs and the crowdshipping supply network, where matching criteria incorporating both demand and supply conditions are proposed.

With the methodology developed, the simulation tests the impacts of one demand variable and two supply variables on the transport performance of crowdshipping service for outlier parcel delivery, which provides the answers to the main research question.

1.4. Thesis scope

The Hague is chosen as the study area of this study. The Hague is the third largest city in the Netherlands and is one of the most highly urbanised and dense areas in the country, where there are more potential demand and supply for crowdshipping service and the critical mass is more likely to be reached for the success of this service. Therefore, investigating the performance of this innovative city logistics concept in The Hague would provide useful insights into its potential impacts.

1.5. Thesis outline

The remainder of this thesis is organized as follows: Chapter 2 presents a literature review of the state-of-art knowledge about crowdshipping services and the academic contribution of this study. Next, chapter 3 describes the methods used in each module of this project. Following that, chapter 4 entails the implementation results of the conceptualised methods in each module, as well as the verification and validation of the methods. Chapter 5 synthesizes the three modules and analyses the simulation results of the proposed crowdshipping delivery scenarios. Finally, chapter 6 concludes this thesis by presenting the answers to the research questions and discussing the recommendations and limitations of this project.

2
Literature review

This chapter presents the state-of-art knowledge about crowdshipping service and the research gaps will be identified. First, a general overview of the crowdshipping service including the stakeholders, opportunities and challenges is presented. Second, as this study wants to incorporate individual decision-making in the matching of parcel demand and traveller supply, the behaviour studies are reviewed to gain more knowledge on traveller's willingness to work as occasional couriers. Next, a systematic review of different scenario settings and modelling methods of crowdshipping services are described, as this study uses an agent-based modelling approach to simulate the service. Finally, this chapter concludes with how this project could contribute to this field.

2.1. Crowdshipping overview

According to the definition by Mehmann, Frehe, and Teuteberg (2015), crowdshipping is the "outsourcing of logistics services to a mass of actors." The idea of crowdshipping relates to the concept of the Physical Internet, which envisions smart interconnected logistics where physical products move seamlessly through distributed multi-segment intermodal transportation networks (Rougès & Montreuil, 2014). The potential benefits of this novel logistics concept include: utilizing excess transportation capacity of current passenger trips to improve the transport system efficiency, reducing the transport externalities caused by last-mile delivery (Rai, Verlinde, Merckx, & Macharis, 2017), helping logistics service providers reduce delivery costs, promoting social collaboration (Pourrahmani & Jaller, 2021), increase customers' accessibility to new products and offer faster delivery speed for customers (Rougès & Montreuil, 2014).

One promising field of crowdshipping service is food and retailers, where in-store customers can be employed as occasional couriers to provide same-day delivery to online customers (Le & Ukkusuri, 2019). Large retailers such as Walmart had launched two pilot projects respectively in 2013 and 2017 to ask in-store customers to deliver online ordered packages (Pourrahmani & Jaller, 2021). Similarly, Amazon initiated Amazon Flex service in 2015 which comprises occasional drivers to handle its one-and-2h deliveries (Flex, 2015). DHL, the large logistics company, also launched its DHL MyWays platform to involve local residents in its last-mile deliveries in Stockholm in 2013, which ended at the end of 2013 (DHL, 2013). There are also tech start-ups such as Deliv (2012-2020) and Shyp (2013-2018) providing same-day delivery service based on crowdsourced couriers (Pourrahmani & Jaller, 2021).

Besides, Paloheimo, Lettenmeier, and Waris (2016) conducted a pioneering case study of using crowdshipping service for library deliveries in Finland and found that existing library deliveries can be successfully crowdshipped. Their results showed that each crowdshipped delivery reduces an average of 1.6 km driven by car, despite 80 per cent of the deliveries being made within less than a 5 km distance.

There are several share and stakeholders involved in the business model of crowdshipping service, namely service/platform providers, senders/commissioners, occasional couriers/ occasional couriers, receivers, conventional logistics service providers and administrative authority. Rai et al. (2017) analysed 18 characteristics of different stakeholders and concluded that the three characteristics that affect economic, social and environmental sustainability are: third-party involvement, crowd motivation and modal choice. Similarly, Carbone, Rouquet, and Roussat (2017) conceptualised the crowd as a co-creator of logistics value in crowdshipping service by analysing 57 crowd logistics initiatives around the world. According to Pourrahmani and Jaller (2021), by reviewing the operation characteristics of both state-of-practice and state-of-art knowledge of crowdshipping service, they identified four core factors that differentiate services: platform (service) type, delivery type, delivery mode, and pricing strategy. For the platform type or business models, three major distinctions identified by Rougès and Montreuil (2014) are: efficiency versus human, trust versus control and business versus community.

Empirically, A. Ermagun and Stathopoulos (2020) analysed the empirical data of 2 years of operation from a real crowdshipping service in the U.S. and their results showed a significant variation in the performance of urban and suburban shipping context, and the different stages of delivery. They found that a higher supply of potential drivers in urban areas leads to a higher probability of securing shipment bids, and of successful deliveries. Buldeo Rai, Verlinde, and Macharis (2018) analysed the environmental impacts of crowdshipping service based on data from an operational crowd logistics platform in Belgium. Their results show that the current platform usage results in higher external transport costs and thus a higher environmental impact, when compared to traditional parcel delivery, because of a high share of dedicated trips. They pointed out the critical role the platform provider played in adjusting their operations to steer the effective vehicle use of the crowd. They also suggested the development of crowdshipping service in more rural areas could achieve larger cost and emission savings than in dense urban areas, as the less dense demand makes it more competitive to traditional LSPs, which have a major advantage of consolidating parcels in dense urban areas.

To conclude, this section reviews the opportunities and challenges of crowdshipping service and one of the most important factors that affect its potential performance is crowd motivation.

2.2. Behavioral studies on traveller's willingness to work (WtW)

To achieve the promising benefits of this novel mobility idea, much literature points out the key is to achieve a critical mass from the traveller (Rougès & Montreuil, 2014). From this perspective, the investigation of the traveller's willingness to work from a behavioural aspect is the main research topic. Le and Ukkusuri (2019) carried out a stated preference survey in the U.S. to analyse the traveller's willingness to work as crowdshipping couriers. About 80% of the respondents are willing to work as crowdshipping couriers and their clustering results showed that people with cars, children, full-time jobs with lower incomes, or part-time jobs are more likely to be occasional couriers and people are more likely to work during their commutes or free time. V. Gatta, Marcucci, Nigro, and Serafini (2019) conducted a stated preference survey in the city of Rome to identify the most important features of choice of acting as an occasional courier. They proposed a hypothetical scenario where small packages can be picked up/dropped off in Automated Parcel Lockers (APLs) located either inside metro stations or in their surroundings. Their results showed that APLs location is the most relevant feature even more important than remuneration. Fessler, Thorhauge, Mabit, and Haustein (2022) set up a stated choice survey on public transport passengers' willingness to work in the Greater Copenhagen Area. Their results indicated that young(er) individuals, students and (to a lesser extent) employed and self-employed individuals are more likely to participate in crowdshipping. Compensation level is the most direct attribute for willingness to work and is more sensitive among different age and occupation groups than different income groups. Also, a non-linear relationship between compensation level and willingness to work is found. Other factors such as time, size and weight of parcels are negatively associated with the willingness to work. The willingness to work on time is found to be around 0.43 euro/min, which is fairly close to the value of waiting time for public transport passengers. Cebeci, Tapia, Nadi, de Bok, and Tavasszy (2023) conducted a SP survey on travellers' WtW in The Netherlands, with two distinguished delivery trip types: newly generated delivery trip and the existing trip. Their results showed that the low-income group are more likely to participate and the value of time for the low-income group is 14.43 euro/h for newly generated trips and 38.57 for existing trips.

This section reviews the factors affecting the traveller's willingness to work for crowdshipping services. Compensation level, the most dominant factor, together with the location of parcel lockers and other sociodemographic characteristics, affect the probability of being an occasional courier.

2.3. Modelling of crowdshipping

The majority of literature about crowdshipping modelling focuses on the operation level, using either optimization or simulation models to evaluate its performance. Research from both methods is reviewed and the focus is on the scenario formulation modelling method and impact assessment.

Agent-based simulation model (ABM) is commonly used in the simulation of crowdshipping services. The reason why ABM is suitable to model crowdshipping service is because of its capability of modelling the interactions as well as behaviours of agents to understand how various structures, institutions, and patterns emerge as a result (Macal, 2016). Crowdshipping has many stakeholders and they interact in multiple ways, making it fit well in the setting of ABM.

Chen and Chankov (2017) built an agent-based simulation model and studied two parameters, maximum detour time accepted by crowd couriers and crowdshipping supply/demand ratio. The parcel is matched if the detour time is below the threshold. They found that a high supply/demand ratio enables the crowd to achieve high service level with very little time spent on detour, which is in line with the ”critical mass” proposed by Rougès and Montreuil (2014). Simoni, Marcucci, Gatta, and Claudel (2020) adopted a hybrid dynamic traffic simulation that combines macroscopic traffic features such as queue spill backs with microscopic delivery features such as delivery vehicle routes. Their case study in Rome indicated that crowdshipped deliveries by car have generally higher negative traffic impacts than corresponding deliveries by public transit. And the crowdshipping externalities can be reduced significantly by some operation strategies such as limiting the deviations of occasional couriers from the original trips, providing adequate parking options, and incentivizing off-peak deliveries. Dötterl, Bruns, Dunkel, and Ossowski (2020) built an agent-based simulation model from the occasional couriers' perspective, they modelled the agent's decision based on shipping plans, which can be easily adapted to different acceptance strategies from the crowd workers such as maximum detour accepted, minimum compensation required. In their model, agents (crowd workers) choose the shipping plan with the minimum necessary travel distance and the validation results showed that their model can plausibly represent the real-world operations of crowdshipping service. Tapia et al. (2023) built an agent-based model that disaggregately matches parcel and travellers based on travellers' travel utility function. The utility for potential bringers is based on travel costs with compensation, travel time with detour time and the simulation of error terms. The one with maximum gains in utility between the trip with the delivery task and the original trip is matched with this parcel. Car and bike are considered in their model and the results showed that crowdshipping service could result in increased CO_2 emissions and total vehicle distances travelled. This could be explained as simulation models consider more behavioural aspects from occasional couriers and thus the decisions are generated from the individual's perspective instead of the urban transport system's perspective.

From the perspective of operations research, a variety of studies has been conducted to study how to assign delivery jobs to both van drivers and occasional couriers, and generally four main decisions are considered in their research: matching, routing, driver scheduling, and compensation (Alnaggar, Gzara, & Bookbinder, 2021). As this project focuses more on the occasional couriers' side, operations research about crowdshipping service from the platform and logistical service provider's perspectives are less reviewed due to low relevance. Literature with distinguished scenario settings is the main focus as it can provide insights for feasible scenario formulations.

Ballare and Lin (2020) proposed a crowdshipping scenario of micro hubs with crowdshipping service. The main part of LMD from depot to zonal micro hubs is performed by conventional vans and the intra-zonal part of LMD is performed by crowdshipping. Their results showed that the combined scenario is able to reduce average VKT and average total daily operating costs. And its performance increases with the increase in the network size of micro hubs, which indicates that such a scenario is more suitable for cities with medium to high customer densities. Similarly, Kafle, Zou, and Lin (2017) proposed a crowdshipping scenario which crowdsourced cyclists and pedestrians perform the last leg of LMD. Their system involves the truck carrier posting delivery jobs to the crowd, receiving bids, selecting bids and planning truck routes of relay points. Some parcel demands are delivered by occasional couriers while others are not. Their results showed that total cost and truck VKTs can be significantly reduced compared to pure-truck delivery and over half of the customers will be served by occasional couriers.

In addition to private transport modes available for crowdshipping, some operations studies consider public transport as the main mode for its sustainable potential and most of them consider a parcel locker network as the transfer points between the delivery van and occasional couriers, as parcel lockers have the potential of addressing the failed delivery problem in LMD as well as promoting the integration of passenger and freight transport (Oliveira et al., 2022).

Kızıl and Yıldız (2023) proposed a scenario in which public transit with automated service points (parcel lockers) act as a backbone network, and crowdshipping performs the first and last leg of LMD with the backup option of zero-emission vehicles. Their case study results in Istanbul indicated that with reasonable occasional courier participation (less than 3% of the rail system passengers in the city), the suggested system can achieve same-day delivery for more than 96% of the demand that comes throughout the day with an average delivery time under 2.5 hours. Zhang, Cheah, and Courcoubetis (2023) considered public transport users as potential occasional couriers and parcel lockers act as transfer points between conventional couriers and public transport based occasional couriers located at metro stations. They modelled the fraction of available occasional couriers among all public bus passengers as a probability function with regard to different compensation levels. And the matching of parcels and occasional couriers is based on the closeness of both origin and destination. Unmatched parcels will be transported to customers by delivery vans and the objective in their model is to assign a sequence of visiting points to each van with minimum total working time. Their model results showed that crowdshipping can help reduce the fleet VKT by 15% and reduce the fleet size by 20% to 29.3%. The reduction in VKT is more relevant to the increase in the number of parcel lockers than the compensation level. Following the same idea, Zhang and Cheah (2023) then considered prioritising spatial outlier parcels in crowdshipping as removing a parcel from low-demand areas is more cost-saving than removing a parcel in more dense areas, which is in line with one of the major problems facing LMD identified by Gevaers et al. (2011): the level of consumer density not high enough to operate at an acceptable level of costs. The results of prioritizing outlier parcels for crowdshipping service showed that up to 11% of parcels can potentially be redirected to occasional couriers. Comparing the results for all parcel demand from the same model, the reduction in VKT becomes larger, increasing from 15% to 19%. Their results also indicated that the reduction in delivery cost is 1.45 S$ per parcel, which is larger than the average public trip fare of 1.34 S$ in Singapore. This indicates that crowdshipping might be attractive as compensation to public transport users.

In conclusion, this section systematically reviews different crowdshipping scenarios modelled by simulation or optimization method and their model results. The scenarios generally differ in the part(s) of LMD that is outsourced to crowdshipping service, the main transport modes of crowdshipping service and the matching procedures. Overall the results show that crowdshipping service could have a positive impact on solving the environmental problems in LMD and crowdshipping service with occasional couriers as public transport commuters could have a larger savings in the operation costs. Regarding the modelling methods, some negative transport impacts are observed in simulation studies as they consider more behavioural aspects, while most operation optimization studies reported positive performance.

In addition, while almost all studies reviewed in this section use all parcels as potential demand for crowdshipping, there is only one study pointing out and justifying the effectiveness of prioritizing outlier parcels, which are defined as spatial outlier parcels in low-demand areas, for crowdshipping service, which could save more delivery vehicle kilometres travelled and associated carbon dioxide emissions than a regular crowdshipping service, making it a promising research direction and worth further and deeper understanding.

2.4. The contribution of this study

In general, both the potentially positive impacts and negative impacts of crowdshipping services have been acknowledged in both real-life practice and academic research. Uncertainties persist regarding how and to what extent crowdshipping services could be implemented, as well as how to ensure their potential positive impacts.

While most studies take all parcel demand as potential demand for crowdshipping service, a notable gap exists in understanding which category of parcels is most suitable for crowdshipping, to achieve positive environmental impacts and efficiency gains.

In addition, while some studies have been carried out on studying the traveller's willingness to work as occasional couriers, others focus on designing and evaluating the operation strategies of crowdshipping service from the transport system's perspective, few studies integrate the individual's behaviours and decision making into the design and modelling of crowdshipping operation strategy, which could provide more realistic results on its potential impacts.

Therefore, this study will extend our knowledge of the transport and environmental impacts of crowdshipping service for outlier parcel delivery in last-mile delivery, by applying the environmental impacts as a definition rule for outlier parcels and employing behaviourally consistent decision rules in an agent-based simulation model.

3
Methodology

This chapter presents the methodology proposed for each of the three modules as shown in Figure 1.1. The three modules respectively focus on the demand side, the supply side and the matching of demand and supply. From the demand side, the outlier parcels are defined from the environmental perspective the the parcels with high environmental impacts are segregated as outlier parcels. From the supply side, a public transport-based crowdshipping supply system with a parcel locker network is proposed. As for the matching of demand and supply, the decision making of both logistics service providers and travellers are taken into consideration.

3.1. Outlier parcel segregation

This section presents the answer to the first sub-research question: *What definition rule can be formulated for identifying outlier parcels?* The section starts by motivating the choice of selecting the environmental factor as the base for the decision rule and then presents the formation and measurement method of the decision rule.

3.1.1. Environmental factor and carbon footprint

As the last-mile delivery sector grapples with the challenge of inefficiency, five factors that define the efficiency of LMD identified by Gevaers et al. (2011) are service levels, security & type of delivery, geographical area & market penetration, fleet & technology, and environment. Among these they described the environment as a characteristic/ determinant of innovations in the last mile, as consumers become more aware of the environmental issues of logistics and they expect more environmentally friendly delivery solutions without compromising the service level. As crowdshipping service is an innovative solution in last-mile delivery with sustainability potentials, especially in mitigating the environmental externalities in LMD, this project, therefore, takes the environmental factor as the definition rule for identifying the outlier parcels. By outsourcing the parcels with larger environmental externalities, the potential environmental and transport benefits of crowdshipping service can be examined.

The focus on the environmental factor leads to the widely accepted concept of the carbon footprint, a key metric in addressing climate change responsibilities. In the context of last-mile delivery, the measurement of each parcel's carbon footprint becomes a pivotal criterion for identifying outlier parcels.

3.1.2. Delivery effort-based carbon footprint measurement

In the context of last-mile delivery, the carbon footprint of each parcel is intricately linked with the delivery effort exerted by the logistics service providers. The methodology employed defines outlier parcels as those requiring more delivery effort, thereby having a higher carbon footprint and environmental impact. In other words, the measurement of carbon footprint in this study is a function of the delivery effort in LMD.

The calculation method of carbon footprint in logistics from Connekt (2021) is used in this study, as this method allocates the total emissions fairly to each parcel. This method is performed on a delivery tour basis, thus it is executed for every delivery tour of every delivery vehicle from the delivery schedule. And as the delivery schedule is on a zonal level, i.e., the delivery van delivers a certain number of parcels to a zone, thus it is assumed that all parcels have uniform weights and they are evenly distributed within the zone.

Figure 3.1 shows the visualisation of this method. The process begins by quantifying the total carbon footprint of a delivery tour. This total tour carbon footprint is then allocated to each delivery zone based on zonal weighting factors. And finally, the zonal carbon footprint is allocated to individual parcels equally.

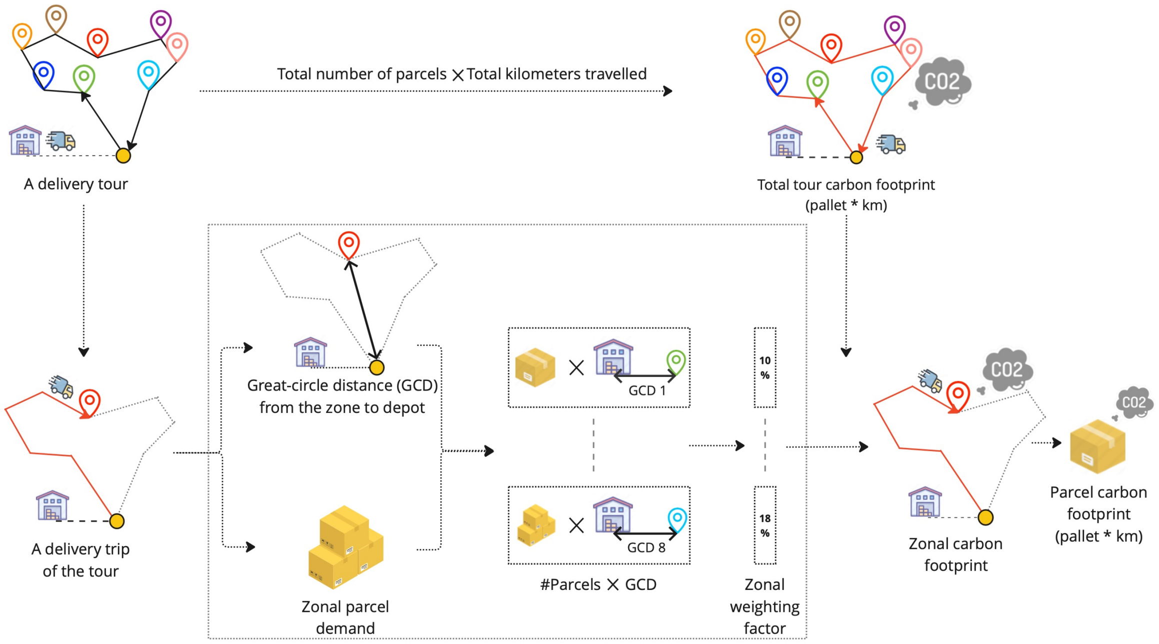


Figure 3.1: Visualisation of delivery effort-based carbon footprint measurement

The starting point of this delivery effort-based carbon footprint measurement method is the measurement of the total carbon footprint of the delivery tour, which is measured as the total van kilometres travelled (VKT) times the total number of parcels of this delivery tour, as shown in Equation 3.1. Thus by definition, the unit of carbon footprint is *pallet*km*.

$$TourCarbonFootprint = VKT \times \#Parcels \tag{3.1}$$

A delivery tour consists of multiple delivery trips and each trip visits a zone, where a certain amount of parcels are delivered to this zone. To allocate the tour carbon footprint to each zone, the weighting factor for each zone is calculated. Two additional measurements of delivery effort are considered for the calculation of the zonal weighting factor, which are the great-circle distance (GCD) between the zone and the parcel depot, and the zonal parcel demand. The advantage of selecting the GCD rather than the kilometres travelled from the depot to the zone as a measurement of delivery effort is that the GCD is not determined by the route driven, thus avoiding too much carbon footprint being allocated to the later visited zones and ensuring a fair allocation.

Besides the GCD, the delivery effort of a delivery trip also considers the zonal parcel weight, to include the energy consumed by this weight in allocation. Note that as the weight information of each parcel is difficult to obtain and most of the parcel weights are similar, this method assumes that all parcels have the same weight and the number of parcels is therefore taken as the measurement of the parcel weights.

The zonal weighting factor (ZWF) is calculated for each zone and is defined as the product of the number of parcels in this zone (zone *i*) and the GCD from this zone *i* to the parcel depot, divided by the sum of this product for all zones that this delivery tour needs to visit. This indicates that the ZWF represents the percentage of the tour carbon footprint that is allocated to each zone, and the sum of all ZWFs of a delivery tour is thus equal to 1. Equation 3.2 shows the calculation of the zonal weighting factor for zone *i* in a total of *n* zones.

$$ZWF_i = \frac{\#Parcels_i \times km_i^{GCD}}{\sum_{i=1}^{n}(\#Parcels_i \times km_i^{GCD})} \tag{3.2}$$

where:

ZWF_i = Zone weighting factor for zone *i*
$\#Parcels_i$ = The parcel demand in zone *i*
km_i^{GCD} = The great-circle distance between the zone *i* and the depot

The calculated zonal weighting factor then allows the allocation of the total tour carbon footprint to each delivery trip/zone of the delivery tour. Equation 3.3 shows the allocation of the total tour carbon footprint to zone *i*.

$$ZonalCarbonFootprint_i = TourCarbonFootprint \times ZWF_i \tag{3.3}$$

The final step of the method is to allocate the zonal carbon footprint to each parcel in the zone. According to the assumption of the uniform parcel weight and the parcels are evenly distributed within the zone, the carbon footprint per parcel is therefore calculated as the zonal carbon footprint divided by the number of parcels in the zone. Equation 3.4 shows the carbon footprint calculation for each and every parcel in zone *i*. And as the allocation does not make changes to the unit of carbon footprint, thus the parcel carbon footprint has the unit of *pallet*km* as the tour carbon footprint.

$$ParcelCarbonFootprint = \frac{ZonalCarbonFootprint_i}{\#Parcels_i} \tag{3.4}$$

Overall, this approach indicates that the further the parcel is transported and the more capacity that is taken up, the greater the percentage of carbon footprint allocated to the parcel. This approach offers a practical and fair method for assessing the carbon footprint of individual parcels within a delivery tour (Connekt, 2021).

3.2. Crowdshipping supply system

This section presents the answer to the second sub-research question: *What are the possible scenarios to test the impact of crowdshipping service for outlier parcel delivery?* This section starts with the selection of suitable transport modes and infrastructure alternatives to facilitate the operation of crowdshipping service for occasional couriers. Following that, the delivery scenarios are formulated, and a detailed matching strategy and algorithm for the crowdshipping delivery scenario are elaborated.

3.2.1. Transport mode selection

As for the transport mode of the occasional couriers, three modes are mostly studied in the literature, namely private car, public transport and bicycle.

Private car is the most studied one, with the occasional courier as the driver or passenger. The benefits of deploying private cars include the potential of using the excess capacity of the vehicle, a large supply of private car users, and accessibility to most places. However, as mentioned in Chapter 2, results from both real-world practice and academic research show that a high share of dedicated trips exists because of the motivation for compensation fees, and this could lead to detours and thus generate more traffic externalities compared to traditional delivery service (Pourrahmani & Jaller, 2021). As this project focuses on investigating the potential environmental benefits of crowdshipping service, private car is excluded and more focus is given to sustainable transport modes.

Both public transport (PT) and bicycles are considered sustainable transport modes, with large potential to integrate passenger and freight transport (Valerio Gatta, Marcucci, Nigro, Patella, & Serafini, 2019). However, as the distance a bicycle can travel is limited, it is more suitable for short-distance and local travel. As the study area in this project is The Hague and the municipalities around it, which require some medium-to-long-distance delivery journey, PT can provide a larger pool of medium-to-long-distance travellers than bicycles, which is more aligned with the scope of this project. Therefore PT is considered the most suitable transport mode to perform the delivery tasks for outlier parcels and selected as the main transport mode of the crowdshipping supply system in this project. Potential occasional couriers are therefore focused on PT passengers.

To have a closer look into the PT passengers, figure 3.2 shows the modal split of passenger transport in The Netherlands, of which public transport takes up 8.2 % of the total passenger kilometres travelled. And within the public transport domain, about 3/4 are travelled by train, indicating that people travelled by train very frequently. This background information is further elaborated in the crowdshipping delivery scenario formulation.

3.2.2. Infrastructure alternative selection

As Carbone et al. (2017) pointed out, the growth of crowdshipping service is influenced by the perceived attractiveness of this service from the crowd, in terms of proximity, speed, flexibility and accessibility. This indicates the need to research the advancements in infrastructure to improve the service for occasional couriers. Automated parcel locker (PL), can act as transfer points to facilitate a smoother transition between conventional couriers and occasional couriers, between occasional couriers and end customers and between different occasional couriers in parcel relay crowdshipping scenarios (Kafle et al., 2017; Oliveira et al., 2022). On the other hand, PL can help bundle the parcels at one point and reduce the delivery effort of traditional couriers (Janjevic & Ndiaye, 2014).

According to V. Gatta et al. (2019), the location of PL is the most important factor affecting occasional couriers' willingness to work, even more important than compensation. Therefore, PL should be installed at major traveller demand locations to increase the attractiveness of crowdshipping service and thus obtain a larger potential supply of occasional couriers.

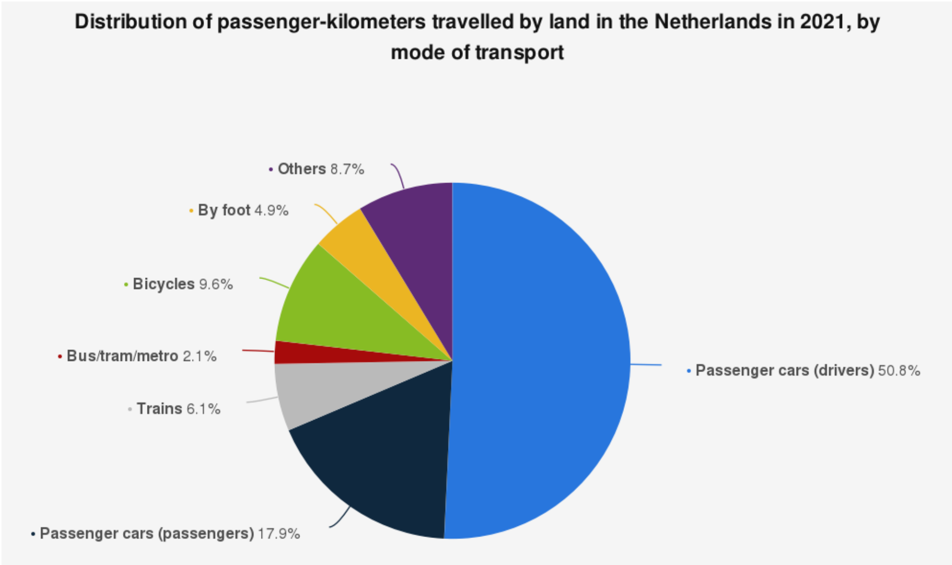


Figure 3.2: Netherlands: modal split of passenger transport on land 2021,Centraal Bureau voor de Statistiek (2023)

3.2.3. Crowdshipping delivery scenario

With the selection of the two key elements of a crowdshipping supply network, the delivery scenario can therefore be formulated. As mentioned in Section 3.2.1, the train is a very frequently used PT mode in The Netherlands. The train stations have a large traveller demand, and with the parcel lockers being installed at the station, there is a high potential of matching parcels with train travellers as occasional couriers (OC). Figure 3.3 demonstrates how crowdshipping service would operate with parcel lockers at the train station and train as the main transport mode in the formulated crowdshipping delivery scenario.

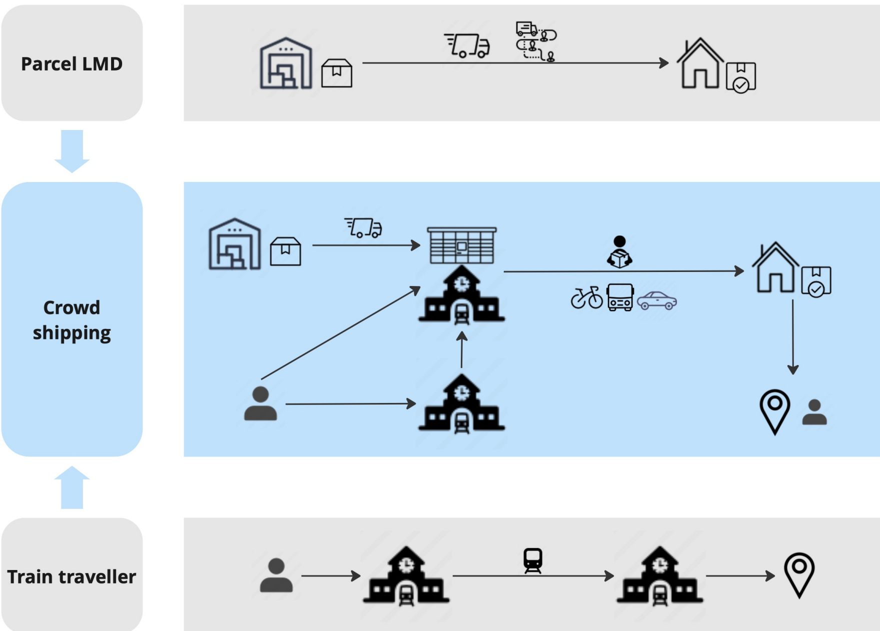


Figure 3.3: Visualisation of crowdshipping delivery scenario

The top grey block shows the current operation of Parcel LMD, where the parcels are delivered from the depot to the customer's final destinations by a delivery van following the delivery route. The bottom grey block shows the typical travel pattern of a train journey. The modes of the first and last leg are not limited. The middle blue block shows the formulated crowdshipping delivery scenario. Parcel lockers are installed at the selected train stations in the study area, and parcels that have been matched with OC are bundled and delivered to their corresponding parcel lockers by conventional couriers. Train travellers who are willing to work as OC pick up the parcel from the parcel locker located at their destination stations, make a detour to deliver it to its customer's final destination, and finally go to their destinations. The parcel lockers installed at the train stations act as the transhipment point between conventional couriers and OC.

There are a few important assumptions made in the delivery scenario:

1. Parcel lockers are installed at all selected train stations in the study area.
2. Train travellers as OC do not change their original origin and destination stations.
3. The matching of parcel and OC are performed before the departure of a delivery van and train traveller.
4. OC and parcel must be in the same destination zone to avoid too much detour by OC.
5. Each OC can only deliver one parcel in a delivery trip.
6. For full flexibility an OC can pick up a parcel at the station of either origin or destination.

3.2.4. Occasional courier supply

To implement the delivery scenario, a train traveller journey dataset with information about the passing stations is first needed. The method used to select train trips from all the PT trips and assign the train station to its origin and/or destination is mainly based on geographic proximity. The radius of the catchment area of the train station is assumed to be 1 km (El-Geneidy, Grimsrud, Wasfi, Tétreault, & Surprenant-Legault, 2014). PT Trips with origin and/or destination within a Euclidean distance of less than 1 km to any of the train stations are considered train trips, following that the closest station is assigned to the trip origin/destination.

If the trip destination is assigned to a train station, the following trips of this train trip are selected, where the delivery task of OC would take place. If the trip origin is assigned to a train station, then this PT trip is selected. The two types of trips are combined as the potential supply for OCs.

3.2.5. Occasional courier selection

With the station travellers as the potential supply for the crowdshipping service, the occasional courier selection module is used to determine whether or not a station traveller is willing to work as an occasional courier (OC) and select the potential OCs. This is done by comparing the value of time (VoT) that crowdshipping service could offer to the occasional courier's preferred VoT. The ones with VoT gains are then considered as potential OCs, and among all the potential OCs, the one with the highest VoT gains is selected as OC.

Traveller's pre-defined/preferred willingness to work as OC is obtained from the results of a recent stated preference (SP) experiment by Cebeci et al. (2023). This SP experiment is conducted in The Netherlands, and four operational attributes are included: number of parcels, extra travel time, delivery point, and remuneration. They made a distinction between planned trips and newly generated delivery trips. The results of their latent class choice model show that income appears to be an important factor determining traveller's willingness to work.

Table 3.1 below shows the VoT results from this SP experiment. Home-based by their definition is the newly generated delivery trip by an occasional courier, while commuted-based is delivering the parcel during the existing trips. The latter is in line with the scenario proposed by this project where OC delivers the parcel on their way to their destination, thus the two values on the right column are used as travellers' preference about VoT for them to work as OC. For the low-income group, 38.57 euros per hour is around 0.64 euros per minute.

	Home-based	Commute-based
Low income	14.43	38.57
High income	73.83	122.77

Table 3.1: VoT for travellers to work as OC (Cebeci, Tapia, Nadi, de Bok, & Tavasszy, 2023)

Figure 3.4 shows the flow diagram for selecting potential occasional couriers. The additional travel time for a train traveller consists of three components, namely pickup time, detour time and drop-off time. The pickup of an outlier parcel is very quick as the PL at the station can facilitate a smooth process.

The detour time is calculated as the detour distance divided by the detour speed. One of the matching criteria is that the traveller and the outlier parcel have the same destination zone, so the detour only happens within the destination zone. As the detailed coordinate information of the parcel destination is missing, an assumption about the detour distance is made. The detour distance is calculated as twice the intrazonal Manhattan distance. The latter is calculated as the Manhattan distance from the zone centroid to each vertex of the zone. The equation below shows how to calculate the Manhattan distance for any two points:

$$ManhattanDistance(point_1, point_2) = |x_1 - x_2| + |y_1 - y_2| \tag{3.5}$$

For each zone, a normal distribution of its intrazonal Manhattan distance is created, from which a random value is drawn to represent the detour distance for each pair of parcels and travellers. As this randomly drawn value is only from the centroid of the zone to one random location in the zone, thus this value is multiplied by 2 to represent the detour distance of the OC.

The drop-off time is when the OC delivers the parcel to its customer and is dependent on the OC's transport mode as different modes have different parking times. As the OC's delivery trip is either the last leg of a train journey or a public transport trip started at the train station, for the former case, the transport mode of the last leg is considered when calculating the drop-off time. The assumption made here is that for cycling and walking, the drop-off time is on average 1.5 min with a standard deviation of 1 minute, and for cars, the drop-off time is on average 3.5 min with a standard deviation of 1 minute, as research by Perboli and Rosano (2019) finds that delivery times by vans are around 4-5 minutes, which can be reduced to around 2 min by bicycles because of the reduced time associated with parking.

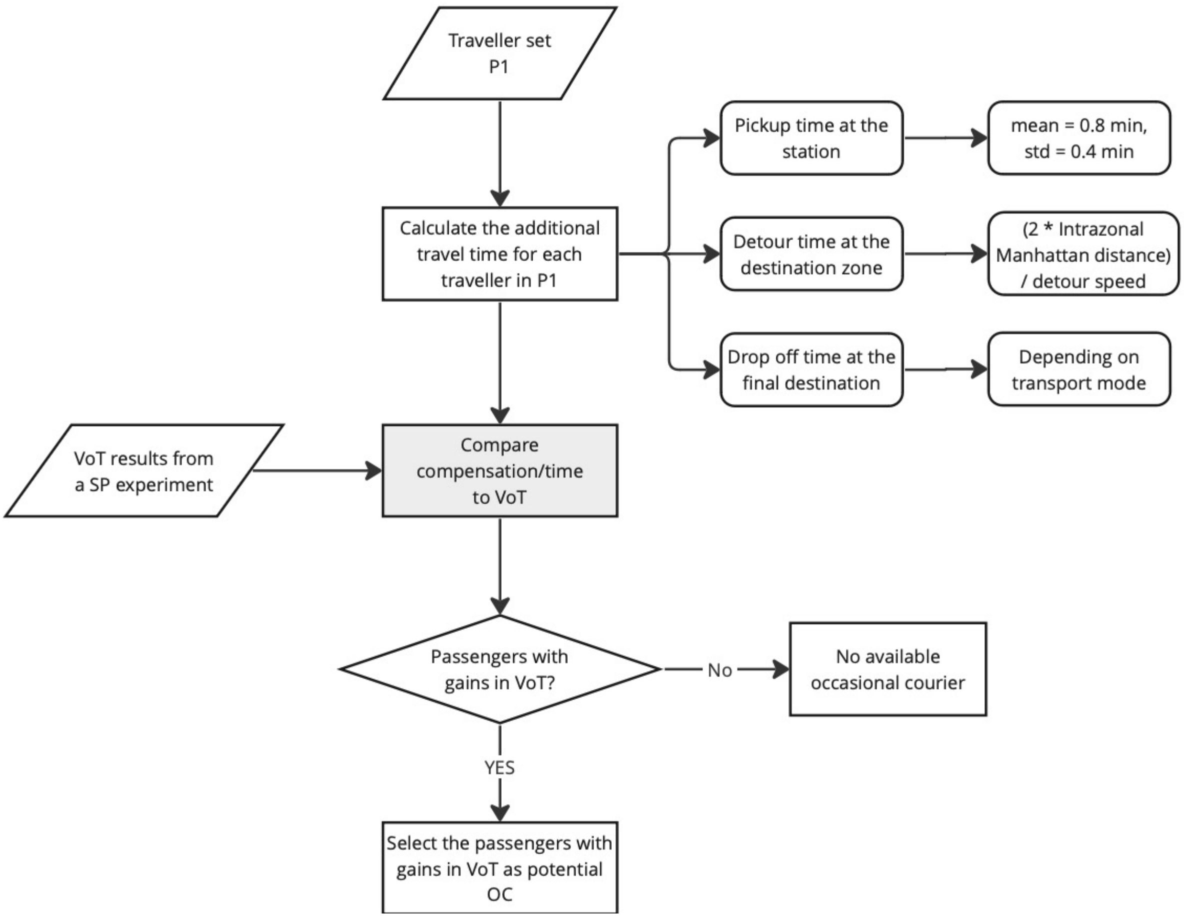


Figure 3.4: Flow diagram for selecting potential occasional couriers

3.3. Crowdshipping demand and supply matching

With both the outlier parcel demand and crowdshipping supply available, an algorithm for matching outlier parcel demand and a crowdshipping supply system is developed.

Figure 3.5 shows the flow diagram of the algorithm of matching outlier parcels with occasional couriers and parcel lockers.

The agent of the matching process is each outlier parcel. The matching algorithm starts from iterating through each parcel from the outlier parcel data set, and searches for train travellers with the same final destination zone as the outlier parcel. If the train travellers are found, they are stored in the traveller set P1, and the stations they pass through are stored as well for further allocation. If no available travellers are found, this parcel is moved back to the conventional delivery set.

Then the algorithm calls the Occasional courier selection module in Section 3.2.5 to select the potential OCs from all the travellers in P1 and sort them with VoT gains.

Following that, the algorithm allocates the parcel to the parcel lockers located at the train stations. The selection of PL is based on the geographic proximity of the train station to the depot of this parcel; it begins with the train station closest to the depot from all the stations that travellers in P1 pass through and checks the remaining PL capacity. If the PL is full, it iterates to further train stations from the available train stations. Once available PL is found, the allocation stops and allocates the parcel to the parcel locker located at this station. A 3-km detour limit is set to the allocation. The distance from the depot to the station is compared with the original delivery distance of this parcel, a maximum of 3 km detour is allowed in the crowdshipping service as the PL provides an improvement of consolidation compared to the original point-to-point delivery.

If no available PL is found for any of the stations, this parcel is removed from the crowdshipping matching process and back to the conventional delivery parcel set. If available PL with remaining capacity and is under the detour limit is found, the traveller in P1 who travels through this station and has the highest gains in VoT is matched with this parcel. Finally, the destination of the matched parcel is changed to the allocated station and this traveller is removed from the traveller set as the project assumes that each OC can only carry one parcel.

3.4. Concluding remarks

In this chapter, the methods in each of the three modules shown in Figure 1.1 are elaborated.

First the delivery effort-based carbon footprint measurement method is described in Section 3.1. The method is able to measure the carbon footprint in a simple way and allocate the tour carbon footprint fairly to each parcel. The parcels with high environmental impacts are defined as outlier parcels.

Second, a public transport-based crowdshipping delivery scenario with parcel lockers installed at the train stations as the transfer points is proposed in the first three subsections of Section 3.2. The proposed delivery scenario considers the sustainability potential and the efficiency of the crowdshipping service, as well as real-world situations.

Following that, the selection of occasional couriers for the crowdshipping supply system is detailed in the last two subsections of Section 3.2. The selection of potential occasional couriers from the train travellers is based on the value of time provided by the crowdshipping service as a ratio of compensation and additional travel time, and it is compared to the value of time results from the stated preference experiment in the literature to determine the willingness to work as an occasional courier for the crowdshipping service.

With both the outlier parcel demand and crowdshipping supply system available, the matching algorithm of crowdshipping demand and supply is presented in Section 3.3. The matching algorithm incorporated the decision-making of both the logistics service providers and the occasional couriers, as well as the sustainable considerations for the crowdshipping service.

In the next chapter, the implementations of these methods will be elaborated.

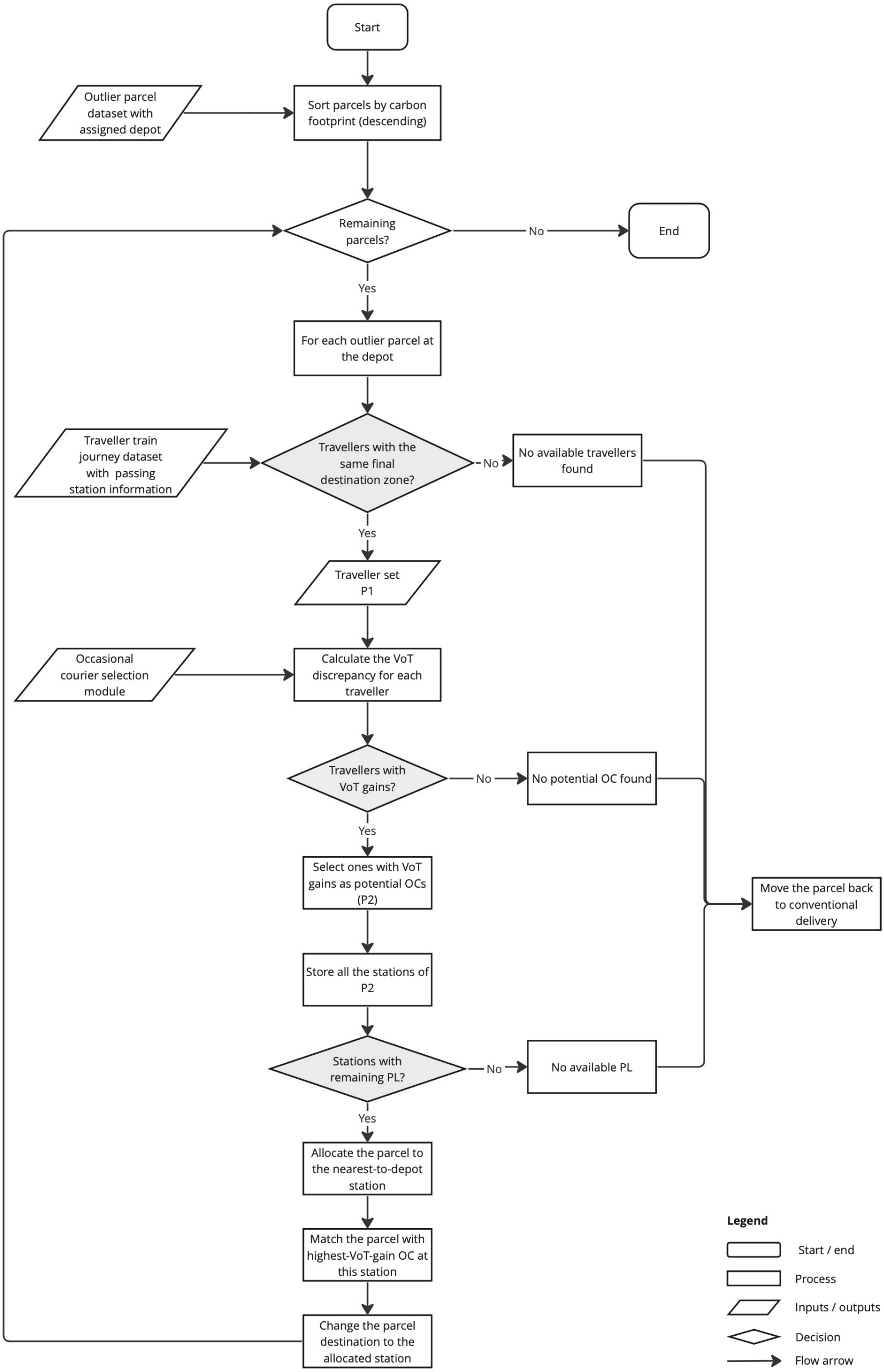


Figure 3.5: Flow diagram for matching outlier parcels with OC and PL

4
Implementation

This chapter presents the implementation results of the methods described in Chapter 3, for each of the three modules in Figure 1.1. First, the data of crowdshipping demand and supply that will be used in this project are introduced. Then, for the Outlier parcel segregation module, the segregation process and results regarding different LSPs are presented and analysed. Following that, the implementation results of the Crowdshipping supply system are presented, which include the distribution of train trips and the selection results of potential occasional couriers (OC). Finally, with the implementation of both crowdshipping demand and supply, the Crowdshipping demand and supply matching module is implemented, and the verification and validation of the matching module are performed.

4.1. Data sources

4.1.1. Operation data of current last-mile delivery

To use the method mentioned in Chapter 3.1 to segregate the outlier parcels, the operation data of the current LMD are needed. This project uses a multi-agent simulator for freight transport, namely MASS-GT, to obtain the operation data of the current LMD. It is a shipment-based micro-simulation framework that builds upon logistics decision-making and empirical freight transport data. It has been used to analyse different freight transport use cases such as the effect of zero-emission zones in Rotterdam (de Bok, Tavasszy, & Sebastiaan Thoen, 2022). Several modules work sequentially to simulate the whole process of logistics operation, for example, shipment & parcel demand module, scheduling module and network module, in this way this model can manage the complexity of real-world logistic chain(de Bok & Tavasszy, 2018).

This project uses the Parcel Demand module, Parcel Market module and Parcel Scheduling module of MASS-GT to sequentially simulate the processes of last-mile delivery. The Parcel Demand module simulates the generation of parcel demand based on sociodemographic data such as household data and empirical logistics data such as average parcel demand volumes and market share of all logistics carriers. The Parcel Market module simulates the corporations of different carriers and detailed segments of LMD such as pickup, consolidation and delivery trips. And Parcel Scheduling module simulates the scheduling of delivery vehicles from the depot to the end customers based on the real transport network configurations and vehicle capacity. The final output from the Parcel Scheduling module is a detailed sheet of all itineraries of the delivery vehicles, including the number of parcels, travel distance and time of every delivery trip.

As mentioned in Chapter 1.4, the study area of this project is The Hague. The duration of the simulation is set to be one day (24 hours). With the simulation results from the three modules of MASS-GT, the parcel demand data with corresponding delivery schedule data are obtained, which are the input data for the Outlier parcel segregation module in this project.

4.1.2. Passenger trip data

As this project focuses on using the existing passenger trips for crowdshipping, passenger trip data is needed for selecting the potential occasional courier based on their current trip information. ALBATROSS data is used in this project. ALBATROSS data contains the simulated journey and trip information of each traveller. A journey consists of multiple sequential trips, and detailed information such as the transport mode, the travel time and the travel purpose of each trip leg for each traveller are included, which provides very detailed travel information for each traveller. For this project, the data included all the journeys that travel to, from and within The Hague, providing a complete journey set of the study area.

4.2. Outlier parcel segregation

This section presents the implementation process and results of outlier parcel segregation. First, an overview of the parcel demand and the parcel carbon footprint are presented, and then the detailed process of segregating the parcels with high carbon footprint from all parcels is described and the results are analysed.

4.2.1. Overview of all parcel demand

With the results from the freight transport simulator, a 24-hour detailed delivery schedule of all LSPs to satisfy the consumer parcel demand in the study area is obtained. Figure 4.1 shows a quick view of the delivery schedule, where information about LSPs, tours, trip sequence, number of parcels and trip distance are included. However, information such as the precise parcel destination, parcel size and weight, and the consumer's expected time window for delivery is unknown.

	TourType	CEP	Depot_ID	Tour_ID	Trip_ID	Unique_ID	O_zone	D_zone	N_parcels	Traveltime	TourDepTime	TripDepTime	TripEndTime	Type	TourDist	VehType	OrigType	DestType
0	0	PostNL	1	1.0_41	1.0_41_0	1.0_41_0_0	2668	2341	180	0.186667	8.720324	8.720	0.0	Delivery	5.607	Van	Depot	HH
1	0	PostNL	1	1.0_41	1.0_41_1	1.0_41_1_0	2341	2668	0	0.193611	8.720324	14.907	0.0	Delivery	6.099	Van	Depot	HH
2	0	PostNL	1	1.0_42	1.0_42_0	1.0_42_0_0	2668	2375	180	0.189167	0.302333	0.302	0.0	Delivery	5.383	Van	Depot	HH
3	0	PostNL	1	1.0_42	1.0_42_1	1.0_42_1_0	2375	2668	0	0.196667	0.302333	6.491	0.0	Delivery	5.371	Van	Depot	HH
4	0	PostNL	1	1.0_43	1.0_43_0	1.0_43_0_0	2668	965	13	0.218611	7.092339	7.092	0.0	Delivery	12.012	Van	Depot	HH
5	0	PostNL	1	1.0_43	1.0_43_1	1.0_43_1_0	965	966	31	0.036944	7.092339	7.744	0.0	Delivery	0.690	Van	Depot	HH
6	0	PostNL	1	1.0_43	1.0_43_2	1.0_43_2_0	966	964	27	0.039444	7.092339	8.815	0.0	Delivery	1.766	Van	Depot	HH
7	0	PostNL	1	1.0_43	1.0_43_3	1.0_43_3_0	964	967	6	0.030278	7.092339	9.754	0.0	Delivery	1.868	Van	Depot	HH
8	0	PostNL	1	1.0_43	1.0_43_4	1.0_43_4_0	967	968	9	0.036944	7.092339	9.984	0.0	Delivery	1.376	Van	Depot	HH
9	0	PostNL	1	1.0_43	1.0_43_5	1.0_43_5_0	968	969	12	0.072778	7.092339	10.321	0.0	Delivery	0.723	Van	Depot	HH

Figure 4.1: Illustration of three simulated delivery schedules for PostNL in MASS-GT

The delivery schedule contains both pickup and delivery trips, which respectively take up 3.7% and 96.3% of the total trips. It also incorporates cargo bikes to deliver local-to-local parcels, which take up around 4% of the total demand. From the perspective of logistics service providers, the potential benefits of outsourcing the delivery trips would be more beneficial, as it accounts for the majority of the delivery costs. Thus pickup trips are filtered out. And since this project focuses on investigating the environmental impacts of crowdshipping service, delivery trips with cargo bikes are excluded as they are sufficiently sustainable.

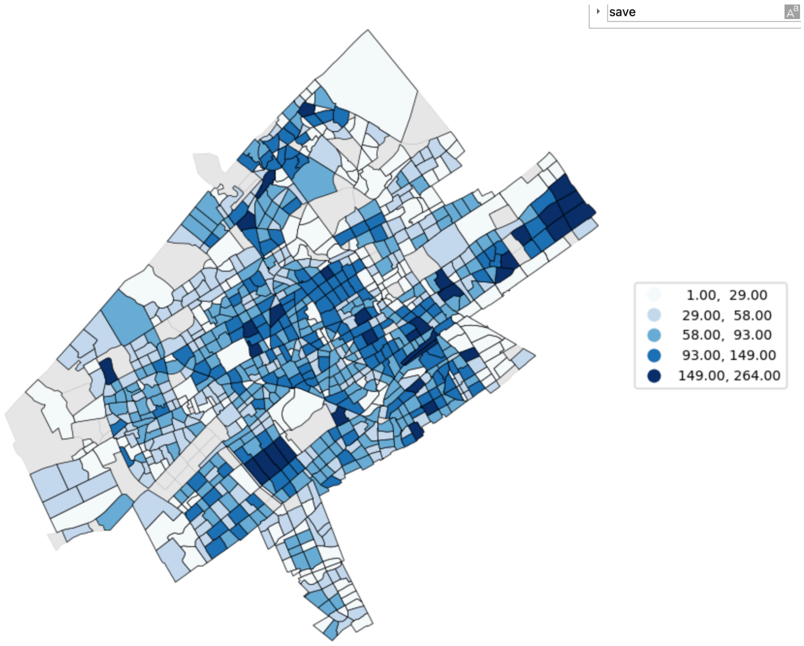


Figure 4.2: Distribution of all parcel demand, results from MASS-GT

Figure 4.2 shows the heat map of all parcel demand, where the geographical and numerical distribution of the parcel demand per zone are presented. The darker the colour shown on the map, the more parcels are to be delivered to that zone. It can be observed that in general, urban areas (close to city centres) have more parcel demand than suburban areas because of the high population density in urban areas. It is worth noting that some areas aren't located near city centres but also have high parcel demand, which might be a result of high residential or industrial density.

The total number of parcels to be delivered in the study area in one day is roughly 90000 pieces. There are 6 major LSPs operating in the study area, namely PostNL, DHL, DPD, UPS, GLS and FedEx. Figure 4.3 shows the market share of different LSPs, based on their total parcel volumes. The parcel demand of PostNL is significantly higher than other LSPs, taking up around 50% of the market share, while the market share for FedEx is only about 2.6%.

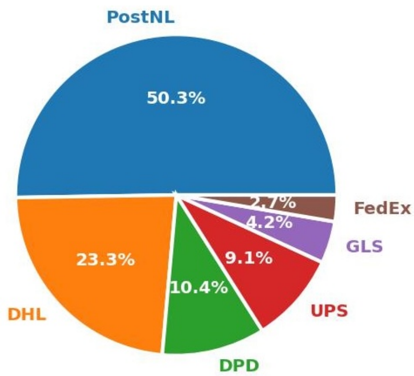


Figure 4.3: Market share of different LSPs (ACM, 2023)

Figure 4.4 shows the geographical distribution of all deployed depots in this project. PostNL and DHL have depots within the study area, which facilitates their efficient operations. While the depots of other LSPs are located outside the study area, especially for FedEx, indicating that they have to travel longer distances to serve the customers in the study area.

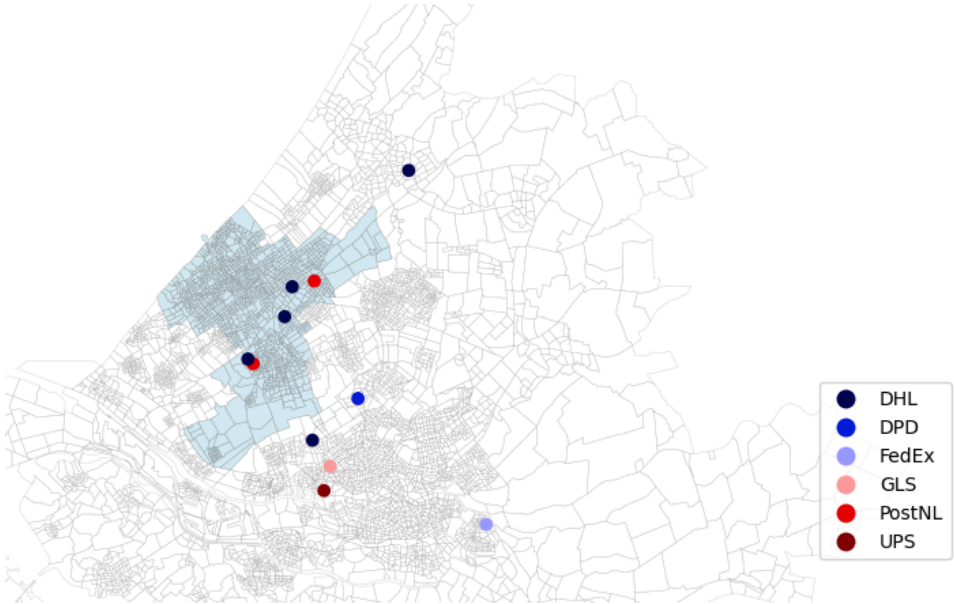
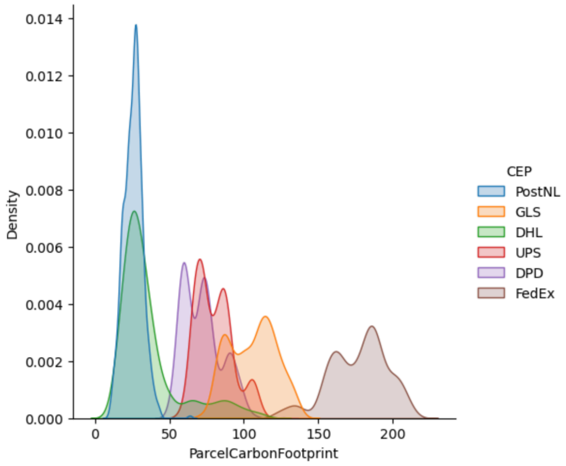


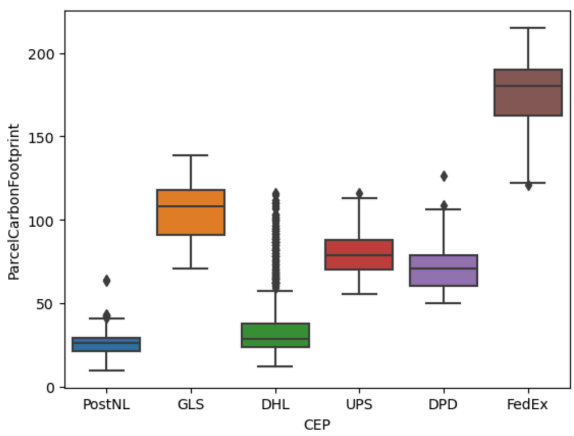
Figure 4.4: Depot distribution of 6 LSPs

4.2.2. Overview of parcel carbon footprint

By implementing the measurement method mentioned in Section 3.1 for every delivery tour, the carbon footprint of all parcels can be calculated. Figure 4.5a and figure 4.5b show the distribution of carbon footprint per parcel for different LSPs. As can be seen in both figures, a significant difference is observed among different LSPs.



(a) Kernel Density Estimation (KDE) curve of parcel carbon footprint for each courier



(b) Box plot of parcel carbon footprint for each courier

Figure 4.5: Overview of parcel carbon footprint (pallet*km) for each courier

For PostNL and DHL, the distribution of parcel carbon footprint is relatively concentrated and low in value, with an average of less than 30 pallet*km per parcel and most of them less than 50. DPD and UPS have a similar distribution of carbon footprints per parcel with an average value of around 90 pallet*km, while GLS has a slightly larger value of carbon footprint per parcel. FedEx, on the other hand, has a significantly larger carbon footprint value per package than the other LSPs, with an average value of more than 150 pallet*km.

The difference in the distribution of carbon footprint among different LSPs could be explained by their depot locations. The remote depot location leads to a large total tour carbon footprint, which then results in the large carbon footprint allocated to each parcel, such as the high carbon footprint values seen in FedEx's parcels.

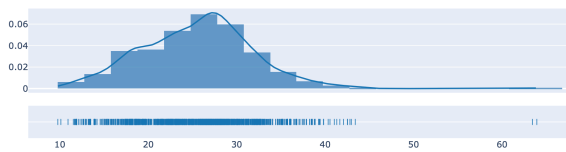
Another explanation for the different carbon footprint distribution among LSPs is their market share. LSPs with large market share, such as PostNL, have a denser distribution of parcel demand which allows them to consolidate and organise more efficient parcel routes (Buldeo Rai et al., 2018), thus their delivery effort per parcel is smaller compared to the LSPs with more scattered parcel demand.

Apart from the large difference observed among different LSPs, one thing they have in common is the existence of a noticeable number of parcels with large carbon footprint values, i.e., the right tails, which can be observed directly from figure 4.5a. This justifies the idea of outlier parcels in this project and validates the effectiveness of the carbon footprint measurement methodology.

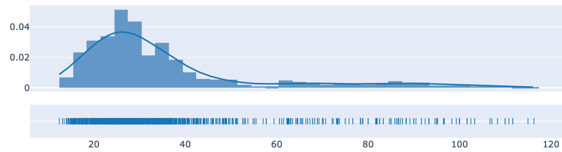
4.2.3. Outlier parcel segregation results

As the carbon footprint per parcel varies remarkably among different LSPs, the segregation of outlier parcels is therefore executed for each courier, instead of regarding all parcels as a whole.

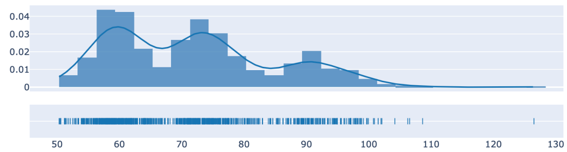
The segregation of high-environmental-impact parcels is based on the selection of a threshold value of carbon footprint per parcel, parcels with carbon footprint above this threshold are considered outliers. The selection of threshold value is based on the observation of the numerical distribution, in this way a more realistic selection could be guaranteed. Figure 4.6 shows the distribution plots for each courier, where histogram, kernel density estimation curve and rug plot are all included. The x-axis shows the parcel carbon footprint value and the y-axis is the corresponding probability.



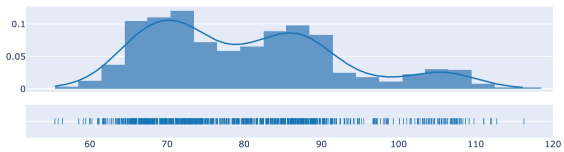
(a) PostNL parcel carbon footprint distribution



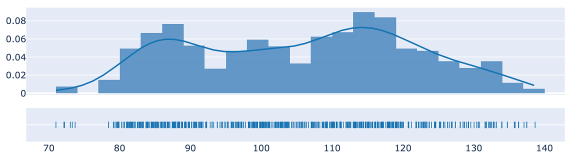
(b) DHL parcel carbon footprint distribution



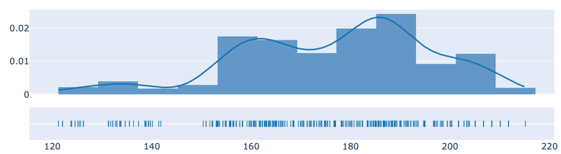
(c) DPD parcel carbon footprint distribution



(d) UPS parcel carbon footprint distribution



(e) GLS parcel carbon footprint distribution



(f) FedEx parcel carbon footprint distribution

Figure 4.6: Parcel carbon footprint distribution for each courier

Overall, the parcel carbon footprint distribution for different LSPs does not only vary on the numerical values, but also on the distribution patterns. For some LSPs, the distribution is more contented with clear outliers shown on the bottom rug plot, as can be observed in PostNL, DHL, DPD and UPS. This can be explained as these 4 LSPs have the top 4 market shares, thus the overall operations are more efficient for the majority of parcel demand, with a small number of parcels requiring more delivery efforts.

Take the one for DHL as an example. A clear gap exists at around the value of 50, where the majority of the parcel carbon footprint values are below this value. Therefore 51 is chosen as the threshold value

Table 4.1: Overview of outlier parcels for each LSP

LSP	Threshold value (pallet * km)	#Outliers	Outliers (%)	Ave. #outliers per zone
PostNL	36	374	3,1	11,33
DHL	51	398	13,4	2,71
DPD	95	207	5,2	4,5
UPS	95	411	11,7	4,03
GLS	128	155	8	2,38
FedEx	195	206	16,1	1,67

for segregating outlier parcels for DHL.

While for other small LSPs (GLS and FedEx), the distribution is more scattered, no clear gap can be observed in the rug plot. This is because the 2 LSPs have the least market shares, thus it's hard for them to achieve efficient operation due to a lack of economies of scale. The inefficiency in GLS and FedEX's operations can also be seen in the negative skewness (long tail on its left side) of the distribution. As can also be seen in 4.5b, half of the parcel carbon footprint values are larger than the mean value.

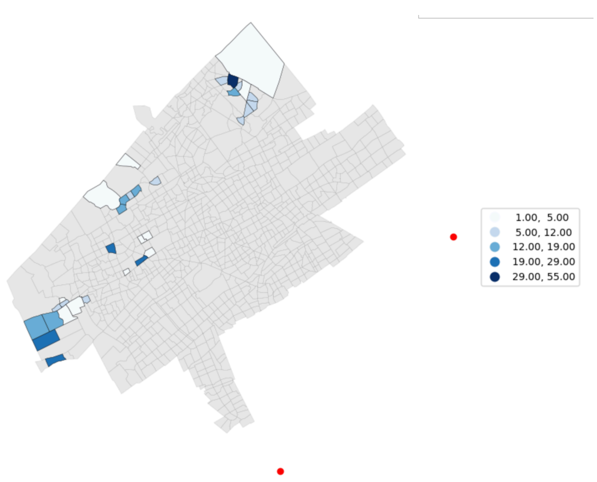
The same segregation process as the example shown above for DHL is applied to every LSP, and table 4.1 shows an overview of the segregation results. A total of 1751 parcels are segregated, which takes up around 3% of the total parcel demand. Overall, DHL, UPS and FedEx have a higher percentage of outliers of their all parcels. The last column shows the average number of outlier parcels per zone, for zones where there are outlier parcels. In general, PostNL have a higher number of outlier parcels per zone, while all other LSPs have a relatively low number of outlier parcels per zone.

Besides the numerical results, figure 4.7 shows the geographical distribution of outlier parcels for each LSP. The legends indicate the number of parcels per zone and the red dots show the depot location for each LSP. Note that the depots that are located far away from the study area are not shown on the map. Overall the outlier parcel distribution for every LSP is clustered to some extent, with few outliers of outliers are scattered.

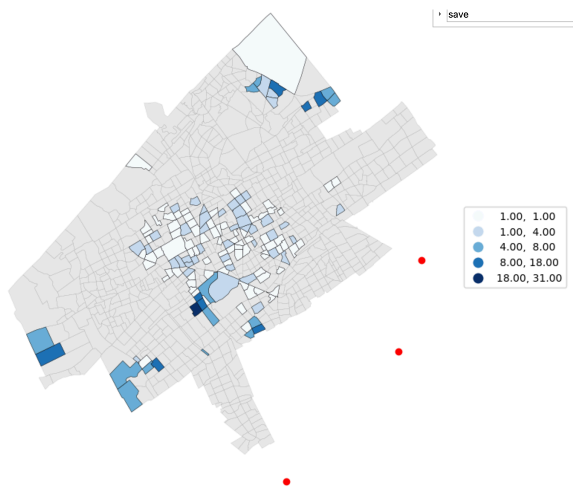
Three distribution patterns can be observed from the maps. The first pattern is that outlier parcels are located at the edge areas with varying numbers of parcels per zone, which can be observed in the case of all LSPs. These outliers are edge parcels in low-demand and remote areas, which take more delivery effort.

The second pattern is that outlier parcels are concentrated in the urban areas, also with a limited number of parcels per zone, which can be seen in DHL. This might be a result of a relatively low parcel demand in these areas compared to other urban areas, which adds to the relatively high delivery effort.

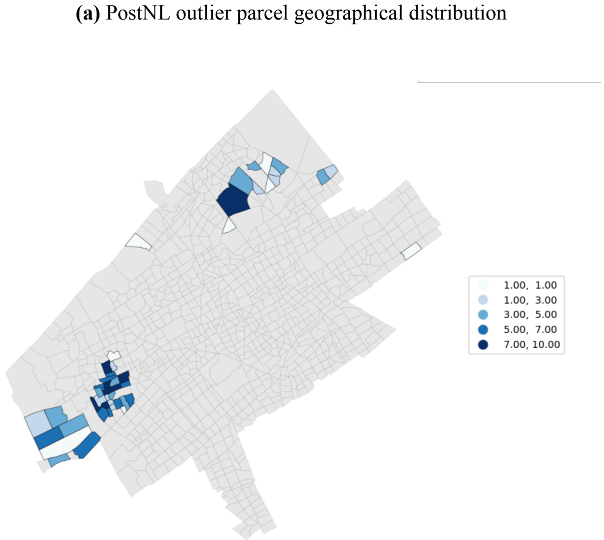
The third pattern is that certain outlier parcels are located at certain zones and these zones are clustered, as can be seen in DPD, UPS, GLS and FedEx. These parcels are from the same delivery tours, which have a high tour carbon footprint. This is because these zones are remote to the LSP's depots and the van kilometres travelled to deliver these parcels are high, resulting in high carbon footprint values for almost all parcels in the delivery tour.



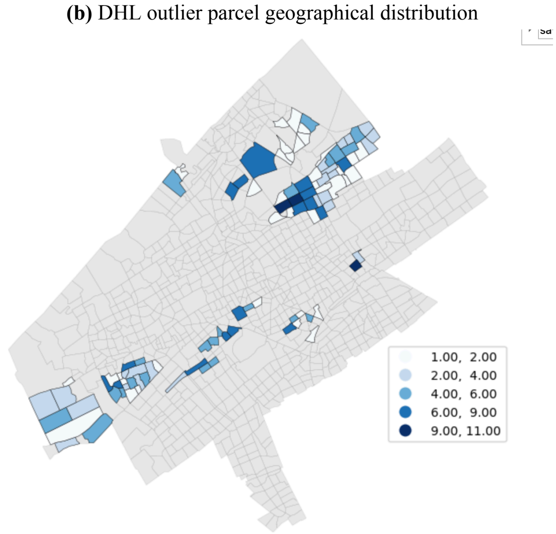
(a) PostNL outlier parcel geographical distribution



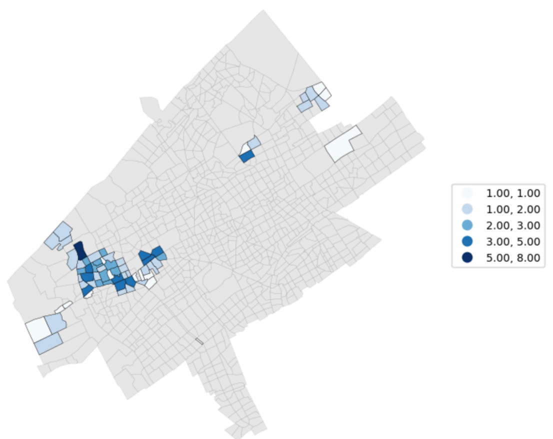
(b) DHL outlier parcel geographical distribution



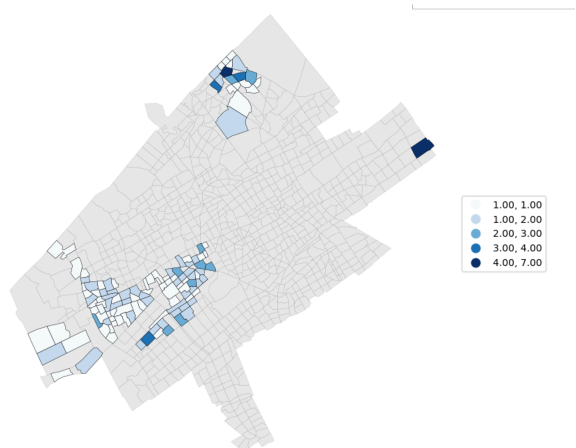
(c) DPD outlier parcel geographical distribution



(d) UPS outlier parcel geographical distribution



(e) GLS outlier parcel geographical distribution



(f) FedEx outlier parcel geographical distribution

Figure 4.7: Geographical distribution of outlier parcels for each LSP

4.3. Crowdshipping supply system

This section presents the implementation of the crowdshipping system described in 3.2. First, the results of selecting train traveller trips are shown. Following that, the results of occasional courier selection are described.

4.3.1. Train trip selection results

In ALBATROSS data, in total there are 860147 trips made in The Hague in a day. Figure 4.8 shows the mode distribution of ALBATROSS trip data, of which public transport takes up 8.3 %, which is in line with the model split statistics as shown in Section 3.2.1. A total of 66752 PT trips is selected for further processing.

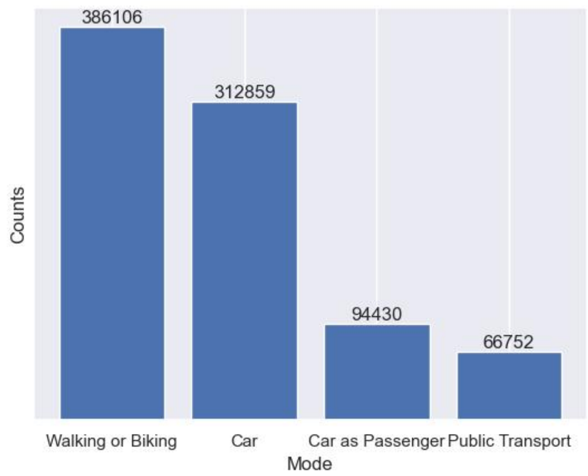


Figure 4.8: Mode distribution of ALBATROSS trip data

Before selecting the train trips from the total PT trips, a sociodemographic filter is set on the age of the passengers. Figure 4.9 shows the age distribution of all PT passengers. Passengers who fall into <35 and 35-55 groups are selected as potential OCs for crowdshipping service. This is because lots of SP studies show that young and middle-aged people are much more willing to work as OCs than the elderly as they have more access to and interest towards digital products and services (Fessler et al., 2022).

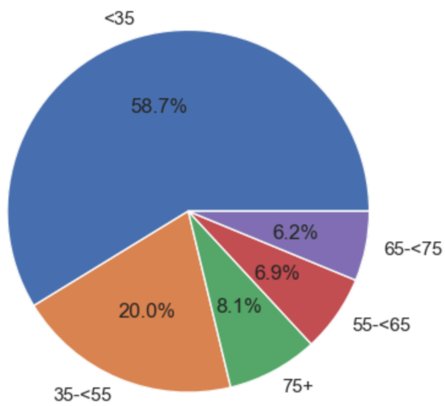


Figure 4.9: Age distribution of all PT passengers in ALBATROSS data

Figure 4.10 shows the geographical distribution of the destination of all PT trips after the sociodemographic filtering. The red dots show the locations of all train stations in the study area. As can be seen, overall the centre areas have more passenger arrivals than the edge areas. Certain zones that are not located in the centre area have high passenger arrivals, this might be because these zones have a high residential population.

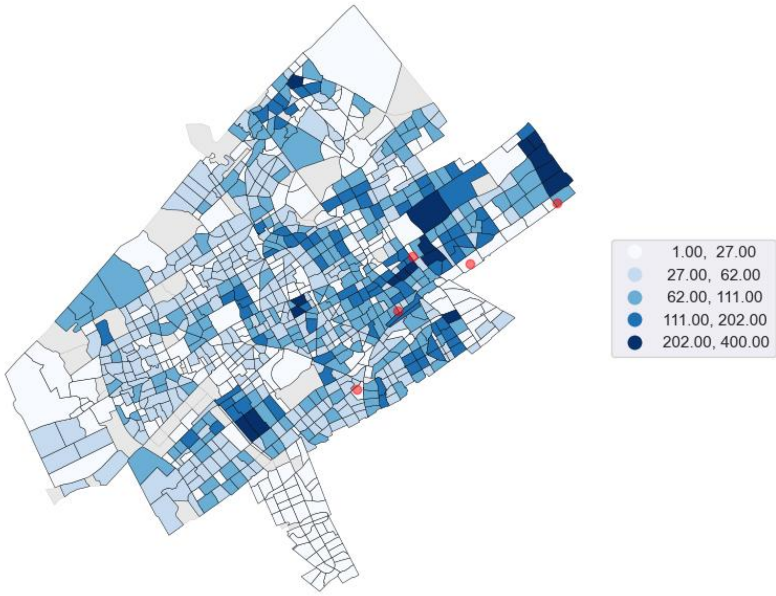


Figure 4.10: Number of all PT trip arrivals in ALBATROSS data

By implementing the proximity-based station selection method described in Section 3.2.4 and including both the PT trips arriving at and departing from train stations, there are around 20000 train trips, which is about 1/3 of all PT trips and 3% of the total trips in the study area.

Figure 4.11 shows the implementation results of train trips. Figure 4.12 shows the geographical distribution of all train trip arrivals.

As can be seen in both figures, train station HS has the most traveller arrivals. This is because station HS is a major train station located in the central area and is well connected to other local public transport options in the study area, which results in the high traveller demand. Station CS has the second largest traveller demand as it is a major train station in the whole train station network in The Netherlands, the good connections to other major stations in other cities make it a popular choice as well. The other three stations mainly serve the local demand and have poorer connection to other train stations in the whole network compared to station CS and HS, therefore the traveller demand are less.

As for the spread of train trip arrivals, the trips depart from station HS spread well over the study areas. And train trips depart from station Moerwijk and station CS also have a good spread all over the study area. While for Station Laan v NOI and Mariahoeve with less traveller demand, the trips departing from there are limited to the areas near the stations.

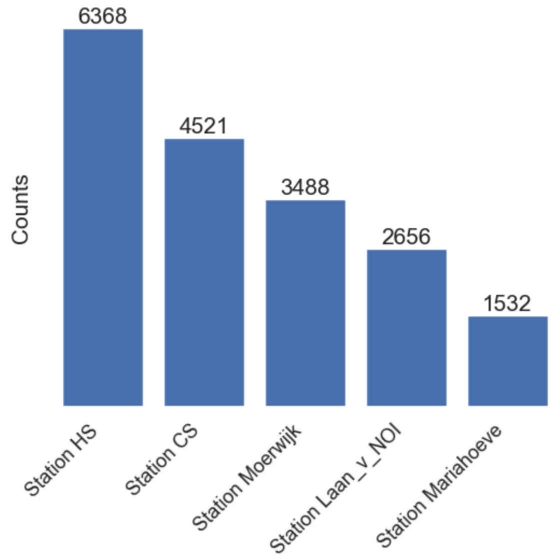
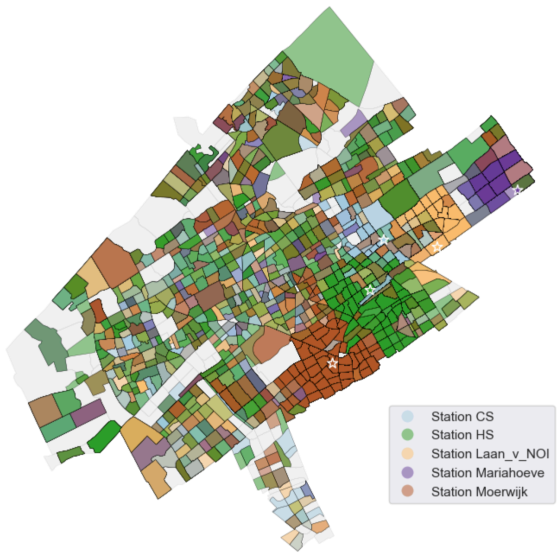
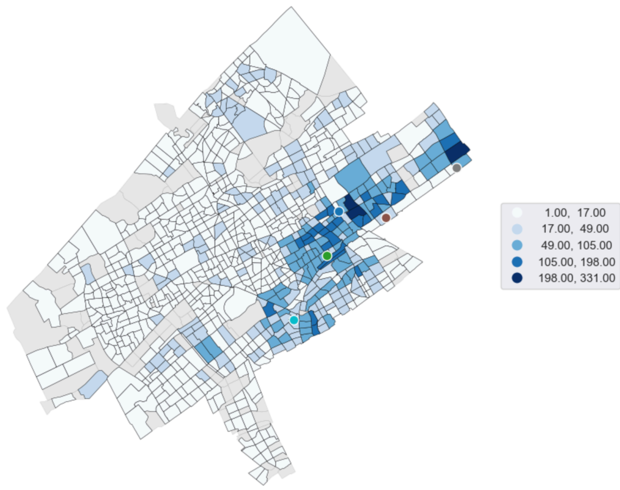


Figure 4.11: Station distribution of train trips



(a) Station distribution of train trip arrivals



(b) Number of train trip arrivals

Figure 4.12: Geographical distribution of train trip arrivals

4.3.2. Occasional courier selection results

This section presents the implementation results of the occasional courier matching module in Section 3.2.5, which compares the provided Value of Time of the crowdshipping supply system to travellers' preferred VoT for them to work as the occasional couriers and selects the ones with VoT gains as potential occasional couriers.

The detour distance is calculated as twice the intrazonal Manhattan distance, and for each zone, both the average value and standard deviation of its intrazonal Manhattan distance are calculated. The implementation result shows that for the whole study area, the average intrazonal Manhattan distance is around 200m, with a standard deviation of 43m. This result is in line with the geographical information of the study area. The total size of the study area is around 70 km^2 and the total number of zones is 940 with an average size of 74500 m^2. The zones are divided very finely so most of the zones are very small, resulting in the relatively small intrazonal Manhattan distance.

As all three components included in additional travel time are not directly influenced by the parcel to be delivered by OC, the additional travel time is only dependent on the OC's destination zone size and the transport mode used for delivering the parcel. The additional travel time can therefore be calculated for each passenger. On average, passengers need to spend a total of 4.56 min (with a standard deviation of 1.56 min) extra time to perform the delivery task.

Figure 4.13 below shows the implementation results of the Occasional courier matching module. The percentage of passengers who are willing to work as OC is calculated regarding different compensations. As the chart shows, when the compensation is 3 euro, only around 25% of all the passengers are willing to work. And then the percentage increases sharply to 30% as the compensation increases from 3 euro to 4 euro, which means given the additional travel time, for 40% of the passengers 4 euros is the minimum requirement. The percentage of potential OC reaches 50% when the compensation is 5 euro, which means to ensure a half of train passengers are willing to work OC, a compensation of 6 euro per outlier parcel is needed. When the compensation increases from 6 euro to 10 euro, the percentage increases gradually from 50% to 80%, where the majority of passengers are willing to work for the crowdshipping service.

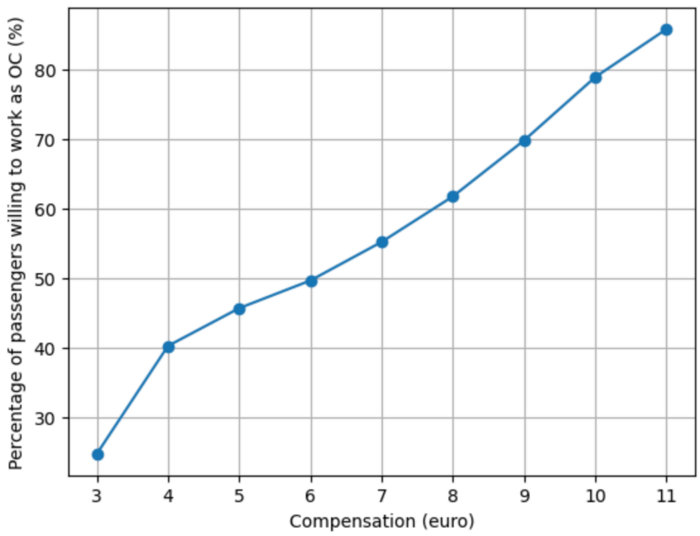


Figure 4.13: Percentage of passengers willing to work as OC regarding different compensations

4.4. Verification and validation

This section presents the verification and validation of the proposed matching model of outlier parcel demand and crowdshipping supply, which is the implementation of the matching algorithm proposed in Section 3.3. As lots of assumptions and choices have been made in the conceptual model, thus model verification and validation are needed to reflect on the model fit and to evaluate to what extent the model contributes to the research goal. Verification focuses on testing if the behaviour of the implemented model is correct and in line with the conceptual model, and validation focuses more on testing if the implemented model can represent the research goal sufficiently (Sargent, 2010).

4.4.1. Verification

The verification mainly presents answers to the question: Is the model implemented according to the specification of the conceptual model? To verify the matching model, balance checks, continuity tests and degeneracy tests are carried out to test if the model behaviours are in line with the model specifications.

Balance checks and continuity tests

First, the matching model is tested in terms of the balance in input and output flows, following that, it is tested with slightly different compensation values to see if the outputs change continually and consistently with the model specifications.

Table 4.2 shows the matching results of 2 test runs, where compensation is set as 6 euros and 9 euros, and the capacity per PL at 5 train stations is set to 400. A total of 1751 outlier parcels are used as input. The matching results are in line with the outputs of the matching model described in Section 3.3, with one matched result and three unmatched results. The three unmatched results are prioritized as shown in the order in the table, and the unmatched parcels can only fall under one result. As can be seen in both test runs, the sum of all matching results is equal to the total number of parcels, which verifies the conservation of input and output flow. In addition, as the compensation increases, the number of parcels with the matching result of "Unmatched: No potential OC" decreases and the number of matched parcels increases, which is in line with the model specifications that compensation functions as the driving factor for travellers' willingness to work as OC, which could then lead to a higher number of potential OC. Moreover, the matching result of "Unmatched: No available PL" increases as a result of the full occupancy rate in station Moerwijk, which is used the most for the successful match of parcels and OC.

Table 4.2: Model verification: Balance checks and continuity tests

	Matching results	Compensation =6	Compensation =9
Number of parcels per matching result	Matched	1112	1214
	Unmatched: No potential OC	559	245
	Unmatched: No available PL	42	146
	Unmatched: No available travellers	38	146
	Sum	1751	1751
	Train stations		
PL occupancy rate per PL at the train stations (%)	Station Moerwijk	90	100
	Station HS	83	99.5
	Station CS	58	58
	Station Laan v NOI	37	37.75
	Station Mariahoeve	10	8.25

The second half of the matching results are about the PL occupancy rate at each train station, which indicates the station distribution of matched parcels. This is to test the proximity-based allocation from depots to PL at train stations. In both cases, station Moerwijk and station HS have the highest occupancy rates, indicating they have the highest successful matching of outlier parcels and train travellers.

Figure 4.14 shows the distance of each LSP's depot to each of the 5 train stations. As can be seen, for two DHL, DPD, GLS and two PostNL depots, station Moerwijk and station HS are the closest. And station Morewijk is also the closest one to the FedEx depot, which is located the farthest to the study area. The closeness to most depots and the sufficient traveller demand of these two stations (Figure 4.11) result in the high occupancy rates of the PL installed at these two stations. While for station Mariehoeve, which is the farthest station to 7 out of the total 9 stations and has the least traveller demand (Figure 4.11), thus the occupancy rate is quite low.

In conclusion, it can be concluded that the matching model works consistently and is in line with the model specifications.

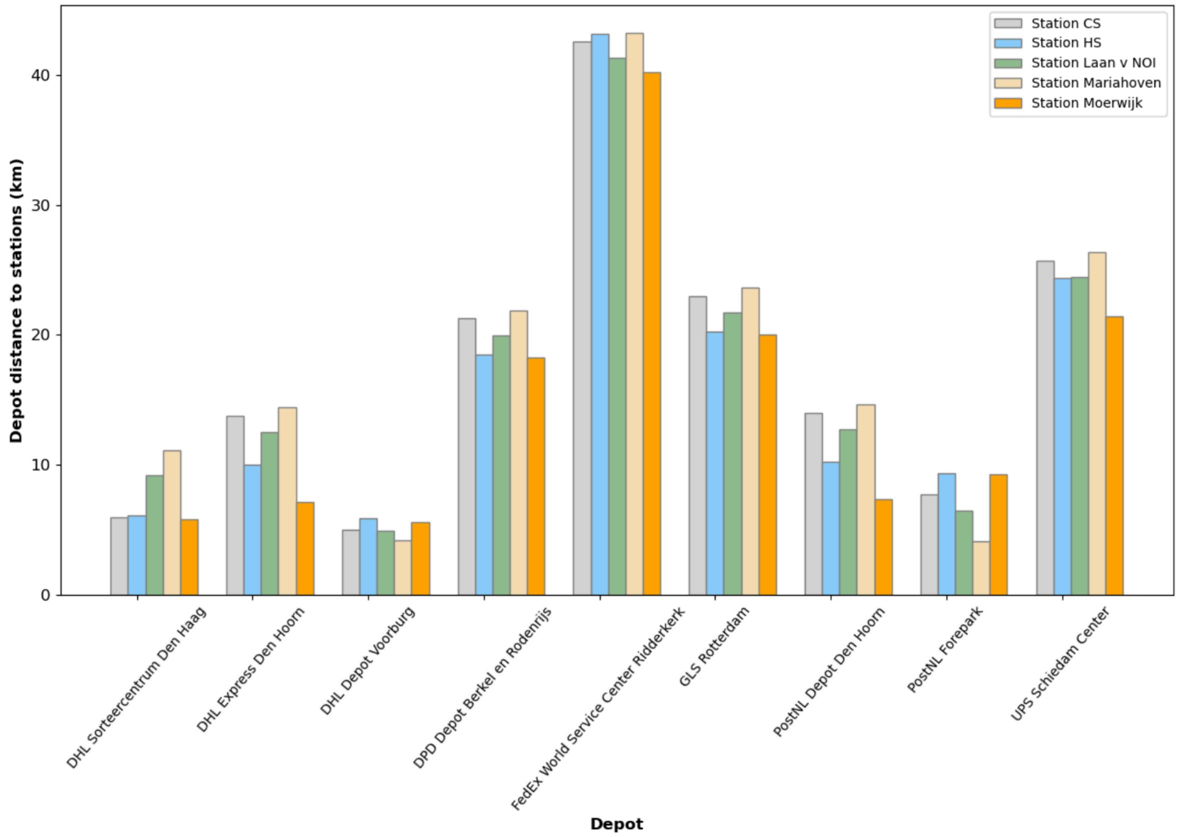


Figure 4.14: Depot distance to train stations

Degeneracy tests: Extreme parameter values

To further verify the matching model, degeneracy tests are performed. In degeneracy tests, the input parameters are set to extreme values to see if the model performs the expected outcomes. Parameters from the crowdshipping supply system, both from the PL network and OC selection, are tested with their corresponding extreme values. Table 4.3 shows the predictions and outcomes of these experiments.

As can be seen in the last column, all experiments pass the degeneracy tests.

Therefore, it can be concluded that the model is implemented according to the specification of the conceptual model described in Chapter 3.

Table 4.3: Model verification: Degeneracy tests

Module	Parameters	Current values	Extreme conditions	Expected outcome	Model outcome
OC selection	Pick up time (min)	[mean = 0.8, std = 0.4]	10000	No parcel is matched	Yes
	Detour travel speed (m/min)	143	1	No parcel is matched	Yes
	Compensation (euro)	6	10000	All parcels that have passengers with the same destination zone are matched	Yes
			0	No parcel is matched	Yes
Crowdshipping supply system	Proximity threshold for selecting train trips (km)	1	0	No available passenger train trips	Yes
			10000	All PT trips are train trips	Yes
	PL capacity	400	10000	All parcels that have passengers with the same destination zone are matched	Yes
			0	No parcel is matched	Yes

4.4.2. Validation

The validation mainly presents the answers to the question: Is the model an accurate representation of the real system? However, as crowdshipping is an innovative logistics solution which has few real-world implementation cases, the validation thus focuses on the validation of parameters used in this project, and to test if the model behaviour is in line with the real-world system.

Table 4.4: Validation of parameters

Parameter	Model values	Literature values
VoT (€/h) for crowdshipping	€38.57/h (low-income) €122.77/h (high-income) (Cebeci, Tapia, Nadi, de Bok, & Tavasszy, 2023)	SP on student cyclists' attitude to work for crowdshipping: €24/h (Wicaksono, Lin, & Tavasszy, 2022) SP on commuters' attitude to work for crowdshipping: €26/h (Fessler, Thorhauge, Mabit, & Haustein, 2022) SP on ride-sourcing drivers: $35 to $81.6/h (Ashkrof, Homem de Almeida Correia, Cats, & van Arem, 2022)
Compensation	€3, €5, €7, €9	Estimation of approximate remuneration values for OC: €6 (Tapia, Kourounioti, Thoen, de Bok, & Tavasszy, 2023)
Catchment area radius of train stations	1000m	Commonly used catchment area radius of rail station: 800m 85th percentile walking distance to commute rail using empirical data: 1259m (El-Geneidy, Grimsrud, Wasfi, Tétreault, & Surprenant-Legault, 2014)
Pickup/interaction time at PL	Mean = 0.8min, standard deviation = 0.4min	Interaction with PL at metro stations from a real-life experiment: maximum 30s (Fessler, Thorhauge, Mabit, & Haustein, 2022)
PL capacity	400 maximum	A PL capacity of PostNL installed at grocery stores: 200 (PostNL, 2021)

Validation of parameters

Table 4.4 shows the parameter values used in this project and compares them to the values from the literature. For VoT for OC to work for crowdshipping, the values used in this project are higher than that in the literature, this is because the VoT used in this project is specific for existing trips, which are higher than VoT of newly generated crowdshipping trips (€14.43 for low-income and € 73.83 for high-income). While the other studies did not make a distinction between the different crowdshipping trip types, so the combined results for the different trip types are lower. Moreover, the VoT range for occasional drivers from ride-sourcing services, a similar service to crowdshipping, also validates the values.

As for the compensation levels chosen to be experimented with in this project and the catchment area radius used for selecting train trips, they are both under the variable range of the results from literatures.

For pickup/interaction time, the mean value is larger than that from the previous study and a variation is added to account for the uncertainties. For PL capacity, the maximum value is set as twice that of real-world operations. This is because as this project is exploring the potential of crowdshipping service with PL network for outlier parcel delivery, a large and sufficient PL capacity can examine the potential of such service.

Behaviour prediction test

Though the real-world operation data of crowdshipping service is lacking and thus the magnitude of the model outputs can not be validated, the direction of model outputs with regards to the changes in operational characteristics can be tested. Figure 4.5 shows the hypothesis from the real-world system and the corresponding model behaviours.

The model passes all four tests, together with the validation of model parameters, it can therefore be concluded that the model is unable to represent the real world and thus can be used to answer the research questions.

Table 4.5: Model validation: Behaviour prediction test

KPI	Hypothesis	Model behaviour
Total VKT	The total VKT would decrease with the implementation of a PT-based crowdshipping service	Yes
Match rate	The match rate would increase as a result of an increase in compensation	Yes
Match rate	The match rate would increase as a result of an increase in number of potential OCs.	Yes
Match rate	The match rate would decrease as a result of a decrease in PL capacity.	Yes

4.5. Concluding remarks

In this chapter, the implementation results of each of the three modules are presented.

For the outlier parcel segregation, large variations are observed in the distribution of carbon footprint values for logistics service providers with different market shares. Thus the segregation of parcels with high carbon footprint values is done for each logistics service provider. A total of 1751 parcels are segregated, which takes up around 3% of the total parcel demand, with varying outlier percentages per logistics service provider. Most of the outlier parcels are located in non-centre areas and three different geographical patterns of outlier parcel distribution are observed.

For the crowdshipping supply system, 9050 train travellers (20000 train trips, around 2.3% of the total trips) are selected as the potential supply for crowdshipping service. As for the station distribution, among the 5 train stations in the study area, station HS and CS have the most traveller demand.

The selection results of potential occasional couriers from the train travellers show that given a compensation of €6, around half of the train travellers are willing to work as occasional couriers.

The implementation of the matching model is verified and validated respectively. The matching model passes the balance checks, continuity tests and degeneracy tests. And due to the lack of real-world crowdshipping use cases, the validation focuses on the choice of model parameters, and a behaviour prediction test is conducted and the model is able to behave in the same directions as the real-world system with regards to some operational changes.

With the implementations of the three modules, the next chapter will synthesize the three models and conduct several simulation experiments to test the performance of the crowdshipping service under different operation settings.

5
Simulation & analysis

This chapter presents the simulation experiments and their results. First, the key performance indicators are defined for a systematic evaluation of the scenarios. Second, scenarios are set up with regard to the variables in each of the three modules implemented. Following that, the results from different scenarios are analysed to evaluate the transport impacts of the proposed crowdshipping service for the last-mile delivery of outlier parcels under different operational settings.

5.1. KPI definition

Table 5.1 below shows the key performance indicators (KPI) defined in this project. There are two categories focusing on different aspects of the performance of crowdshipping services.

Category	Indicator
Crowdshipping service	Number of matched parcels Match rate (%) Compensation paid per VKT reduction (euro/km) Average & Std. Dev. (SD) occupancy rate per PL (%)
Transport & environment	Total LMD VKT (km) Total LMD VKT reduction (%) VKT reduction per matched parcel (km) OC Car percentage (%) Average & SD car detour distance by OC (km) Allocated car detour distance per matched parcel (km)

Table 5.1: KPI definition

The first category focuses on the crowdshipping supply system's performance, with the match rate and the occupancy rate of PL for assessing the usage and efficiency of the service. Moreover, the last indicator of this category looks at how economically efficient the crowdshipping service is in terms of reducing the van kilometres travelled (VKT) in last-mile delivery.

The second category is about the transport performance of the crowdshipping service. The VKT in last-mile delivery is compared to the scenario without crowdshipping service, i.e., the current conventional operations in LMD, to see the transport impacts brought by crowdshipping service. It is worth noting that in this project the commonly used abbreviation VKT refers to **van kilometres travelled** instead of vehicle kilometres travelled, as this project focuses on the urban freight transport system.

Moreover, the detour distance by occasional couriers with private cars as the transport mode for delivery is also included, which are the car detour distance per delivery trip and the allocated car detour distance per matched parcel, to reflect on the traffic externalities brought by crowdshipping. The detour distance by public transport and active modes are not included as they are sustainable modes. It is worth noting that as parcel demand is one of the variables that will change in different scenarios, thus the KPIs mostly focus on the transport impacts brought by each parcel for a better comparison among scenarios.

5.2. Scenario set-up

Table 5.2 shows scenario setup and settings for each scenario, which will be simulated in the following sections.

Table 5.2: Simulation scenarios

Variable	Scenario	Scenario label	Description
	Base scenario	B1	Without crowdshipping
	Reference scenario-1	R1	All parcels are eligible for crowdshipping, randomly select 9050 parcels to be in line with the number of train travellers
	Reference scenario-2	R2	All parcels are eligible for crowdshipping, randomly select 1377 parcels with the same number of outlier parcels
Outlier parcel demand	All couriers	D1	All outlier parcels
	Exclude PostNL & DHL	D2	Exclude two main couriers, current operations of the rest are less efficient
	Exclude PostNL	D3	Only exclude PostNL and include DHL as it has a high outlier percentage
	Only FedEx and GLS	D4	Outlier parcels from the two LSPs with the least market shares
Compen-sation	3,5,7,9 (euro)	C1, C2, C3, C4	Different compensation provided to OC
#PL	Only train stations	P1	5 train stations
	Train stations and tram stops	P2	5 train stations + 3 tram stops
	Fewer train stations	P3	Exclude 1 low-demand station
PL location	Stations and stops with high passenger demand	P4	Select a total of 5 stations and tram stops with high passenger demand
PL capacity allocation	Same capacity	P5	All station have the same capacity.
	Hierarchical capacity	P6	Stations with high match rate have higher capacity.

The scenarios start from the base and reference scenarios. The base scenario is the current LMD scenario, where there is no crowdshipping service and LSPs deliver the parcels to the consumers' final destinations.

The reference scenarios are constructed to test the impacts of outlier parcel segregation. Thus in the reference scenarios, all parcels are eligible for crowdshipping. The first reference scenario looks at the potential of a fully implemented crowdshipping supply system for all parcels, and the second one is specifically set for the simulation scenarios in this project. In Reference Scenario 1, the intention was to try to use all the parcels as the demand of crowdshipping, however, as the number of travellers who travel by the 5 train stations is only 9050, a random selection of 9050 parcels is executed to ensure that the demand is in line with the supply. In the random selection, the market share of different LSPs is kept. In Reference Scenario 2, as the default demand for crowdshipping in the simulation experiments is 1377 (the outlier parcels of the 5 LSPs excluding PostNL), thus 1377 random parcels from all the parcels are selected following the market share of the 5 LSPs.

Then the scenarios are set to test the impacts of and the assumptions made behind the key variable(s) in the model. The simulation experiments mainly focus on the impacts of outlier parcel demand from different LSPs, different compensations provided to OC and different PL network configurations, on the transport and efficiency performance of crowdshipping.

As each category of the simulation experiments focuses on different perspectives of crowdshipping service, it is necessary to keep the irrelevant variables consistent among different scenarios. For outlier parcel demand, scenario D3 where outlier parcels from 5 LSPs exclude PostNL is chosen as the default parcel demand. For compensation, 6 euros is chosen as the default value for compensation, this is because the percentage of all passengers who are willing to work as OC is around 50 % at the compensation of 6 euros, as the results show in Section 3.2.5, providing a moderate level of OC participation For the number of PL and PL capacity, the PL network of 5 train stations functions as the default and starting point of the crowdshipping service, and the default capacity for PL is set as 400 to ensure that PL capacity does not constrain the system performance and the potential of the proposed crowdshipping supply system can be fully examined.

5.3. Base scenario and reference scenario

Table 5.3 shows the performance of base and reference scenarios. The PL capacity is set to large values to accommodate all the parcel demand.

Table 5.3: Simulation results of base and reference scenarios

Scenario specification		**B1**	**R1**	**R2**
Parcel demand (% of total demand)		56801	Random 9050 (15.9%)	Random 1377 (2.42%)
Capacity per PL			1600	400
KPI Category	**Indicator**			
Crowdshipping service	Number of matched parcels		5310	1212
	Match rate (%)		58.67	87.95
	Compensation per VKT reduction (euro/km)		145.29	195.38
	Average (SD) occupancy rate per PL (%)		66.37 (23.71)	60.6 (11.83)
Transport & environmental	Total LMD VKT (km)	13699.31	13480.03	13662.09
	Total VKT reduction (%)		1.6	0.27
	VKT reduction per matched parcel (km)		0.041	0.031
	OC car percentage		6.18	6.9
	Average (SD) car detour distance		0.386 (0.157)	0.373 (0.149)
	Allocated car detour distance per matched parcel (km)		0.023	0.027

Both of the reference scenarios achieve a reduction in VKT, and the VKT reduction per matched parcel is greater than the car detour distance generated per matched parcel, proving the sustainable benefits of the proposed crowdshipping service.

Reference scenario 2 achieves a very high match rate, but these benefits are very little compared to the high compensation paid, making the service very inefficient. This is because the distribution of the sample parcels is very similar to the total parcel demand, thus more parcels are sampled from the high-demand areas. Outsourcing these parcels helps little in reducing VKT as LSPs have to go to those areas anyway, and the low percentage of the sample parcels to the total parcel demand also makes it inefficient to outsource them to the crowdshipping service.

Overall, the results from the two reference scenarios show that the transport benefits of outsourcing all parcels to crowdshipping services exist but are very little, and the service efficiency is very low, making it necessary to investigate which group of parcels are most suitable for and to what extent could them benefit from the crowdshipping services.

5.4. Simulation experiments

5.4.1. Different LSP demand of outlier parcels

The purpose of this experiment is to see how beneficial it would be when different outlier parcel demand is outsourced to crowdshipping. The results are shown in Table 5.4. The green color indicates good performance and the red color indicates the relatively poor performance of different KPIs in each scenario.

Table 5.4: Simulation results of different LSP's outlier parcel demand

Scenario label and specification		D1: All couriers	D2: Exclude PostNL & DHL	D3: Exclude PostNL	D4: Only FedEx and GLS
LSP regular parcel demand		56801	15683	28724	3812
LSP outlier parcel demand (% of total parcel demand)		1751 (3.08)	979 (1.72)	1377 (2.42)	361 (0.64)
Category	**KPI**				
Crowd-shipping service	Number of matched parcels	1124	780	1017	341
	Match rate (%)	64.19	79.67	73.86	94.46
	Compensation per VKT reduction (euro/km)	16.26	15.2	11.82	9.48
	Average (SD) PL occupancy rate (%)	56.2 (30.2)	39.0 (21.83)	50.7 (28.98)	17.05 (10.52)
Transport & environment	Total LMD VKT (km)	13284.49	13391.44	13184.47	13483.59
	Total VKT reduction (%)	3.03	2.25	3.76	1.57
	VKT reduction per matched parcel (km)	0.369	0.395	0.506	0.633
	OC Car percentage (%)	7.56	8.72	7.74	7.92
	Average (SD) car detour distance (km)	0.439 (0.205)	0.41 (0.194)	0.396 (0.157)	0.348 (0.123)
	Allocated car detour distance per matched parcel (km)	0.033	0.036	0.03	0.028

To begin with, all four scenarios with different outlier parcel demands achieve a much larger VKT reduction than the reference scenario R2 (only 0.27%), with the parcel demand in 3 out of the 4 scenarios no greater than that in scenario R2. This proves the effectiveness of crowdshipping service for the last-mile delivery of outlier parcels. By prioritizing the high-environmental-impact parcels to crowdshipping service, a much larger gains in both VKT reduction and service efficiency can be achieved than just outsourcing random parcels.

As for each scenario, first the outlier parcel demand of all couriers is simulated. This scenario (D1) works as a reference for the other scenarios in this experiment. In this scenario, all the outlier parcels segregated in Section 4.2 (which take up around 3% of the total parcel demand) are outsources to crowdshipping service, and a reduction of 3% in the VKT in LMD is achieved. And the allocated car detour distance per matched parcel is very little compared the VKT reduction per matched parcel. The rough equivalence of parcel percentage and VKT reduction indicates that the crowdshipping service performs moderately well in scenario D1.

Following that, as shown in Section 4.2, large differences exist among different LSPs considering their different market shares and the distance from depots to the study area, therefore the second scenario excludes PostNL and DHL, the two largest LSPs with high demand and more efficient operations than other LSPs. The results in Section 4.2 also show that PostNL and DHL have much less carbon footprint than others. Prioritizing the outlier parcels with more carbon footprint from the other 4 LSPs to the crowdshipping service could potentially benefit more to the transport system and environment.

Results of scenario D2 show that excluding the two large LSPs can increase the operation efficiency of the crowdshipping service. Compared to scenario D1, scenario D2 achieves a higher match rate and a slightly higher VKT reduction per matched parcel. However, the total VKT reduction drops from 3.03% to 2.25% as a result of the demand reduction from 1751 to 979 parcels. And the car percentage of OC increases, which could be explained as the outlier parcels from the four LSPs with less market shares are mostly located in non-centre area with less PT coverage, and the percentage of PT travellers who use private cars for their last legs is higher, thus a high car percentage is observed in scenario D2.

Compared to scenario D2, scenario D3 includes the outlier parcels of DHL as well, for a larger crowdshipping demand. In addition, the results in Section 4.2 show that DHL has a very high percentage of outlier parcels, which indicates that DHL does have some parcels of which the LMD is less efficient and have higher environmental impacts. Results of scenario D3 show that, by including the outlier parcels of DHL, both the total VKT reduction and VKT reduction per matched parcel achieve better performance compared to both scenario D1 and scenario D2. The total VKT reduction of 3.76 % and the VKT reduction per matched parcel of 0.506 km are achieved with a percentage of 2.42 % of total parcel demand, proving the transport benefits of outsourcing the 5 LSPs' outlier parcels to crowdshipping. As for the service efficiency, the compensation paid per VKT reduction in scenario D3 also drops to only €11.82.

Scenario D3 outperforms both scenario D1 and scenario D2 in most KPIs, which indicates that outsourcing the outlier parcels of LSPs with low market shares and LSPs with high market share and also a high percentage of outliers to the crowdshipping service could benefit the transport system and achieve high service efficiency, while outsourcing the LSPs with high market share and a small percentage of outliers does not contribute to the reduction of VKT, due to the high operational efficiencies that have already been achieved.

To further test the impacts of crowdshipping for outlier parcels, scenario D4 only includes the outlier parcel demand from the two LSPs (FedEx and GLS) with the least market shares. The results show that the highest matched rate (nearly 95 %), the maximum VKT reduction per matched parcel (0.633km) and the minimum compensation per matched parcel (less than €10) can be achieved in such a scenario with a percentage of only 0.64% of the total parcel demand. The high match rate is because the low outlier parcel demand per zone makes it easier to find sufficient OCs, similarly, the high VKT reduction per parcel is because the low parcel demand per zone makes it more beneficial to outsource the parcels to crowdshipping. And the allocated car detour distance per matched parcel is also the minimum among all 4 scenarios, this is because that the matching algorithm first selects OCs with PT and active modes in their last legs as they take less time dropping off the parcels at consumers' final destination, and the car OCs are only selected when there is relatively high outlier parcel demand in the zones and these zones are mostly small-sized zones as shown in Figure 4.7. However, compared to scenario D3, the total VKT reduction in D4 is less, as a result of the less outlier parcel demand of only 341 parcels.

Overall, the results of scenario D4 indicates that the crowdshipping service is most efficient in reducing VKT when prioritizing the outlier parcels from LSPs with low market shares.

Given the transport and service efficiency performance of each scenario, scenario D3 with the outlier parcels from the 5 LSPs is selected as the default demand for the crowdshipping services this project proposed. This is because scenario D3 archives a balanced performance in both VKT reduction and service efficiency.

(a) Station distribution of matched outlier parcels

(b) Numerical distribution of matched outlier parcels

(c) Numerical distribution of unmatched outlier parcels

(d) Numerical distribution of all outlier parcels

Figure 5.1: Geographical distribution of scenario D3 (outlier parcel demand for all couriers except PostNL)

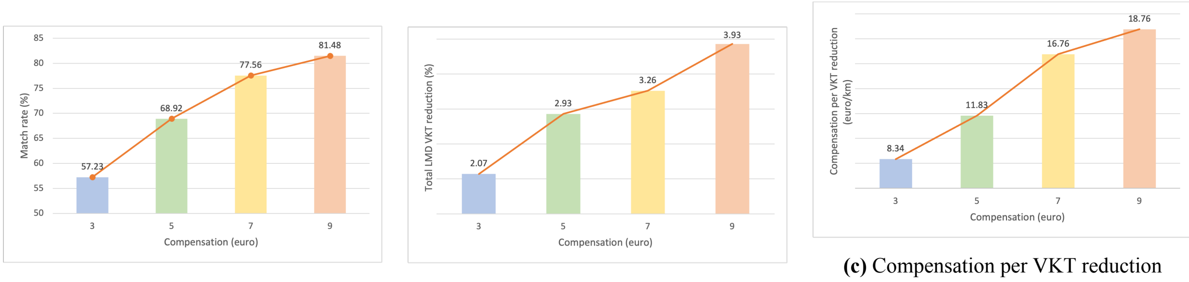
Figure 5.1 shows the geographical distribution of the matched and unmatched parcels in scenario D3. The red dots on the map show the location of the 5 train stations.

As can be seen, station HS and station Moerwijk have the most matched parcels due to their proximity to most depots as shown in Figure 4.14 and the sufficient traveller demand (especially station HS) as shown in Figure 4.11.

As for the spatial and numerical distribution of matched and unmatched parcels, almost all parcels in the centre area with low parcel demand per zone are successfully matched. A large number of outlier parcels in the edge areas are partially matched, with some remaining unmatched as a result of either the lack of PT travellers travelling to those zones or the lack of potential OCs who are willing to work given a compensation of 6 euros.

5.4.2. Different compensation

The purpose of this experiment is to see the effects of the different compensations increases in reducing VKT and service efficiency.



(a) Match rate (%)

(b) VKT reduction (%)

(c) Compensation per VKT reduction (euro/km)

Figure 5.2: Simulation results of different compensations

Figure 5.2 shows the three key KPIs, which are match rate, total VKT reduction and Compensation per VKT reduction, with regards to the compensation of €3, €5, €7 and €9. As shown in the graph, the match rate increases with the increase in compensation, as more passengers are willing to work as OCs. And the more potential OCs, the higher VKT reduction can be achieved by the crowdshipping service. But the service efficiency gets lower as the compensation paid per VKT reduction also increases with the increase in compensation. This indicates a trade-off between transport performance and service efficiency.

Comparing the increase of each of the 2-euro gap, an increase from €3 to €5 is the most efficient one, with both a steady increase in the match rate and the VKT reduction. The increase from €5 to €7 can achieve a steady increase in the number of matched parcels, but the efficiency in reducing VKT is lower, and the compensation per VKT reduction is increasing faster than the one from €3 to €5. The performance of increasing compensation from €7 to €9 is similar to that of increasing from €3 to €5.

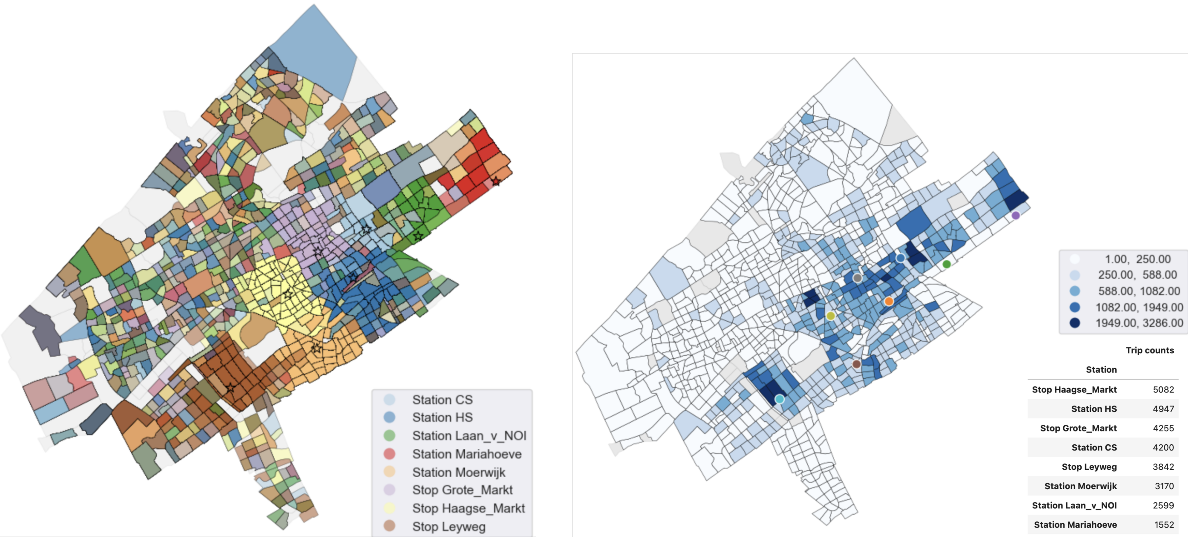
5.4.3. Different parcel locker network configurations

This section focuses on the impacts of different PT-based PL network configurations on the crowdshipping service performance. Two perspectives are considered: network size and PL location. Scenarios of different PL network sizes and different PL location choices are constructed, and the optimal network configuration is explored given the 1377 outlier parcel demand from the 5 LSPs and a compensation of €6.

First, the network size is expanded to include three tram stops in the centre areas. Three tram stops of high traveller demand are selected: Grote Markt, Haagse Market and Leyweg. Together they form a PL network of 5 train stations and 3 tram stops. Figure 5.3 shows the destination distribution of the trips that depart from the 8 PL places, which includes both the station distribution and the numerical distribution. As can be seen, all 8 PLs are located in centre areas which have both high traveller and parcel demand. And most trips have their destinations near the train stations or tram stops. Compared to the default 5-train station PL network, the expanded one has more traveller supply, providing more chances for successful matching with outlier parcels.

Table 5.5 shows the simulation results of the four scenarios with different PL network configurations. Scenario P1 is used as the reference scenario here, which is the same as scenario D3.

With an expanded network of 5 train stations and 3 tram stops in scenario P2, a higher match rate is achieved compared to scenario P1 but it does not help in further reducing the VKT. This is because a larger PL network requires the delivery vans to visit more PLs, and the benefits of more matched outlier parcels do not make up for the increased VKT this results in. And the compensation paid per matched parcel increases, which means the service is less efficient with an expanded network These indicates



(a) Station distribution of train&tram trip arrivals **(b)** Number of train&tram trip arrivals

Figure 5.3: Geographical distribution of 8 train&tram trip arrivals

Table 5.5: Simulation results of different PL network configurations

Scenario specification		P1: 5 train stations	P2: 5 train stations + 3 tram stops	P3: 4 main train stations	P4: 3 train stations + 2 tram stops
# train travellers		9050	12893	8394	10229
Category	**Indicator**				
Crowd-shipping service	Number of matched parcels	1017	1175	983	1053
	Match rate (%)	73.86	85.33	71.39	76.47
	Compensation per VKT reduction (euro/km)	11.82	14.53	15.48	15.15
	Average (SD) PL occupancy rate (%)	50.7 (28.98)	36.72 (20.1)	61.44 (21.75)	52.65 (13.82)
Transport environment	Total LMD VKT (km)	13184.47	13214.06	13318.4	13282.41
	Total VKT reduction (%)	3.76	3.54	2.78	3.04
	VKT reduction per matched parcel (km)	0.506	0.413	0.387	0.396
	OC car percentage (%)	7.74	7.83	7.83	8.45
	Average (SD) car detour distance (km)	0.396 (0.157)	0.417 (0.175)	0.411 (0.169)	0.417 (0.223)
	Car detour distance per matched parcel (km)	0.03	0.033	0.032	0.035

that for a total of 1377 parcels, it's unnecessary to set up a dense PL network and a small-sized network can achieve higher service efficiency and VKT savings.

Scenario P3 is characterized by a PL network of 4 main train stations to test the impact of a reduced network size. Station Mariahoven is excluded as it has the lowest traveller demand. As the red colours in the column show, both the service performance and transport performance decrease. The VKT reduction per matched parcel decreases from 0.506km in the 5-train station PL network to 0.387km with the reduction of station Mariahoven. This indicates that a PL network size of 5 is required to meet the demand of 1377 outlier parcels, as more traveller supply can be guaranteed. Although station Mariehoven is the most distant station to most depots, it is the closest station to one DHL depot (Figure 4.14), which makes it beneficial for DHL to save VKT.

Following this, scenario P4 focuses on the location choice of the PL network where 5 high-traveller-demand train stations and tram stops are selected. This results in a slightly higher match rate compared to scenario P1, but the transport performance is worse than scenario P1, since the distance between the depots and the tram stops with high demand is higher than that of the train stations with lower demand, as shown in Figure 5.4. The benefits brought by higher traveller demand and match rate cannot outweigh the increased distance from the depots to tram stops. A trade-off can be observed in the traveller demand and the distance from depots to the station. The 5-station network might be a balanced choice of high traveller demand and low depot-to-station distance. This trade-off might change given a different outlier parcel demand or geographical distribution.

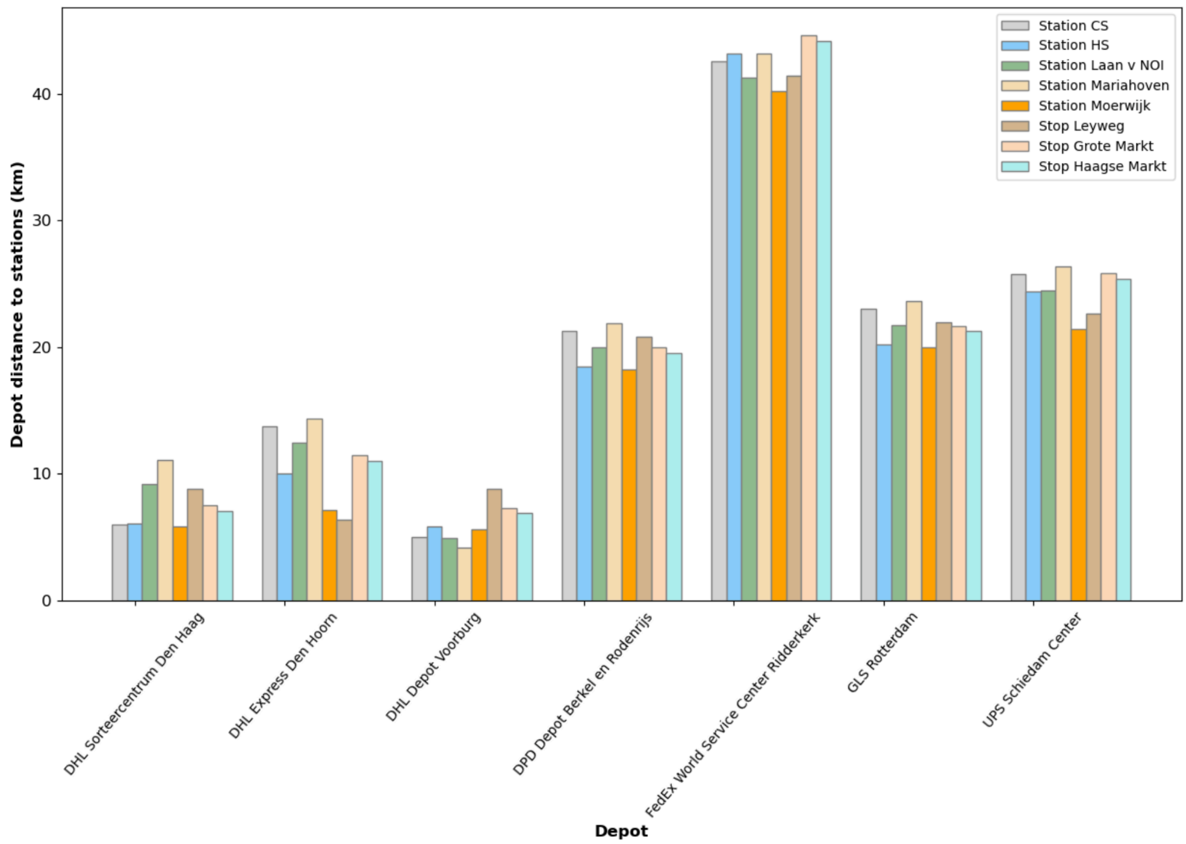


Figure 5.4: Depot distance to stations and stops

5.4.4. Different parcel locker capacity allocation scheme

The purpose of this experiment is to test the impacts of different PL capacity allocation schemes on the performance of the crowdshipping service. Instead of using the default total PL capacity of 2000 (400*5) which is larger than the total outlier parcel demand of 1377, the total PL capacity is reduced to 1250 to set constraints on PL capacity.

Table 5.6 shows the simulation results of different PL capacity allocation scheme. In scenario P5, all PL are allocated with 250 lockers. In scenario P6 the PLs at station Moerwijk and HS are allocated with 400 lockers as they have a higher match rate as shown in Figure 5.1, and the other 3 PLs are therefore allocated with 150 lockers.

Table 5.6: Simulation results of different PL capacity allocation scheme

Scenario specification		P5: Same capacity	P6: Moerwijk and HS more capacity
Per PL capacity		250*5	400*2, 150*3
Total PL capacity		1250	
Category	**Indicator**		
Crowd-shipping service	Number of matched parcels	931	991
	Match rate (%)	67.61	71.97
	Compensation per VKT reduction (euro/km)	13.95	14.59
	Average (SD) PL occupancy rate (%)	74.48 (33.22)	76.22 (28.13)
Transport & environment	Total LMD VKT (km)	13298.93	13291.84
	Total VKT reduction (%)	2.92	2.97
	VKT reduction per matched parcel (km)	0.43	0.411
	Car OC percentage (%)	8.16	7.37
	Average (SD) detour distance by OC (km)	0.414 (0.184)	0.436 (0.201)
	Allocated car detour distance per matched parcel (km)	0.034	0.032

Comparing scenario P6 with scenario P5, a higher match rate is achieved as the larger PL capacity at popular stations can attract more OCs. An increase in PL occupancy rate is also observed in scenario P6, which validates that the hierarchical allocation scheme can increase the PL operation efficiency. However, the service efficiency in reducing VKT drops. This could be explained as that station HS is not the closed station to most depots (Figure 5.4), and the benefits brought by larger PL capacity and higher match rate cannot compensate the increase in VKT. The similar trade-off between PL capacity and distance to depot is observed in this experiment.

5.5. Discussion

In this section, the relevance and significance of the simulation results to the research objectives are discussed and compared with related studies.

This study aims at investigating the transport impacts of crowdshipping services for the last-mile delivery of parcels with high environmental impacts.

The simulation results of the case study in The Hague show that compared to outsource all parcels to crowdshipping, prioritizing outlier parcels for the PT-based crowdshipping service could achieve a larger reduction in van kilometres travelled, thus leading to less traffic congestion and emissions generated by the delivery vans. In addition, as the proposed service mainly uses the extra capacity of PT and active modes for delivery, the car detour distance by OCs is very small. Therefore it can be concluded that a PT-based crowdshipping service for outlier parcels could bring sustainability benefits to LMD.

Given a percentage of 2.4% of outlier parcels, up to 3.93% of VKT reduction can be achieved. The ratio of VKT reduction to outlier percentage is around 2, which is similar to the results of Zhang and Cheah (2023), which show that a total of 11% of parcels could lead to a 20% reduction of delivery vehicle kilometres travelled in a PT-based crowdshipping service.

Moreover, the results show that crowdshipping could be more beneficial to LSPs with lower market shares. A percentage of only 0.64% outlier parcels from the two smallest LSPs can reduce 1.57% of VKT. The ratio of VKT reduction to outlier percentage is larger than the average ratio of 2, which proves the benefits of the crowdshipping service for outlier parcel demand from LSPs with low market shares. For outlier parcels from LSPs with larger market shares, the crowdshipping service might bring negative transport impacts. When the percentage of outlier parcels is quite small, in other words, all parcels have similar low environmental impacts, outsourcing to a crowdshipping service could decrease the operation efficiency and increase VKT.

Behavioural considerations are taken when calculating traveller's willingness to work as OC, and the results show that a compensation of €6 could attract half of the travellers and achieves a moderate VKT reduction, which is in line with the findings by Tapia et al. (2023), where their estimation of approximate compensation values for OC is also €6.

Parcel locker is included in this study as transfer points between conventional couriers (LSPs) and occasional couriers. The results show that expanding the PL network size does not help achieve more VKT reduction. Given the 2.4% outlier parcel demand, the 5-train-station PL network appears to be the optimal option. The diminishing marginal benefits of adding PL are also observed by Zhang et al. (2023), the results of which show that when the matching becomes stabilized under a certain compensation level, the benefits of adding PL are very little.

Next to PL network size, simulation experiments of different PL location choices and different PL capacity allocations show that a trade-off exists between the distance from depot to PL and the travel demand at the PL station. A station with high traveller demand can achieve a high match rate and a potential reduction in VKT, and this effect get amplified when more PL capacity is allocated to this station, but the crowdshipping service efficiency, for example the VKT reduction per matched parcel, might drop as a result of the increased distance from depot to the station.

6 Conclusion & recommendation

This chapter presents the conclusions and recommendations of this study. First, answers to each sub-research question as well as the answer to the main research question in Chapter 1 are presented. Following that, the limitations and recommendations of this study are discussed.

6.1. Conclusion

This study investigates the sustainable potentials of crowdshipping service to address the growing problem of traffic congestion and emission in urban freight systems, with a specific focus on the outlier parcels that have high environmental impacts in last-mile delivery. Four sub-research questions are first answered, and then the answer to the main research question is presented.

RQ1. What definition rule(s) can be formulated for identifying the outlier parcels?

The decision rule for identifying the outlier parcels can be formulated from an environmental perspective. The parcels that have a higher carbon footprint/higher environmental impact generated in the last-mile delivery process are defined as outlier parcels. The parcel carbon footprint is measured as the last-mile delivery effort required for the logistics service providers to deliver it. The outlier parcels are therefore the ones with higher delivery effort, which include the parcels in low-demand areas and the parcels that are located far away from the depots and the parcels.

This decision rule/method is implemented for each logistics service provider respectively, and large differences are observed among logistics service providers with different market shares. Small logistics service providers have a significantly higher overall carbon footprint distribution than large ones, which indicates that their last-mile delivery is less efficient and has a higher environmental impact. This could be explained by the fact that the privatisation of the delivery services leads to multiple service providers, and different levels of operation efficiency because of the gains and losses in economies of scale.

RQ2. What possible scenario(s) can be proposed to test the impacts of crowdshipping services for outlier parcel delivery?

A public transport-based crowdshipping system with parcel lockers installed at the train stations is proposed in this project, where train passengers work as occasional couriers to pick up the parcels at the parcel locker installed at the train stations and deliver the parcels to consumers on their following trips. The transport mode choice is based on the sustainability goal of crowdshipping service and the travel characteristics in the Netherlands. The parcel locker is chosen as the infrastructure alternative to facilitate a smooth transfer between the logistics service providers and occasional couriers and to consolidate the outlier parcels for higher efficiency of crowdshipping service.

There are a few assumptions made in the proposed scenario to avoid new crowdshipping trips and too many detours generated and constrain the traffic externalities brought by the crowdshipping service. The most important ones are that the occasional couriers do not change their original origin and destination zones, and the outlier parcels can only be matched with the occasional courier with the same destination zone.

As for the matching of parcel and occasional courier and the parcel allocation from depots to PL at the train stations, a matching algorithm is proposed. The matching of parcel and occasional courier is based on the gains in value of time of the occasional courier, and the parcel allocation is based on the proximity from depot to PL. In this way both the behavioural and sustainable aspects are taken into consideration.

RQ3. How can the delivery scenarios of crowdshipping service for outlier parcels be simulated?

The delivery scenarios of crowdshipping service for outlier parcels can be simulated in an agent-based simulation way. The agents of the system include: each outlier parcel that is eligible for crowdshipping, each train passenger who is willing to deliver the parcel in his or her trip destination zone, the logistics service provider that determines which station to allocate the parcel and the compensation paid for each delivery task, and the parcel locker installed at the train stations. Each agent has its objectives and constraints, in such a way the system can capture individual decision-making and manage the interaction among agents.

RQ4. How do different crowdshipping service settings affect its performance in last-mile delivery?

A case study is applied in The Hague, a very urbanized city. With the segregation of outlier parcels and the selection of train travellers and train stations in The Hague, three crowdshipping service settings are tested in the simulation experiments, with the first one focusing on the demand side and the other two focus on the supply side of the proposed crowdshipping service: outlier parcel demand from logistics service providers (LSPs) with different market shares, different compensation levels and different parcel locker (PL) networks.

First, the performance of the crowdshipping service is dependent on the different outlier parcel demand from LSPs with different market shares. For large LSPs such as PostNL, as its current operation is efficient enough as a result of the economies of scale brought by the high demand, there are few outlier parcels and thus no need to outsource its parcels. For LSPs with less efficient operations in last-mile delivery as a result of their relatively low parcel demand and depot density, outsourcing the parcels that require high delivery effort to crowdshipping service can help them reduce their van kilometres travelled (VKT) in last-mile delivery. And the service can work quite efficiently, a 1.57% of VKT reduction could be achieved with only 0.64% of the total parcel demand.

Second, compensation has a positive influence on the system performance. The VKT reduction increases with the increase in compensation, as more passengers are willing to work as occasional couriers.

Third, as for the parcel locker network, a small-size parcel locker network performs better than a large one. In an expanded parcel locker network, though more parcels can be matched with occasional couriers, the benefits in VKT reduction brought by the increase in matched parcels is unable to outperform the VKT increase brought by the increased number of PLs that the deliver vans need to visit.

As for the location choice of parcel lockers, train stations and tram stops with high traveller demand could bring more potential supply to crowdshipping service, which could lead to a high number of matched outlier parcels and more VKT reduction in last-mile delivery. However, a trade-off is observed in the traveller demand and the distance from depots to the station, as the VKT increase brought by the increased distance from depots to the station might outweigh the VKT savings brought by the increased number of matched parcels. The same trade-off applies to the allocation scheme of parcel locker capacity. Simply allocating more capacity to parcel lockers at the stations where there is a lot of traveller demand may not improve the performance in VKT reduction.

Answer to the main research question:

To what extent does crowdshipping service for outlier parcel delivery affect the transport performance of last-mile deliveries?

To explore the impacts of crowdshipping service for outlier parcels on last-mile delivery, a delivery effort-based carbon footprint calculation method is applied, a public transport-based crowdshipping delivery scenario with the parcel locker installed at train stations as transfer points is proposed, and a matching algorithm that considers individual traveller's decision making is developed in this project. These methods together form an integral crowdshipping service and are applied to a case study in The Hague, which is one of the most urbanised cities in The Netherlands.

Overall, the results show that the proposed service can be beneficial to the transport system of last-mile delivery, as it mainly uses the extra capacity of public transport and active modes, with few car detour distances generated.

In addition, prioritizing outlier parcels for crowdshipping services is more effective in reducing the total van kilometres travelled than crowdshipping services for all parcels. With 1377 outlier parcels outsourced to the crowdshipping service, which is about 2.4 % of the total parcel demand, a VKT reduction of 4 % can be achieved.

Moreover, the simulation results show that crowdshipping could be more beneficial to LSPs with low market shares. A percentage of only 0.64% outlier parcels from the two smallest LSPs can reduce 1.57% of VKT, while the crowdshipping service might bring negative transport impacts for LSPs with larger market shares. And the service efficiency is also higher when prioritizing outlier parcels from LSPs with low market shares, with a high match rate of nearly 95% and a maximum of 0.633km reduction in VKT can be achieved by single outlier parcel. This is because for the LSPs with low market shares, a higher parcel carbon footprint is observed, as the low parcel demand makes it hard to achieve the economies of scale and thus a less efficient operation in last-mile delivery. By outsourcing these parcels with high carbon footprint to the crowdshipping service, the increase in LMD operation efficiency could be maximized and thus the crowdshipping service could achieve its largest sustainability potential.

Nevertheless, the costs of implementing such a system could be very high, as the travellers might require a very high compensation for them to travel additional time to deliver a parcel. The project uses €6 as the compensation for each delivery task, and the results show that the lowest compensation paid per VKT reduction (km) is around €10.

As the proposed crowdshipping service uses parcel lockers as the transfer points between LSPs and OCs, the service performance is also dependent on the PL network configurations. The results show that a small-size PL network with a certain level of consolidation works the best for the crowdshipping service, with good performance in both VKT reduction and service efficiency. And the traveller demand at the train stations and the distance from depots to PLs/train stations could respectively increase and decrease the service performance, which emphasized the importance of carefully balancing this trade-off when determining PL location and allocating locker capacity.

6.2. Recommendation

The section begins with a reflection on the methodology used in this study and the potential improvements for these limitations are elaborated. Following that, a recommendation on the possible future research directions is discussed.

Reflection on the methodology

To begin with, there are a few strict assumptions made in the formulation of the delivery scenario, such as the same destination zone constraint and each OC can only carry one parcel, though the same destination zone assumption is made to limit the possible traffic externalities brought by the crowdshipping service, it is still a simplification of the real-world operations. Relieving some of these assumptions and/or exploring the impacts of these operational characteristics on crowdshipping services could provide a more detailed evaluation of the service.

Second, to calculate the additional travel time for OCs to deliver the parcel in the parcel destination zone, twice the Manhattan distance is taken to represent the intrazonal detour distance. This is a very rough approximation and more detailed research needs to be done on calculating the detour distances, such as incorporating a more microscopic simulation of the detailed parcel destination and a traffic assignment model that takes into account the real-world road network and generates a more realistic routing.

Third, the simulation model only simulates the static operation of a crowdshipping service of 1 day and assumes that the PL should have a capacity that can accommodate all the outlier parcels, a more realistic evaluation on the performance of PL could be achieved by incorporating the dynamic operations such as the real-time variations in PL remaining capacity, as the time travellers would pickup and LSPs would drop off parcels is spread throughout the day.

Fourth, the crowdshipping demand and supply algorithm proposed in this study uses the proximity of depots to PLs as a main matching criteria and does not consider the distance from PLs to the final parcel destination for OCs. It would be interesting to incorporate more travel attributes of OCs' existing trips from PLs at the train stations to their final destination zones into the matching algorithm.

Fifth, the implemented PL network assumes that it is shared by all LSPs, while the single-operation mode of PL might be more beneficial in terms of efficiency gains. It is recommended to investigate the different operation modes of PL network among different LSPs, which could facilitate a better implementation of crowdshipping services.

Sixth, the value of time for working as OC is taken from an SP experiment from literature and remains constant under different crowdshipping scenarios. It would be interesting to conduct real-life pilot experiments to examine the behavioural preferences among different operational characteristics and test how the preferences might change with the development of the service.

Seventh, the compensation paid per delivery tasks is assumed to be fixed in this study, which is a simplistic representation of the crowdshipping operation. A dynamic pricing scheme, which includes more operational characteristics such as the carbon footprint value, as well as the distance from depot to PLs and from PLs to final destination, would lead to a more detailed design and evaluation of the service.

Eighth, the train traveller trip data is collected by selecting the PT trips with origins and/or destinations within the 1-km proximity of the train stations, which is a very rough approximation. It is recommended to employ a traffic simulation model that incorporates the real-world road network and PT information to generate detailed itinerary information given the trip origin and destination, which could provide more precise train traveller trip data.

Directions for future research

To better understand the impacts of crowdshipping service for outlier parcels in last-mile delivery, there are some recommendations for future research directions.

From a broader point of view, it would be interesting to test the proposed scenario on a larger geographical scale. As the proposed method of applying public transport stations and stops as transfer points between LSPs and OCs aims at using existing traveller trip capacity to reduce the van kilometres travelled (VKT) in LMD, it might be more beneficial to implement it on a larger geographical scale. This is because LSPs with smaller market share usually do not have a dense network of depots, as can be seen in the report, they need to travel across cities to deliver the parcels. Implementing the train station-based PL system on a larger scale would allow the parcel to be matched with cross-city travellers, i.e., a higher percentage of LMD could be outsourced to existing PT traveller trips, which could save more VKT per parcel than the implemented within-city scale. And as cross-city train trips are quite popular in The Netherlands and the large train trip volume could provide a large supply of potential occasional couriers for crowdshipping service. A possible example could be an occasional courier departing from Rotterdam Central Station, picking up an outlier parcel of FedEx at a parcel locker installed at the station, and bringing it to The Hague by train. In such a way, FedEx could save almost all the last-mile delivery effort of this parcel, since its depot is located quite close to Rotterdam Central Station.

What's more, it is recommended to investigate the definition rules of outlier parcels from different perspectives. Environmental impact in the LMD from a societal perspective is chosen in this study, other perspectives such as from the LSPs' perspective, the delivery cost might be chosen as the definition rule, as they might want to reduce the increasing delivery costs in LMD. By comparing the service performance of different definition rules for outlier parcels, crowdshipping services for outlier parcels could be evaluated more systematically.

In addition, in it also recommended to use the outlier segregation results, the proposed delivery scenario and simulation results as a starting point and elaborate it with long-term development of the crowdshipping service. For example, PLs could also be installed as the transfer points between OCs and end customers, if the outlier parcel demand in certain zones are high enough to reach the economies of scale. By implementing this, the failed delivery of crowdshipping service could be avoided. Or more travellers could be involved in the crowdshipping service rather than just PT travellers, as the train stations are often located in urban areas with lots of places of interests.

Following that, more research could be done on the efficient design a PT-based crowdshipping system. As this study shows the sustainable potential of such a system in a simplified setting, more extensive studies such as those on the PT-based PL network design could provide more insights on the potential of PT-based crowdshipping service.

Lastly, investigating on the different strategies for dealing with the failed delivery of crowdshipping service would bring more complete evaluation of the crowdshipping service, as the failed delivery would pose a large challenge to the successful implementation of this service.

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A
Python code

Four main parts of python code are included here:

- Parcel carbon footprint calculation.
- The calculation of intrazonal distance and the selection and sorting of potential OCs.
- The matching of crowdshipping demand and supply.
- Updating the destination zone of matched parcels.

The first part is about the parcel carbon footprint calculation:

Listing A.1: Code for parcel carbon footprint calculation

```python
def CF_calculation(label):

    # Import Schedule data
    path = f'Input/ParcelSchedule_{label}_TotalUrbanDelivery.csv'
    parcels = pd.read_csv(path)

    # TourCarbonFootprint
    # calculate the total tour distance and total number of parcels
    parcels['TotalTourDist'] = np.round((parcels.groupby('Tour_ID')['TourDist'].transform('sum')),4)
    parcels['Total#Parcels'] = np.round((parcels.groupby('Tour_ID')['N_parcels'].transform('sum')),4)
    # Calculate the total carbon footprint for each tour
    parcels['TourCarbonFootprint'] = np.round((parcels['TotalTourDist']*parcels['Total#Parcels']),4)

    # ClusterWeightingFactor
    # add the great-circle distance (GCD) of each cluster
    parcels['ClusterGCD'] = 0.0
    for index, cluster in parcels.iterrows():
        parcels.at[index,'ClusterGCD'] = DepotSkim[invZoneDict[cluster['D_zone']]-1,cluster['Depot_ID']-1]
    # calculate the weight for each cluster
    parcels['ClusterWeight'] = np.round((parcels['N_parcels']*parcels['ClusterGCD']),4)
    # in order to calculate weighting factor, first need to calculate the total weight for each delivery tour
    parcels['TotalClusterWeight'] = np.round((parcels.groupby('Tour_ID')['ClusterWeight'].transform('sum')),4)
    parcels['ClusterWeightingFactor'] = np.round((parcels['ClusterWeight']/parcels['TotalClusterWeight']),4)
```

```
    # ParcelCarbonFootprint
    parcels['ClusterCarbonFootprint'] = parcels['TourCarbonFootprint']*parcels['
        ClusterWeightingFactor']
    parcels['ParcelCarbonFootprint'] = parcels['ClusterCarbonFootprint']/parcels['
        N_parcels']

    return parcels, DepotSkim
```

The second part is about calculating intrazonal distance and selecting and sorting potential OCs:

Listing A.2: Code for calculating intrazonal distance and selecting potential and sorting OCs

```
def intra_distance (gdf):

    gdf['Intra Manhattan distance'] = ""
    gdf['Ave. Intra Manhattan distance']= ""
    gdf['Std. Intra Manhattan distance'] = ""

    # gdf['Euclidean distance']=""

    for i, area in gdf.iterrows():
        polygon = area.geometry
        coor_list = list(polygon.exterior.coords[:-1])
        # n = len(coor_list)
        centroid_x = polygon.centroid.x
        centroid_y = polygon.centroid.y
        dist = []
        dist2 = []

        for coor in coor_list:
            x = coor[0]
            y = coor[1]
            dist.append(abs(x-centroid_x) + abs(y-centroid_y))
            # dist2.append(math.dist([centroid_x,centroid_y],[x,y]))
            mean = np.mean(dist)
            std = np.std(dist)

        gdf.at[i,'Intra Manhattan distance'] = dist
        gdf.at[i,'Ave. Intra Manhattan distance'] = mean
        gdf.at[i,'Std. Intra Manhattan distance'] = std
        # np.mean(dist)
        # gdf.at[i,'Euclidean distance'] = dist2
    return gdf

d = {'home_based': pd.Series([14.43,73.83],
                      index=['low_income', 'high_income']),
     'commute_based': pd.Series([38.57, 122.77],
                      index=['low_income', 'high_income'])}
vot = pd.DataFrame(d)

def compare_vot(trip, gdf, compensation):
    '''
    input: one passenger trip
    output: return the choice (to be or not to be an OC) and the discrepancy of
        two VoTs
    '''
    #### calculate the addtional travel time (in min)

    # pickup time at the PL at station is a random number, following a normal
        distribution

    time_pickup = (np.random.default_rng().normal(0.8,0.4))/60 # in hour


    # detour distance is calculated as twice the randomly drawed Intrazonal
        Manhattan distance
    # the draw also follows a normal distribution
    # in meters
    zone = int(trip['D_zone'])
    mean = gdf.loc[zone]['Ave. Intra Manhattan distance']
```

```python
    std = gdf.loc[zone]['Std. Intra Manhattan distance']
    dist_detour = (2 * (np.random.default_rng().normal(mean,std)))/1000 # in kilometers(km)
    if dist_detour<0: dist_detour = 0

    v_walk = 4.8
    v_cycle = 17.3
    # https://swov.nl/en/fact/pedelecs-7-how-fast-do-pedelec-and-speed-pedelec-riders-cycle
    v_car = 50
    # https://autotraveler.ru/en/netherlands/#speed-limit

    if trip['Mode'] == 'Public Transport':
        speed_detour = (v_walk + v_cycle)/2

    elif trip['Mode'] == 'Walking or Biking':
        # average speed of bicylce and walk, in km/h
        speed_detour = v_walk * 0.7 + v_cycle * 0.3

    elif trip['Mode'] in ['Car','Car as Passenger']:
        speed_detour = v_car

    ### detour time in h
    time_detour = dist_detour/speed_detour #in h

    ### drop-off time (in hour)
    # https://www.sciencedirect.com/science/article/pii/S1361920919309277?via%3Dihub#s0030
    if trip['Mode'] in ['Car','Car as Passenger']:
        time_dropoff = (np.random.default_rng().normal(3.5,1))/60
    else:
        time_dropoff = (np.random.default_rng().normal(1.5,1))/60

    # sum up all additional time
    add_time = time_pickup + time_detour + time_dropoff
    trip['additonal time'] = add_time
    trip['compensation'] =  compensation

    ### Vot of CS (euro/h)
    vot_cs = compensation/add_time
    # trip['VoT CS'] = vot_cs

    # VoT
    d = {'home_based': pd.Series([14.43,73.83],
                      index=['low_income', 'high_income']),
     'commute_based': pd.Series([38.57, 122.77],
                      index=['low_income', 'high_income'])}
    vot = pd.DataFrame(d)

    home_based = ['Home', 'Groceries', 'BringGet','Leisure', 'Other']
    commute_based = ['Work', 'Social','Business', 'Touring', 'Services', 'NonGroc']

    if trip['income'] != 'high' and trip['following_purpose'] in home_based:
        vot_diff = vot_cs - vot.iloc[0,1]
    elif trip['income'] == 'high' and trip['following_purpose'] in home_based:
        vot_diff = vot_cs - vot.iloc[1,1]
    elif trip['income'] != 'high' and trip['following_purpose'] in commute_based:
        vot_diff = vot_cs - vot.iloc[0,1]
    elif trip['income'] == 'high' and trip['following_purpose'] in commute_based:
        vot_diff = vot_cs - vot.iloc[1,1]
```

```
    else:
        print(trip)

    trip['VoT discrepancy'] = vot_diff

    # add a column indicating CS choice
    if vot_diff > 0:
        trip['CS'] = 'Eligible'
    else:
        trip['CS'] = 'No'

    return trip['additonal time']*60, trip['compensation'],trip['VoT discrepancy'], trip['CS'], dist_detour

def sort_OC (trips,gdf,compensation):

    trips1 = trips.copy()
    trips1.loc[:,['CS']] = pd.Series(dtype='object')

    # start iterate through the trip set, calculate utility for each
    for i,trip in trips1.iterrows():
        trips1.loc[i,['additonal time (min)']], trips1.loc[i,['compensation']], \
        trips1.loc[i,['VoT discrepancy']],trips1.loc[i,['CS']], trips1.loc[i, ['Detour distance']] = compare_vot(trip, gdf,compensation)

    # sort the utility from highest to lowest, and exclude the ones with negative values
    trips_valid0 = trips1[trips1['CS'] == 'Eligible'].sort_values(by='VoT discrepancy',ascending = False)
    trips_valid = trips_valid0.sort_values(by='Mode',ascending = False)

    return trips_valid
```

The third part is about the matching of crowdshipping demand and supply:

Listing A.3: Code for matching parcels with OC and PL

```
def import_parcels(parcels_csv):

    # import parcel data
    parcels = pd.read_csv(parcels_csv)

    # Merge parcel data with depot location
    parcels_depot = parcels.join(depots.set_index('Depot_ID'), on = 'Depot_ID', rsuffix='_1')

    # keep necessary columns
    cols = ['Unnamed: 0', 'CEP', 'Name', 'Depot_ID','O_zone',
           'D_zone', 'N_parcels','AREANR', 'x', 'y','ParcelCarbonFootprint']

    # sort the df by 'ParcelCarbonFootprint' in descending order
    parcels_depot_1 = parcels_depot[cols].rename(columns={'AREANR':'Depot_zone'}).sort_values(by='ParcelCarbonFootprint',ascending = False)

    return parcels_depot_1

def expand_parcel(parcels_depot):

    # Create a new DataFrame with additional rows based on 'N_parcels'
    expanded_parcels = pd.DataFrame()

    for _, row in parcels_depot.iterrows():
        n_parcels = row['N_parcels']
        # Create additional rows based on 'N_parcels'
        expanded_parcels = pd.concat([expanded_parcels, pd.DataFrame([row] * n_parcels)], ignore_index=True)

    # Set the value in 'N_parcels' to 1
    expanded_parcels['N_parcels'] = 1

    # Display the result
    return expanded_parcels

def select_parcel(expanded_parcels, n):

    selected_parcels = pd.DataFrame()

    cep_list = expanded_parcels['CEP'].drop_duplicates().values.tolist()

    for cep in cep_list:
        cep_parcels = expanded_parcels[expanded_parcels['CEP'] == cep]
        cep_share = len(cep_parcels)/len(expand_parcels)

        cep_sample_size = int(np.floor(n*cep_share))
        cep_select = cep_parcels.sample(cep_sample_size)

        selected_parcels = pd.concat([selected_parcels, cep_select], ignore_index=True)

    return selected_parcels

def find_nearest_available_station(parcel, station_set):
    """
    Find the name of the nearest availble station to a depot

```

```
    Parameters:
    - static_depot_coordinates (tuple): Coordinates of the static depot (e.g., (x, y)).
    - the destination zone of the parcel
    - available_stations (pd.DataFrame): DataFrame containing stations with columns 'name', 'x_coor', 'y_coor', and 'remaining_capacity'.

    Returns:
    - str or None: Name of the nearest station if available, None if all stations are full.
    - pd.DataFrame: Updated DataFrame of available stations with usage information of remaining capacity.
    """

    parcel_depot_zone = invZoneDict[int(parcel['Depot_zone'])]
    parcel_dest_zone = invZoneDict[int(parcel['D_zone'])]
    available_stations = station_set.copy()

    nearest_station_name = None


    # Check if there is any remaining capacity in any station
    if (available_stations['remaining_capacity'] == 0).all():
        status = 'All stations are full'
        print(available_stations)

    else:

        depot_dest_dist = SkimDistance[(parcel_depot_zone-1)*nZones+(parcel_dest_zone-1)] / 1000

        eligible_stations = available_stations.copy()

        for j, stationj in available_stations.iterrows():

            staion_zone = invZoneDict[stationj['AREANR']]
            depot_station_dist = SkimDistance[(parcel_depot_zone-1)*nZones+(staion_zone-1)] / 1000

            eligible_stations.loc[j,['Depot to station distance']] = depot_station_dist

            if depot_station_dist > depot_dest_dist + 3.0: eligible_stations = eligible_stations.drop(j)

        print(eligible_stations)

        if len(eligible_stations) != 0:

            real_availble_station = eligible_stations[eligible_stations['remaining_capacity']>0]

            if len(real_availble_station) != 0:
                real_availble_station = real_availble_station.sort_values(by='Depot to station distance').iloc[0]
                nearest_station_name = real_availble_station['name']
                status = 'Yes'
            else:
                status = 'All eligible stations are full'
        else:
            status = 'No eligible stations'
```

```python

    # Return the nearest station name
    return nearest_station_name, status

def depot_station_passenger(trips,parcels_depot,station, areas_intra, compensation
,PL_capacity, PL_capacity_IC):
    """
    Match each parcel to most suitable PL at the station and passenger with the
       same destination zone

    Parameters:
    - trips (pd.Dataframe): passenger trips with assigned stations.
    - parcels_depot (pd.Dataframe): parcel sets with depot coordinates
    - station (pd.Dataframe): all available station sets with coordinates
    - compensation (int)
    - PL_capacity (int)

    Returns:
    - pd.DataFrame: Updated DataFrame of matched and unmatched parcels.
    """

    # protect the original datasets
    pas_trips = trips.copy()
    parcels = parcels_depot.copy()
    pas_stations = station.copy()

    # initialize new columns
    parcels['CS'] = ""
    parcels['Crowdshipper'] = ""
    parcels['Station'] = ""
    parcels['New_D_zone'] = ""
    # this df is just for function operation
    pas_trips['CS'] = ""
    # this df stores all the trips with a 'CS' column
    full_trips = pas_trips.copy()
    # this df only stores the trips which the OC is delivering the parcel
    oc_trips = pd.DataFrame()

    # initialize the capacity of PL
    for h, stationh in pas_stations.iterrows():
        #if stationh['type'] == 'IC station':
        if stationh['name'] in ['Station Moerwijk', 'Station HS']:
            pas_stations.at[h,'PL capacity'] = PL_capacity_IC
            pas_stations.at[h,'remaining_capacity'] = PL_capacity_IC
            pas_stations.at[h,'PL usage'] = 0

        else:
            pas_stations.at[h,'PL capacity'] = PL_capacity
            pas_stations.at[h,'remaining_capacity'] = PL_capacity
            pas_stations.at[h,'PL usage'] = 0


    #### the main agent of the simulation is PARCEL

    for i,parcel in parcels.iterrows():

        # print('Starting the matching for parcel:',i)

        # get the coordinates of the depot of this parcel
        x = parcel['x']
        y = parcel['y']
```

```
        parcel_dest = parcel['D_zone']
        parcel_depot_id = parcel['Depot_ID']

         # Store all passenger destinations in one list
        # pas_trips_valid = pas_trips[pas_trips['CS'] != 'Yes']
        pas_dest_list = pas_trips['D_zone'].drop_duplicates().values.tolist()


        #### first check if there are passengers with the same destination
        if parcel_dest in pas_dest_list:

            # print(f'Destination {parcel_dest} found for parcel {i}')

            # store all passengers with the same destination into one dataset (P1)
            pas_set_p1 = pas_trips[pas_trips['D_zone'] == parcel_dest]

            # Calculate the VoT discrepancy for each traveller in P1,
            # filter the ones with VoT gains
            # and sort by VoT gains (highest to lowest)
            pas_set_p2 = sort_OC(pas_set_p1,areas_intra,compensation)

            if len(pas_set_p2)==0:
                    # print(f'No eligble travellers found for parcel {i}')
                    parcels.at[i,'CS'] = 'No eligble travellers found'

            # found eligible travellers in P1 and store them in set P2
            else:
                # Store all the stations of P2
                p2_station_list = pas_set_p2['Station'].drop_duplicates().values.tolist()
                p2_station = pas_stations[pas_stations['name'].isin(p2_station_list)]
                # print(p2_station)
                nearest_available_station, find_station_status = find_nearest_available_station(parcel, p2_station)

                if nearest_available_station is not None:

                    parcels.at[i,'CS'] = 'Yes'

                    pas_set_p3 = pas_set_p2[pas_set_p2['Station'] == nearest_available_station]

                    # match the parcel with OC with highest VoT gains of whom travels by the nearest availble station
                    pas_index = pas_set_p3.index[0]
                    # mark this trip in the full_trip df
                    full_trips.loc[pas_index,'CS'] = 'Yes'
                    # store all matched trips into oc_trip df
                    oc_trips = pd.concat([oc_trips,pas_set_p3.iloc[0].to_frame().T])

                    # get the person id
                    person_id = pas_set_p3['person_id'].values[0]

                    print(f"Passenger {person_id} at Station {nearest_available_station} is found for parcel {i} to destination {parcel_dest}")

                    parcels.at[i,'Crowdshipper'] = person_id
                    parcels.at[i, 'Station'] = nearest_available_station
```

```
                     parcels.at[i,'New_D_zone'] = p2_station[p2_station['name'] == nearest_available_station]['AREANR'].values[0]
                     parcels.at[i,'Mode'] = pas_set_p3.iloc[0]['Mode']

                     ### Update the remaining capacity
                     # Find the index of the row where the 'name' column matches the 'nearest_available_station'
                     index_to_update = pas_stations.index[pas_stations['name'] == nearest_available_station].tolist()

                     # Update the 'remaining_capacity' column for the found row
                     # if index_to_update:
                     pas_stations.loc[index_to_update, 'remaining_capacity'] -= 1
                     pas_stations.loc[index_to_update, 'PL usage'] += 1


                     # remove this passenger from the initial passenger set, as one passenger can only bring 1 parcel
                     # pas_trips.loc[lambda pas_trips: pas_trips['person_id'] == person_id, 'CS'] = 'Yes'
                     pas_trips = pas_trips.drop(pas_trips[pas_trips['person_id'] == person_id].index)
                 else:

                     # print(f'No available/eligible PL found for parcel {i} at destination {parcel_dest}: {find_station_status}')
                     parcels.at[i,'CS'] = find_station_status

            # No passengers with the same destination
        else:
            # print(f'No destination {parcel_dest} found for parcel {i}')
            parcels.at[i,'CS'] = 'No passengers with the same destination.'

    for i, stationi in pas_stations.iterrows():
        pas_stations.at[i, 'PL occupancy rate'] = np.round(100*((stationi['PL capacity'] - stationi["remaining_capacity"])/stationi['PL capacity']),2)


    print('--------- print KPIs -------------')
    # Total number of outlier parcels'
    print(f'Total number of outlier parcels is: {len(parcels)}')
    # Number of matched parcel
    matched = parcels[parcels['CS'] == 'Yes']
    print(f'Total number of matched parcels is: {len(matched)}')
    # match rate
    print(f'Match rate is: {np.round(100*len(matched)/len(parcels),2)}')

    # Total detour by OC
    print(f'Total detour distance (km) by OC is: {np.round(np.sum(oc_trips["Detour distance"]),2)}')
    print(f'Average detour distance (km) by OC is: {np.round(np.mean(oc_trips["Detour distance"]),3)} ({np.round(np.std(oc_trips["Detour distance"]),3)})')
     # detour by car only
    oc_trips_car = oc_trips[oc_trips['Mode'].isin(['Car','Car as Passenger'])]
    print(f'Car percentage is: {np.round(100*len(oc_trips_car)/len(oc_trips),2)}')
    print(f'Total detour distance (km) by car is:{np.round(np.sum(oc_trips_car["Detour distance"]),2)}')
    print(f'Average detour distance (km) by car is: {np.round(np.mean(oc_trips_car["Detour distance"]),3)} ({np.round(np.std(oc_trips_car["Detour distance"])
```

```
        ,3)})')
    print(f'Car detour distance per matched parcel is: {np.round((np.sum(
        oc_trips_car["Detour distance"])/len(matched)),3)}')
    # total compensation paid
    print(f'Total compensatoin paid is {compensation*len(matched)}')
    # PL usage
    print(f'Average PL occupancy rate: {np.round(np.mean(pas_stations["PL
        occupancy rate"]),2)} ({np.round(np.std(pas_stations["PL occupancy rate"])
        ,2)})')

    pas_stations = pas_stations.drop(columns=['remaining_capacity'])

    return parcels, pas_stations, oc_trips

# prepare the inputs for the matching algorithm
label = 'Total outliers_base_new'
expand_parcels = expand_parcel(import_parcels(f'Input/{label}.csv'))

#select_parcels = select_parcel(expand_parcels, 9052)
#select_parcels = select_parcel(expand_parcels, 1380)
#select_parcels

## choose different LSP demand
#expand_parcels1 = select_parcels.copy()
# expand_parcels1 = expand_parcels[expand_parcels['CEP'].isin(['FedEx', 'GLS'])]
#expand_parcels1 = expand_parcels.copy()
expand_parcels1 = expand_parcels[~expand_parcels['CEP'].isin(['PostNL'])]

station5 = station[station['type'] != 'Tram stop']

# call the matching algorithm
matching, stationing, trips1 = depot_station_passenger(trips,expand_parcels1,
    station5,areas_intra,6,250,250)

# show the matching result
stationing = stationing.sort_values(by='PL occupancy rate', ascending = False)
matching.groupby('CS').agg({'CS':'count'})
matched = matching[matching['CS'] == 'Yes']

## Plot the spatial distribution of matched parcels
matched1 = matched.rename(columns={'D_zone':'AREANR'})

matched_areas = pd.merge(areas, matched1, on='AREANR',how = 'inner')
# matched_areas

f, ax = plt.subplots(1, figsize=(10, 8))
areas.plot(ax=ax, facecolor='lightgrey', alpha=0.3, edgecolor='grey',linewidth
    =0.2)
matched_areas.plot(ax=ax, column='Station', cmap='Paired',
                   alpha=0.5, edgecolor='black', linewidth=0.3, legend=True,
                  legend_kwds={"loc": "best", "bbox_to_anchor": (1, 0.3)})


stationing.plot(ax=ax, column='name', cmap='Paired',marker = '*',markersize=80,
    edgecolor='black',linewidth=0.5)
ax.set_axis_off()
# f.suptitle('Station distribution of matched outlier parcels', size=12)
plt.show()
```

The final part is about updating the destination zone of matched parcels:

Listing A.4: Code for updating the destination zone of matched parcels

```python
import geopandas as gpd
import pandas as pd
import numpy as np

def matching_to_schedule (parcels_matched, innitial_schedule_input):
    '''
    Input1: matched outlier parcels with updated D_zone (station), no parcel_id
    Input2: Initial parcel demand, including all parcels in the study area
    Function: updating D_zone of matched parcels
    Output: updated parcel demand with updated D_zone
    '''
    initial_demand = innitial_schedule_input
    updated_demand = pd.DataFrame()
    list_all_cep = innitial_schedule_input['CEP'].drop_duplicates().values.tolist
        ()

    # first sort matched parcels by CEP
    # loop over each CEP in the matched parcel dataset
    list_cep = parcels_matched['CEP'].drop_duplicates().values.tolist()
    for cep in list_cep:
        # print(cep)

        cep_initial_demand = initial_demand[initial_demand['CEP']== cep]
        cep_parcels_matched = parcels_matched[parcels_matched['CEP']== cep]

        cep_updated_demand = cep_initial_demand.copy()

        # count the number of matched parcels per zone
        # matched_zones_count = cep_parcels_matched.groupby('D_zone').agg({'D_zone
            ':'count'}).rename(columns={'D_zone':'count'})
        list_matched_zones = cep_parcels_matched['D_zone'].drop_duplicates().
            values.tolist()

        # then focus on zones where there are matched parcels
        # loop over each zone
        for zone in list_matched_zones:

            # slice demand of this zone
            matched_zone_demand = cep_initial_demand[cep_initial_demand['D_zone']
                == zone]
            list_parcels_index = matched_zone_demand.index.values

            # access the number of matched parcels of this zone
            # counts = matched_zones_count[matched_zones_count.index == zone]['
                count'].values[0]

            # slice the matched parcel of this zone
            zone_matched_parcels = cep_parcels_matched[cep_parcels_matched['D_zone
                '] == zone]


            # loop over each matched parcel
            for n in range(len(zone_matched_parcels)):

                # update the D_zone of the sliced demand df
                matched_zone_demand.iloc[n, matched_zone_demand.columns.get_loc('
                    D_zone')] = zone_matched_parcels.iloc[n, zone_matched_parcels.
                    columns.get_loc('New_D_zone')]
```

```

            # update the demand df
            for index in list_parcels_index:

                cep_updated_demand.loc[index, 'D_zone'] = matched_zone_demand.loc[index, 'D_zone']

        # concat all cep demand
        updated_demand = pd.concat([updated_demand, cep_updated_demand])

    # concat other cep with no matched parcels
    if len(list_cep) < len(list_all_cep):
        list_unmatched_cep = [x for x in list_all_cep if x not in list_cep]
        updated_demand = pd.concat([updated_demand,initial_demand[initial_demand['CEP'].isin(list_unmatched_cep)]])

    return updated_demand
```

B
Scientific paper

Crowdshipping as a delivery solution for outlier parcels: A case study in The Hague

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Abstract: The increasing parcel demand is resulting in increasing traffic congestion and emission problems for last-mile delivery. Crowdshipping is an innovative solution which envisions using the excess capacity in existing passenger transport to perform delivery tasks. However, it may bring extra vehicle kilometres travelled due to detours and new trips generated. This study aims to investigate the transport impacts of a public transport-based crowdshipping service for outlier parcels with high environmental impacts. Firstly, the parcel carbon footprint is calculated to segregate the high-impact ones. Then, the outlier parcels are matched with commuters who pick up the parcel at the parcel locker in the train stations. The simulation results show that outsourcing outlier parcels to crowdshipping is beneficial to the transport system and prioritizing outlier parcels of logistics service providers with low market shares can achieve more savings in transport and higher service efficiency.

I. Introduction

With the steady growth of the e-commerce industry, more and more people are opting for online shopping than in-store shopping. In The Netherlands, the number of parcels delivered increased from 399 million in 2019 to 654 million in 2021 [1]. Besides the increase in parcel demand, customers are becoming more aware of the environmental issues in parcel delivery and expecting it to be fast, reliable, cheap, environmentally friendly, and have the option for on-demand and personalized service [2]. Last mile delivery (LMD) refers to the last leg of the logistics chain where goods are transported from local distribution centres to end customers in urban areas, which accounts for from 13% up to 75% of the total supply chain costs, consumes the most energy and generates the most emission of the whole supply chain [2]. The increasing parcel demand and customer expectations result in increasing urban freight transport brought by LMD, which adds to the traffic congestion and emission problems. To address these problems, innovative logistics solutions for LMD are needed.

Crowdshipping is an innovative logistics initiative that aims at utilising excess capacity in existing passenger trips to perform delivery tasks. Crowdshipping service mainly involves service providers/crowdshipping platforms, senders, and occasional couriers (OC). The senders post delivery requests they plan to outsource to the individual travellers on the platform, and individuals who are willing to carry the packages with them during their journeys act as occasional couriers and get compensation for completing the delivery tasks. The potential benefits of crowdshipping include: reducing the traffic externalities brought by LMD, reducing delivery costs, and increasing flexibility and accessibility to new products. However, similar to other shared mobility services such as ride-sharing, crowdshipping service may bring extra vehicle kilometres travelled due to detours and new trips generated such as drivers being motivated by monetary compensation [3].

To address the possible traffic externalises brought by crowdshipping service and better navigate it to achieve its potential benefits, various studies have been conducted to design and optimize the operation strategy and evaluate the corresponding impacts of crowdshipping service. However, most studies consider all parcel demand as potential crowdshipping demand, while prioritising certain parcels, such as parcels in geographically remote areas, for crowdshipping service could achieve more transport and environmental benefits [4]. Also, few studies focus on integrating the modelling approach with the behavioural aspect, which could provide a more realistic performance evaluation of this decentralised logistics concept [5].

Therefore, this study aims to investigate the transport impacts of crowdshipping services for the last-mile delivery of high-environmental-impact parcels, which are used interchangeably as outlier parcels in this paper, through an agent-based modelling approach that takes into account individual decisions. Different crowdshipping scenarios will be simulated to test the impacts of different operation characteristics.

The structure of the paper is organized as follows: Section II presents a literature review of the state-of-art knowledge about crowdshipping services and identifies the research gap that this study aims to contribute. Section III describes the methodology this study proposed for the design and simulation of crowdshipping services. Following that, Section IV presents the simulation results of different crowdshipping scenarios. Section V discusses the results and the limitations and recommendations of this study. Finally, Section VI presents the conclusion of this study.

II. Literature review

A. Crowdshipping overview

According to the definition by [6], crowdshipping is the "outsourcing of logistics services to a mass of actors." The potential benefits of this novel logistics concept include: utilizing excess transportation capacity of current passenger trips to improve the transport system efficiency, reducing the transport externalities caused by last-mile delivery [7], helping logistics service providers reduce delivery costs, promoting social collaboration [3], increase customers' accessibility to new products and offer faster delivery speed for customers [8].

One promising field of crowdshipping service is food and retailers, where in-store customers can be employed as occasional couriers (OC) to provide same-day delivery to online customers [9]. Large retailers such as Walmart launched two pilot projects respectively in 2013 and 2017 to ask in-store customers to deliver online ordered packages [3]. Besides, [10] conducted a pioneering case study using a crowdshipping service for library deliveries in Finland and found that existing library deliveries can be successfully crowdshipped. Their results showed that each crowdshipped delivery reduces an average of 1.6 km driven by car, despite 80 per cent of the deliveries being made within less than a 5 km distance. [11] analysed the environmental impacts of crowdshipping service based on data from an operational crowd logistics platform in Belgium. Their results show that the current platform usage results in higher external transport costs and thus a higher environmental impact, when compared to traditional parcel delivery, because of a high share of dedicated trips. They pointed out the critical role the platform provider played in adjusting their operations to steer the effective vehicle use of the crowd. They also suggested the development of crowdshipping service in more rural areas could achieve larger cost and emission savings than in dense urban areas, as the less dense demand makes it more competitive to traditional logistics service providers (LSPs), which have a major advantage of consolidating parcels in dense urban areas.

B. Behavioral studies on crowd's willingness to work (WtW)

To achieve the promising benefits of this novel mobility idea, many literatures point out the key is to achieve a critical mass from the crowd [8]. [12] conducted a stated preference (SP) survey in the city of Rome to investigate commuters' WtW as an OC. They proposed a hypothetical scenario where small packages can be picked up/dropped off in automated parcel lockers (APL) located either inside metro stations or in their surroundings and their results showed that APL location is the most relevant feature. Similarly, [13] set up a SP survey on public transport passengers' willingness to work in the Greater Copenhagen Area. Their results indicated that young(er) individuals, students and (to a lesser extent) employed and self-employed individuals are more likely to participate in crowdshipping and compensation level is the most direct attribute for WtW. The WtW to time is found to be around 25.8 euro/h, which is fairly close to the value of waiting time for public transport passengers. [14] conducted a SP survey on travellers' WtW in The Netherlands and showed that the low-income group are more likely to participate and the value of time for the low-income group is 14.43 euro/h for newly generated trips and 38.57 for existing trips.

C. Modelling of crowdshipping

Different crowdshipping scenarios are proposed in the literature, with either simulation or optimization methods employed to model and evaluate the service. The scenarios differ in the OC's transport mode, the part(s) of LMD that is outsourced to crowdshipping, and the matching procedures.

For transport mode, crowdshipping with private cars has the probability of generating negative traffic impacts, while the modelling results of crowdshipping service with active modes and public transport are quite positive. [15] adopted a hybrid dynamic traffic simulation model to simulate crowdshipping for LMD and their case study in Rome indicated that crowdshipped deliveries by car have higher negative traffic impacts than corresponding deliveries by public transit, and the crowdshipping externalities can be reduced significantly by operation strategies such as limiting the detours of OC and incentivizing off-peak deliveries. [5] built an agent-based model that disaggregately matches parcel and crowd based on crowd's travel utility gains. They considered local-to-local parcels as the demand for crowdshipping and included both cars and bikes. Similarly, their results showed negative traffic impacts.

[16] proposed a crowdshipping scenario in which crowdsourced cyclists and pedestrians perform the last leg of LMD. The main part of LMD from depot to parcel relay points is performed by conventional vans. Their results showed that total cost and van kilometres travelled (VKT) can be significantly reduced compared to pure-truck delivery. Similar results are shown by the micro hub scenario where the intrazonal part of LMD is outsourced to crowdshipping [17]. The performance increases with the increase in the network size of micro hubs, which indicates that such a scenario is more suitable for cities with medium to high customer densities.

Public transport (PT)-based crowdshipping services are often modelled with parcel lockers (PL) as transfer points, as PL have the potential of addressing failed delivery and promoting the integration of passenger and freight transport [18]. [19] proposed a scenario in which public transit acts as a backbone network, PL as a transfer point, and crowdshipping performs the first and last leg of LMD with the backup option of zero-emission vehicles. Their case study results in Istanbul indicated that with reasonable OC participation, the suggested system can achieve more than 96% of the total daily demand with an average delivery time of under 2.5 hours. Similarly, [20] found that the fleet VKT can be reduced by 15% with a PT-based crowdshipping service with PL network at the metro stations in Singapore.

While most studies do not distinguish among different parcel demands, [4] proposed a scenario where the so-called outlier parcels, the parcels in low-parcel-demand areas, are prioritized for a PT-based crowdshipping service. Their results showed that the VKT reduction increases from 15% to 19% compared to crowdshipping for all parcel demand.

D. The contribution of this study

The research gaps are identified as follows:

1. A lack of investigation into which category of parcels are most suitable for crowdshipping that can achieve the most gains in environment and operation efficiency.

2. A lack of incorporating behavioural study with a modelling approach in the matching process of parcel and OC, which could provide a more realistic evaluation of the service.

This study aims to fill these two gaps by investigating the transport and environmental impacts of crowdshipping services for outlier parcel delivery and employing behaviorally consistent decision rules in an agent-based simulation model.

III. Methodology

To be able to test the impacts of crowdshipping service for parcels with high environmental impacts in an agent-based modelling way, three modules respectively focusing on the demand, supply and the matching of demand and supply are proposed.

A. Outlier parcel segregation

To segregate parcels with high environmental impacts, a delivery effort-based carbon footprint calculation method is employed to calculate the carbon footprint of each parcel from the total parcel demand. After that, the segregation is executed based on the distribution of parcel carbon footprint. This method is chosen as it offers a practical and fair method for assessing the carbon footprint of individual parcels within a delivery tour [21].

Figure 1 shows the visualisation of this method. The method is performed on each delivery tour. It starts by quantifying the total carbon footprint (CF) of a delivery tour, determined by the total kilometres travelled by the delivery van and the total number of parcels in the delivery tour, as shown in Equation 1.

The parcel demand is aggregated on a zonal level, thus the next step is to allocate the total tour carbon footprint to to each trip/zone, which is done based on the Zonal Weighting Factor (ZWF). Equation 2 below shows the calculation of the ZWF for zone *i* in a total of *n* zones visited by a delivery tour. ZWF for zone *i* is calculated as the product of the number of parcel demand in this zone *i* and the great-circle distance(GCD) from the depot to this zone *i*, divided by the sum of this product for all *n* trips in this delivery tour.

The advantage of selecting the GCD rather than the van kilometres travelled as a measurement of delivery effort is that the GCD is not determined by the route driven, thus avoiding too much carbon footprint being allocated to the later trips unfairly.

The ZWF represents the percentage of the tour carbon footprint that is allocated to each zone, and the sum of all ZWFs of a delivery tour is thus equal to 1. Equation 3 shows the allocation of the tour carbon footprint to zone *i*. The method assumes that all parcels within a zone have similar weights and are evenly distributed, thus the zonal carbon footprint can be equally allocated to each parcel in the zone, as shown in Equation 4.

$$TourCF = VKT \times \#Parcels \tag{1}$$

$$ZWF_i = \frac{\#Parcels_i \times km_i^{GCD}}{\sum_{i=1}^{n}(\#Parcels_i \times km_i^{GCD})} \tag{2}$$

$$ZonalCF_i = TourCF \times ZWF_i \tag{3}$$

$$ParcelCF = ZonalCF_i \setminus \#Parcels_i \tag{4}$$

In conclusion, in such a way, the farther away the parcel is the more capacity it takes up, and the greater carbon footprint is allocated to the parcel.

Once the carbon footprint for each parcel is calculated, the segregation of outlier parcels is done by selecting the parcels with high carbon footprint values. Kernel density distribution plots are used here to select the threshold value for outliers.

B. Crowdshipping supply system

The supply system of crowdshipping services mainly involves the formation of delivery scenario and the selection of potential occasional couriers.

1. Crowdshipping delivery scenario

Figure 2 shows the public transport(PT)-based crowdshipping delivery scenario with parcel lockers (PL) as the transfer points between LSP and OC. Train stations are chosen as the potential locations for instilling PL. This is because train is a very frequently used PT mode in The Netherlands [22], where the high traveller demand could provide a large pool of potential OC.

There are a few assumptions made. First, the matching of parcel and OC is performed before the departure of a delivery van and train traveller. Thus the matched parcels are bundled and delivered to their corresponding train station by conventional couriers. Train travellers as OC do not change their original travel journey and the primary matching criteria is that the parcel and OC must have the same destination zone. Train travellers as OC can pick up the parcel from the PL located at either their destination or origin stations, and they make a detour to deliver it to their customers before going to their own destinations. Each OC can only bring one parcel on a delivery trip.

2. Occasional courier selection

Given a parcel to be matched, the OC selection is performed on train travellers who have the same destination zone as the parcel to select the potential OCs and match it with the one with the highest willingness to work as an OC.

Figure 3 shows the selection method, which is based on the value of time (VoT) gains for train travellers. The VoT provided by crowdshipping is calculated as the ratio of compensation to additional travel time, with the latter being calculated as the sum of pickup, detour and dropoff time. Given a certain level of compensation, this ratio is compared to the preferred VoT for crowdshipping service by

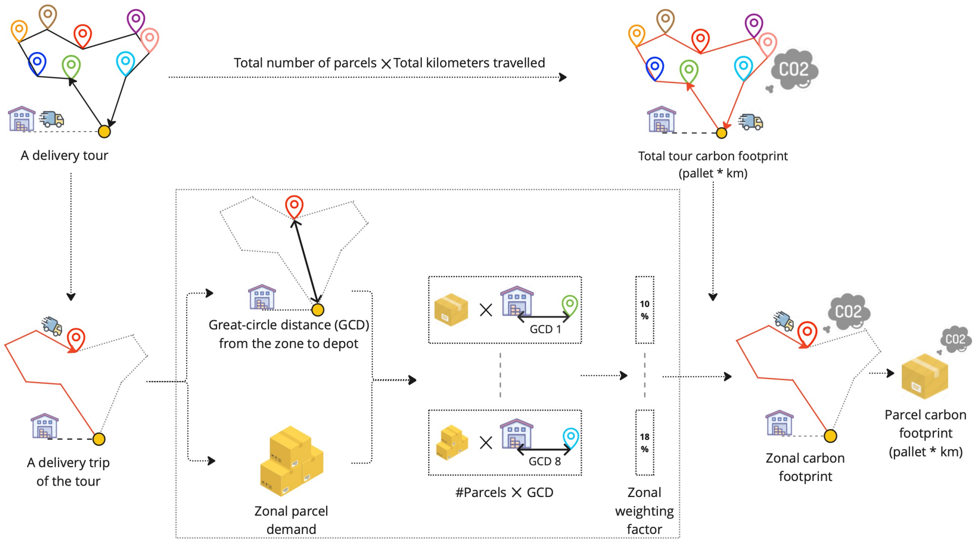

Figure 1. Visualisation of delivery effort-based carbon footprint calculation method

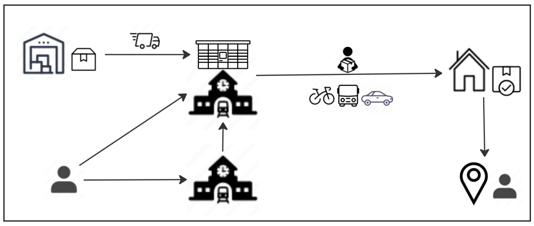

Figure 2. Visualisation of crowdshipping delivery scenario

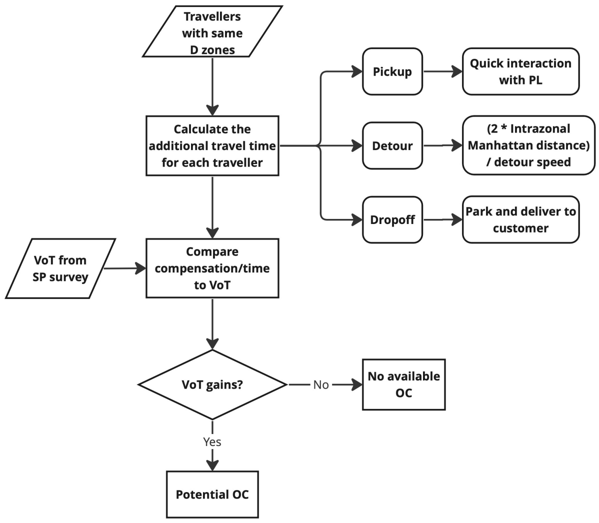

Figure 3. Flow diagram for selecting potential OC

travellers from an SP experiment. If the ratio is greater than the preferred VoT, it indicates that the crowdshipping service provides a VoT gain, and the greater the difference, the more the traveller is willing to work as OCs.

C. Crowdshipping matching

With both the parcel demand and crowdshipping supply available, the matching is performed as shown in Figure 4. It is worth noting that the parcel allocation from depot to station is based on the proximity, in such a way the maximum benefits in VKT can be examined.

IV. Results

The proposed method and scenario are implemented in the city of The Hague, which is one of the most highly urbanised and dense areas in the Netherlands, providing high potential demand and supply for crowdshipping service and thus the critical mass is more likely to be reached for the success of this service. The parcel demand and traveller trip data are from simulation models MASS-GT and ALBATROSS respectively, and the simulation duration is 1 day.

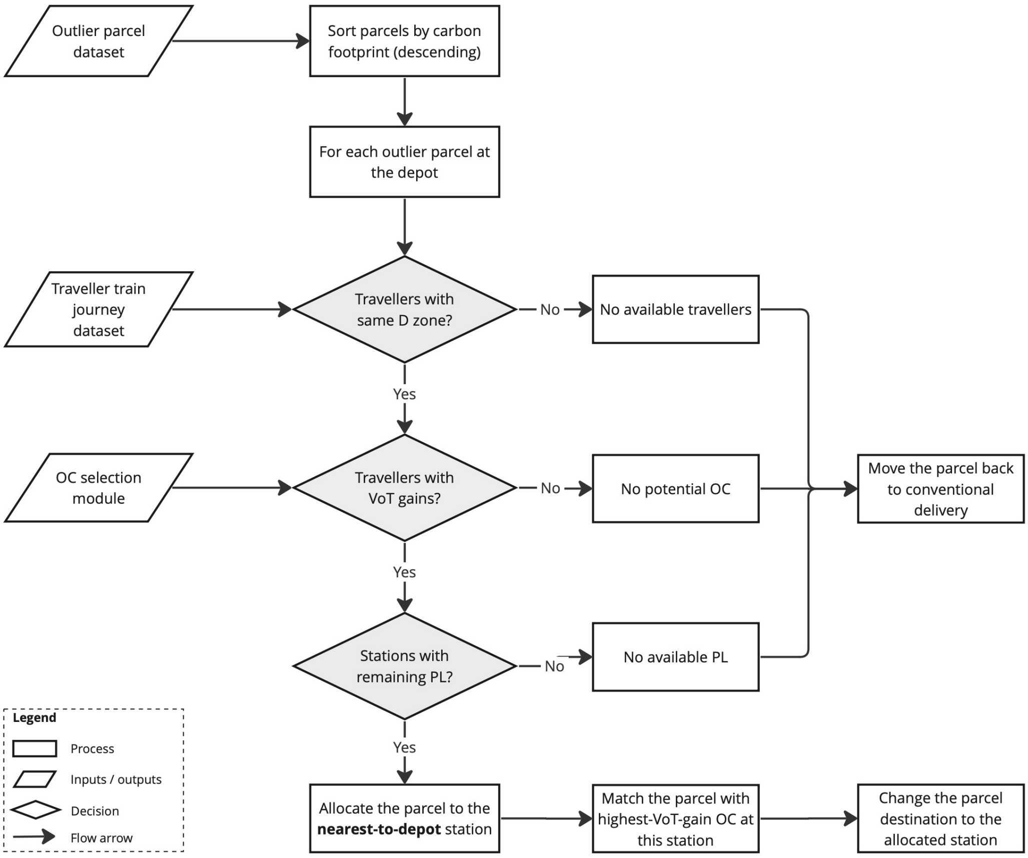

Figure 4. Flow diagram for matching outlier parcels with OC and PL

A. Parcel carbon footprint and segregation results

There are 6 major logistics service providers (LSPs) in the study area, Figure 5 shows the parcel carbon footprint distribution for each LSP. Large variations are observed among different LSPs in terms of the value and distribution of parcel carbon footprint. PostNL and DHL have the lowest carbon footprint and the overall distribution is concentrated, with DHL having a large tail of outliers. DPD, UPS and GLS have a moderate overall carbon footprint distribution, while FedEx has a significantly higher carbon footprint distribution. And all the four LSPs have a more scattered distribution, as can be seen in the length of the boxes.

The large variations can be explained as the different market shares and depot distributions of different LSPs, as shown in Figure 6 and Figure 7. PostNL takes up half of the market share and has a dense network of depots, the high economies of scale facilitate a highly efficient operation in LMD and lower parcel carbon footprint. While for FedEx, with the least market share

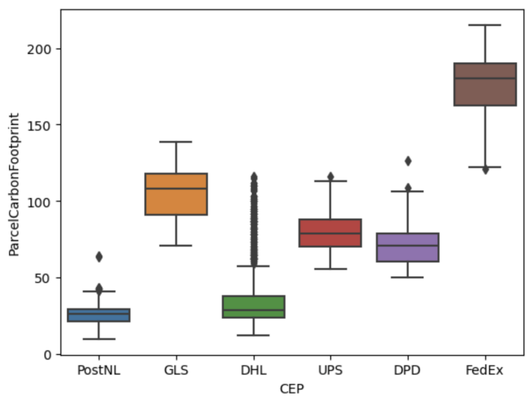

Figure 5. Box plot of parcel carbon footprint for each LSP

and only one depot in the province of Zuid Holland, the low parcel demand and remote depot location lead to an inefficient operation and thus a high parcel carbon footprint. The large variations could be further explained by the fact that the privatisation of the delivery services leads to multiple service providers, and different levels of operation efficiency because of the gains and losses in economies of scale.

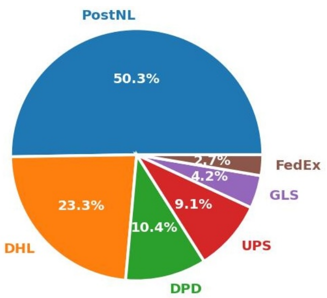

Figure 6. Market shares of 6 main LSPs [1]

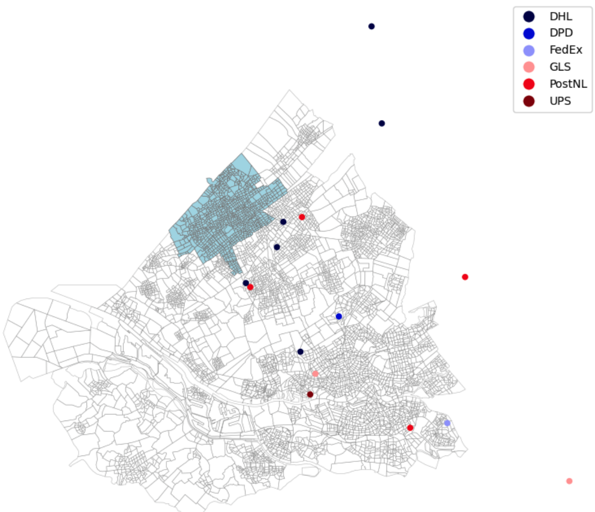

Figure 7. Depot location distribution

Because of the large variations of carbon footprint distribution among different LSPs, the segregation is performed for each LSP. Parcels with high carbon footprint are considered as outlier parcels, as they have high environmental impact. In total, 1751 out of a total of 56801 parcels are segregated, with the outlier percentage ranging from 3.1% (PostNL) to 16.1% (FedEx). The outlier parcels are located at both remote low-demand areas and central areas, which indicates that both the low parcel demand and distance from the depots can lead to outlier parcels.

B. Simulation scenarios

Table 1 gives an overview of the crowdshipping scenarios that will be elaborated on in the following sections. The scenario setup starts by defining the base and reference scenarios as the min and max crowdshipping scenarios. The simulation experiments mainly focus on the outlier parcel demand from different LSPs, different compensations provided to OC and different PL network configurations, to test the impacts of these settings on the transport and efficiency performance of crowdshipping.

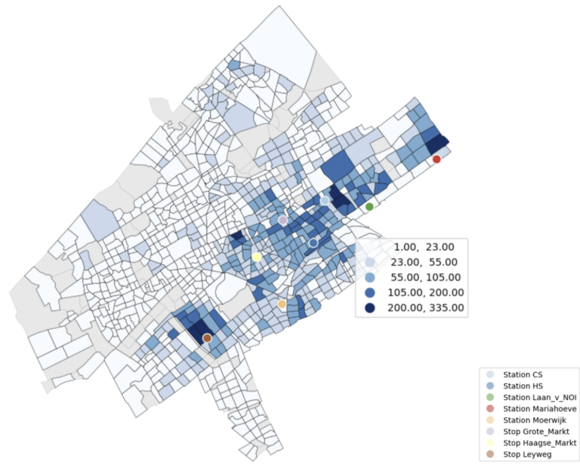

Figure 8. Distribution of train stations, tram stops and number of PT trip arrivals per zone

For PL network configurations, as mentioned in Section III, train stations are considered as the potential locations for PL and there are in total 5 train stations in The Hague. Figure 8 shows the geographical distribution of the 5 train stations and the 3 tram stops with high traveller demand as potential PL locations in an expanded PL network and the number of trip arrivals for each zone. The default setting of compensation is set to be 6 euros because the implementation results of the OC selection method mentioned in section III show that half of the travellers were willing to be OC when the compensation was €6, providing a moderate level of OC participation. And the model by default allocates a sufficient capacity of 400 to each PL.

Table 2 shows the results of base and reference scenarios. The PL capacity is set to large values to

Table 1. Simulation scenarios

Variable	Scenario	Scenario label	Description
	Base scenario	B1	Without crowdshipping
	Reference scenario-1	R1	All parcels are eligible for crowdshipping, randomly select 9050 parcels to be in line with the number of train travellers
	Reference scenario-2	R2	All parcels are eligible for crowdshipping, randomly select 1377 parcels with the same number of outlier parcels
Outlier parcel demand	All couriers	D1	All outlier parcels
	Exclude PostNL & DHL	D2	Exclude two main couriers, current operations of the rest are less efficient
	Exclude PostNL	D3	Only exclude PostNL and include DHL as it has a high outlier percentage
	Only FedEx and GLS	D4	Outlier parcels from the two LSPs with the least market shares
Compen-sation	3,5,7,9 (euro)	C1, C2, C3, C4	Different compensation provided to OC
#PL	Only train stations	P1	5 train stations
	Train stations and tram stops	P2	5 train stations + 3 tram stops
	Fewer train stations	P3	Exclude 1 low-demand station
PL location	Stations and stops with high passenger demand	P4	Select a total of 5 stations and tram stops with high passenger demand

Table 2. Results of base and reference scenarios

Scenario label	B1	R1	R2
Parcel demand (% of total demand)	56801	9050 (15.9)	1377 (2.42)
Match rate (%)	-	58.67	87.95
Total VKT reduction (%)	-	1.6	0.27
VKT reduction per matched parcel (km)	-	0.041	0.031
Compensation per VKT reduction (euro/km)	-	145.29	195.38

accommodate all the parcel demand. With a certain portion of parcels eligible for crowdshipping, a small reduction in van kilometres travelled (VKT) can be achieved, and the operation is quite inefficient as the VKT reduction per parcel is very little and the compensation paid per VKT reduction is quite high. Therefore, it is very necessary to investigate which group of parcels are most suitable for crowdshipping.

C. Simulation experiments and results

Three experiments are conducted, with one focusing on the demand side and two focusing on the supply side. The verification and validation of the simulation model can be found in Appendix.

Table 3. Simulation results of different LSP's outlier parcel demand

Scenario label	D1	D2	D3	D4
Outlier parcel demand (% of total demand)	1751 (3.08)	979 (1.72)	1377 (2.42)	361 (0.64)
Match rate (%)	64.19	79.67	73.86	94.46
Total VKT reduction (%)	3.03	2.25	3.76	1.57
VKT reduction per matched parcel (km)	0.369	0.395	0.506	0.633
Compensation per VKT reduction (euro/km)	16.26	15.2	11.82	9.48

1. Different LSP demand of outlier parcels

Table 3 shows the simulation results of different outlier parcel demand. All three scenarios achieve a larger VKT reduction than the reference scenario R2, with the parcel demand no greater than that in R2. This proves the effectiveness of crowdshipping service for outlier parcels.

Among all scenarios, scenario D4 which only includes the two LSPs with the least market shares achieves the highest matched rate, the maximum VKT reduction per matched parcel and the minimum compensation per matched parcel. The high match rate is because the low outlier parcel demand per zone makes it easier to find sufficient OCs, similarly, the high VKT reduction per parcel is because the low parcel demand per zone makes it more beneficial to outsource the parcels to crowdshipping. This indicates that crowdshipping can achieve higher performance when prioritizing the outlier parcels from LSPs with low market share.

In addition, scenario D3 which includes all LSPs except PostNL's outlier parcel demand achieves higher total VKT reduction than D1 and D2, which indicates that outsourcing the outlier parcels of LSPs with low market shares and LSPs with high market share and also high percentage of outliers to crowdshipping services could benefit the transport system, while outsourcing the LSPs with high market share and a small percentage of outliers does not contribute to the reduction of VKT due to the high operational efficiencies that have been achieved.

2. Different compensations
The parcel demand of scenario D3 is used here, which is 1377 outlier parcels from all LSPs except PostNL and takes up 2.4% of the total parcel demand, to provide a more complete picture of the outlier parcels.

Table 4 shows the simulation results of different compensations provided to OC for performing a delivery task. As expected, the transport performance increases with the increase in compensation. However, the efficiency drops with the increase in compensation, as the compensation per VKT reduction increases from €8.34 to €18.76. Moreover, among the three compensation increases, the increase from €5 (C2) to €7 (C3) is the least efficient in reducing VKT, and the compensation per VKT reduction also increases the fastest.

Table 4. Simulation results of different compensations

Scenario label	**C1**	**C1**	**C3**	**C4**
Match rate (%)	57.23	68.92	77.56	81.48
Total VKT reduction (%)	2.07	2.93	3.26	3.93
VKT reduction per matched parcel (km)	0.360	0.423	0.418	0.48
Compensation per VKT reduction (euro/km)	8.34	11.83	16.76	18.76

3. Different PL network configurations
Table 5 shows the simulation results with regard to the change in PL network size and locations. Scenario P1 is used as the reference scenario here, which is the same as scenario D3.

With an expanded network of 5 train stations and 3 tram stops in scenario P2, a higher match rate is achieved but it does not help in further reducing the VKT, this is because a larger PL network requires the delivery vans to visit more PLs, and the benefits of more matched outlier parcels do not make up for the increased VKT this results in.

Scenario P3 is characterized by a PL network of 4 main train stations and the performance decreases, which indicates that a PL network size of 5 is optimal for the 1377 parcel demand. Following this, scenario P4 focuses on the location choice of the PL network where 5 high-traveller-demand train stations and tram stops are selected. This results in a slightly higher match rate compared to scenario P1, but the transport performance is worse than scenario P1, since the distance between the tram stops with high demand and the depot is further than that of the train stations with low demand. The benefits brought by higher traveller demand cannot outweigh the increased distance from the depots to tram stops.

Table 5. Simulation results of different PL network configurations

Scenario label	**P1**	**P2**	**P3**	**P4**
Match rate (%)	73.86	85.33	71.39	76.47
Total VKT reduction (%)	3.76	3.54	2.78	3.04
VKT reduction per matched parcel (km)	0.506	0.413	0.387	0.396
Compensation per VKT reduction (euro/km)	11.82	14.53	15.48	15.15

In conclusion, scenario P1 with the PL network of 5 train stations performs the best.

V. Discussion

1. Discussion of the results
This study aims at investigating the transport impacts of crowdshipping services for outlier parcels, which are defined as the ones with high environmental impacts.

The results of the case study in The Hague show that prioritizing outlier parcels for PT-based crowdshipping service could achieve a larger reduction in van kilometres travelled, thus leading to less traffic congestion and emissions generated by delivery vans. In addition, as the proposed service mainly uses the extra capacity of PT and active modes for delivery, the detour vehicle kilometres travelled by OCs are very small. Therefore it can be concluded that a PT-based crowdshipping service for outlier parcels could bring sustainability benefits to LMD.

Given a percentage of 2.4% of outlier parcels, up to 3.93% of VKT reduction can be achieved. The ratio of VKT reduction to outlier percentage is around 2, which is similar to the results of [4], where a total of 11% of parcels could lead to a 20% reduction of delivery vehicle kilometres travelled.

Moreover, the results show that crowdshipping could be more beneficial to LSPs with lower market shares. A percentage of only 0.64% outlier parcels from the two small LSPs can reduce 1.57% of VKT. The ratio of VKT reduction to outlier percentage is larger than the average ratio of 2, which proves the efficiency of crowdshipping for outlier parcel demand from LSPs with low market share. For outlier parcels from LSPs with larger market shares, the crowdshipping service might bring negative transport impacts. When the percentage of outlier parcels is quite small, in other words, all parcels have about the same low environmental impacts, outsourcing to a crowdshipping service could decrease the operation efficiency and increase VKT.

Behavioural considerations are taken when calculating traveller's willingness to work as OC, and the results show that a compensation of €6 could attract half of the travellers and achieves a moderate VKT reduction, which is in line with the findings by [5], where their estimation of approximate compensation values for OC is also €6.

Parcel locker is included in this study as transfer points between conventional couriers and occasional couriers. The results show expanding the PL network size does not help achieve more VKT reduction. The diminishing marginal benefits of adding PL are also observed by [20], as when the matching becomes stabilized under a certain compensation level, the benefits of adding PL are very little. Next to PL network size, the results of different PL locations show that there is a trade-off between the distance from depot to PL and the traveller demand at PL stations, and given the 2.4% outlier parcel demand, the 5 train station network appears to be the most balanced option.

2. Limitations and recommendations

A reflection on the methodology is described first. To begin with, there are a few strict assumptions made in the formulation of the delivery scenario, such as the same destination zone constraint and each OC can only carry one parcel, which relieves some of them and might provide a more realistic delivery scenario for evaluation. Second, for calculating the additional travel time, twice the Manhattan distance is taken to represent the intrazonal detour distance. This is a very rough approximation and more detailed research needs to be done on calculating the detour distances. Third, the simulation model simulates the static operation of a crowdshipping service of 1 day, it would be interesting to incorporate the dynamic operations such as the changes in PL remaining capacity, which could simulate more realistic crowdshipping operations. Fourth, the implemented PL network assumes that it is shared by all LSPs, while the single-operation mode of PL might be more beneficial in terms of efficiency gains. Would be interesting to investigate the different operation modes of PL. Fifth, the value of time for working as OC is taken from an SP experiment from literature and remains constant under different crowdshipping scenarios. It would be interesting to conduct real-life pilot experiments to examine behavioural preferences and test how the preferences might change with the development of the service.

From a broader point of view, it would be interesting to implement the proposed scenario on a larger geographical scale, which could provide more insights into the potential of such PT-based crowdshipping service as cross-city train trips could save more VKT. What's more, it is also recommended to investigate the definition rules of outlier parcels from different perspectives. Environmental impacts from a societal perspective are chosen in this study, other perspectives such as from LSPs' perspective delivery cost might be chosen as the definition rule.

VI. Conclusion

To explore the transport impacts of crowdshipping service for outlier parcels in last-mile delivery, a delivery effort-based carbon footprint calculation method is applied, a public transport-based crowdshipping delivery scenario with the parcel as transfer points is proposed, and a matching algorithm that considers travellers' travel itineraries is developed. These methods are applied to a case study in The Hague, which is one of the most urbanised cities in The Netherlands.

Overall, the results show that the proposed service can be beneficial to the transport system, as it mainly uses the extra capacity of public transport and active modes. In addition, prioritizing outlier parcels for crowdshipping services is more effective in reducing the total van kilometres travelled than crowdshipping services for all parcels.

What's more, large differences exist in parcel carbon footprint among different logistics service providers with different market shares. A lower parcel carbon footprint is observed for the ones with high market shares, as a high parcel demand helps them achieve higher economies of scale and thus more efficient operations in last-mile delivery. This large difference also leads to the different impacts of crowdshipping service for outlier parcel demand from different logistics service providers. Prioritizing the outlier parcels from small providers can achieve high savings in van kilometres travelled and a high efficiency of crowdshipping service.

Lastly, crowdshipping service with a small-scale parcel locker network as transfer points performs well in terms of service efficiency and sustainable benefits.

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Appendix

The verification and validation of the matching algorithm are presented, with the main focus on the verification, as the validation is hard to implement due to a lack of real-world crowdshipping use cases.

Table 6 shows the matching results of 2 test runs, where a total of 1751 outlier parcels are used as input. The parcel matching results include one matched result and three unmatched results, the sum of which is in line with the input parcel demand, which verifies the flow conservation of the algorithm.

In addition, as the compensation increases, the number of parcels with the matching result of "Unmatched: No potential OC" decreases and the number of matched parcels increases, which is in line with the model specifications that compensation functions as the driving factor for travellers' willingness to work as OC.

Table 6. Model verification: Balance checks and continuity tests

	Matching results	Compensation =6	Compensation =9
Number of parcels per matching result	Matched	1112	1214
	Unmatched: No potential OC	559	245
	Unmatched: No available PL	42	146
	Unmatched: No available travellers	38	146
	Sum	1751	1751
	Train stations		
PL occupancy rate per PL at the train stations (%)	Station Moerwijk	90	100
	Station HS	83	99.5
	Station CS	58	58
	Station Laan v NOI	37	37.75
	Station Mariahoeve	10	8.25

The second half of the matching results are about the PL occupancy rate at each train station, which indicates the station distribution of matched parcels. This is to test the proximity-based allocation from depots to PL at train stations. In both cases, station Moerwijk had the highest occupancy rates. This is because it is the closest station to 7 out of 9 depots, as shown in Figure 9. This verifies the depot-proximity-based allocation method.

For validation, as mentioned, the lack of real-world crowdshipping services makes it hard to validate if or not the model is an accurate representation of the real system. The key parameter used in this study, travellers' preference value of time is validated using literature. A stated preference experiment (SPE) on student cyclists' attitude to work for crowdshipping found the VoT to be €24/h[23]. The VoT used in this study is higher than the cyclists' one, this is because

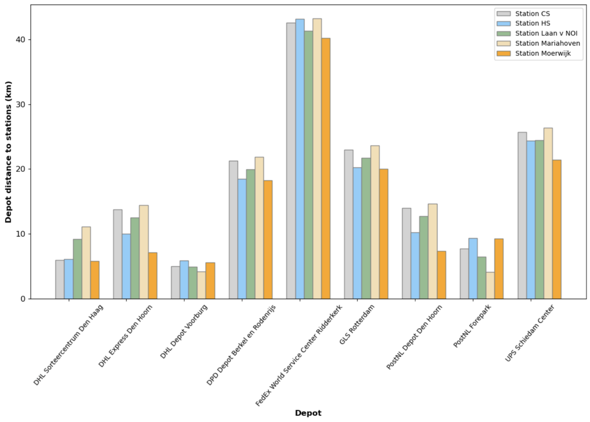

Figure 9. Depot distance to train stations

a distinction is made between newly generated trips and existing trips in the VoT used, which is higher than the the combined results[14]. But it's within the variable range, as a SPE on occasional drivers for ride-sourcing, a similar service to crowdshipping, found the VoT to be $35 to $81.6/h[24].