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Public Planning of Freight Transport in Logistically Complicated Small Cities

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Contents

Introduction

City logistics is an essential component of our modern urban environment, facilitating the movement of goods and services that sustain the urban economy and enhance the quality of life for residents. However, as cities continue to grow and urbanise, the growing need for freight transport is leading to significant challenges, such as congestion, emissions, and pollution, among others. Addressing this increasing need is crucial for enhanced city livability, as the impact of freight transport is often significantly greater than that of passenger transport (Anderson et al. 2005), which is often the main focus of public authorities. Friedrich (2022), summarising the findings of Douglas et al. (2020), notes that while light and heavy-duty vehicles (which are typically used in freight transport) account for only 13.2% of the total driven distance in Germany, they are responsible for a significantly higher share of negative externalities: around 24.7% of CO_2 emissions, 34.8% of NO_x emissions, and 36% of particulate matter emissions. Similar observations are reported by Coulombel et al. (2018) for Paris, where freight transport, though constituting only 8% of the driven distance, contributes up to 30% of pollutant emissions. These impacts are expected to be intensified further due to growing internet trade, increasing home deliveries, and the rise of gig economy services that enable individuals to engage in delivery services. As a result, there will be increased freight volume and deliveries in urban areas, typically handled by freight carriers of varying sizes, which can result in more traffic and higher energy consumption. Without proper planning, this situation could affect the living conditions of a growing urban population.

Public authorities may intervene in carriers' operations to mitigate their impact on urban environments through regulations or incentives that promote sustainable practices. However, authorities often lack the specific knowledge required to analyse carriers' operations and implement corresponding measures. As highlighted by van Heeswijk (2017), this challenge is particularly pressing for authorities in small European cities. These authorities must navigate logistically complex landscapes characterised by medieval structures, narrow roads, and limited parking spaces. The infrastructure in these cities was not designed to accommodate modern logistics needs, resulting in significant impacts from freight transport. This thesis originates from this context and aims to bridge the knowledge gap between public planning and freight transport in small, logistically complicated cities as part of the Research Council of Norway funded CityFreight[1] project. The overall objective of the project is to guide public authorities in such cities toward planning sustainable freight transport, considering the unique logistical challenges inherent in their built environments. To achieve this, the project brings together

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[1] https://prosjektbanken.forskningsradet.no/en/project/FORISS/308790

various academic disciplines and industry partners (including the City of Bergen, the National Public Roads Authority, the Vestland County Council, the Bergen Chamber of Commerce and Industry, the Port of Bergen, and the Nordic Edge) to establish knowledge production and exchange related to making policy decisions that are based on a realistic understanding of freight carrier operations.

Vehicle routing problems (VRPs) are widely used to model the operations of freight carriers and have been extensively studied in the literature, covering a range of variants and applications. While traditionally applied in an operational context, VRPs can also be utilised to quantify the impacts of freight carriers on urban environments for policy-making, using metrics such as distance driven and the frequency and duration of curb space occupation. For a comprehensive overview of VRPs, readers can refer to Toth & Vigo (2014).

The methodological framework of this thesis primarily utilises the VRPs with park-and-loop, a variant first introduced by Bodin & Levy (2000). In this problem, drivers park their vehicles, serve a set of customers on foot, and then return to their vehicles to continue their routes. The objective, in this regard, is to identify optimal parking locations that minimise both walking and driving distances for carriers. The problem has gained attention in the literature recently in order to enhance the operational planning of carriers (e.g., Nguyên et al. 2019, Le Colleter et al. 2023, Reed et al. 2024). Although the problem does not explicitly address curb space occupation by carriers, which is an important measure for authorities, it can inherently provide insights for policy-making by shifting the focus from carriers to authorities. Specifically, rather than focusing on the exact parking locations for optimal route planning from the carriers' operational perspective, the emphasis can be on how often and for how long curb space is occupied from the authorities' strategic perspective. By changing the viewpoint, the corresponding model can be adapted to analyse and quantify the impact of carrier activities on urban curb space, along with the distance driven by them. This perspective shift is crucial for capturing the objectives of authorities and guiding them through the public planning of freight transport.

The first three papers of this thesis employ this perspective shift to model carriers' operations and address policy concerns related to freight transport. Specifically, Paper I elaborates on this perspective change from a modelling standpoint and examines the value of freight consolidation from the perspective of authorities. Freight consolidation is a logistics practice that combines multiple shipments based on geographical proximity to optimise transport efficiency. As a sustainable practice, freight consolidation helps reduce the number of trips within urban areas, thereby minimising the negative externalities of freight transport such as emissions and congestion. Despite its benefits, achieving consolidation among freight carriers can be challenging and may require certain regulations to facilitate the process. However, Dablanc (2007) asserts that only very strict regulations can significantly influence carrier behaviour; although, such regulations may violate constitutional principles (van Heeswijk 2017). Given this context, rather than focusing on specific regulatory measures related to consolidation, we identified the key objectives that consolidation should achieve for logistically complex small cities, using a case study in Bergen, Norway. This approach provides authorities with the foundational knowledge needed to design regulations that can mitigate the impact of carriers on urban environments through consolidation. In this regard, by analysing various market structures characterised by different numbers and sizes of carriers (which define different degrees of consolidation), we conclude that small carriers significantly contribute to negative externalities of freight transport. Implementing a delivery network where these carriers do not deliver directly to end customers would greatly enhance city livability.

Paper II examines a regulatory measure designed by the authorities in Bergen to prevent through traffic in the city centre. The measure divides the city into three distinct zones, redirecting traffic between zones using major roads and tunnels located outside the city center. While measures to restrict through traffic have attracted attention from authorities around the world, they are primarily aimed at mitigating the impacts of private transport, overlooking the impacts of freight transport in these decisions. Hence, this paper analyses how the zoning decision would affect freight transport and quantifies its impact on the urban environment. Our findings indicate that the measure would, as expected, increase the distance driven by freight carriers. However, it would also lead to an increase in distance driven within the city centre itself. To address these impacts, we evaluated another policy under consideration by the authorities in Bergen, which involves using a micro-hub for consolidation and conducting last-mile deliveries with bicycles. Our conclusion is that this setup would significantly reduce the negative externalities of freight transport, especially in light of the new zoning decision.

Paper III focuses on the concept of 15-minute cities, which aim to reduce residents' dependency on private vehicles for their daily needs, thereby mitigating the environmental impacts of their trips. By establishing self-sufficient communities, this concept seeks to create neighbourhoods where residents can access all essential needs and services within a 15-minute walk or bike ride. Despite the necessity for various deliveries in all neighbourhoods, such as e-commerce shipments or grocery supplies, the integration of freight transport into the 15-minute city model has not been thoroughly addressed. In fact, this aspect is framed by the European Road Transport Research Advisory Council as one of the most pressing policy issues in deploying the concept (ERTAC 2023). In response, we analysed e-commerce shipments within the framework of 15-minute cities, using a case study in Bergen and adopting a dense, carrier-agnostic parcel locker network. Our findings suggest that such a network can significantly reduce the negative externalities of freight transport by eliminating first-time delivery failures and expanding the delivery range. This improvement is particularly crucial for small carriers, who lack the resources to deploy parcel lockers independently.

The sustainable practices advocated in the CityFreight project for freight transport planning have led to exploring how to integrate such practices into the route planning of carriers. In this regard, Paper IV addresses how to re-plan the sequence of customer visits once a vehicle returns back to the depot in the VRPs with stochastic demand. Re-planning (or re-routing) would be beneficial in addressing the complications caused by the intricate road networks in small cities, which often consist of narrow, one-way streets, thereby reducing the impact of carriers on urban areas. The corresponding problem exhibits a multistage structure, and the paper discusses how to formulate such problems (and under which conditions) by repeatedly reusing a single static representation of uncertainty (a single scenario set).

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Paper I

Assessing macro effects of freight consolidation on the livability of small cities using vehicle routing as micro models: The case of Bergen, Norway[*]

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Abstract

This paper provides guidance for local authorities in small cities by equipping them with tools to comprehend and quantify freight consolidation within their urban areas, enabling them to integrate this into their regulatory decisions for enhanced city livability. Rather than advocating specific regulatory measures to facilitate consolidation, which is a political decision and can change over time, the paper establishes a basis for making informed policy decisions concerning consolidation. In this context, we focus on the perspective of authorities and, through an analysis of diverse market structures characterized by different degrees of consolidation, identify what is important to achieve in order to enhance city livability, measured by driven distance as well as the number and duration of stops. To this end, we propose a policy guidance framework tailored for authorities in small cities, adopting vehicle routing models as micro models to evaluate macro consolidation impacts for authorities. We apply the framework to a case that represents parcel distribution in Bergen, a small medieval city in Norway with a complicated street pattern and lack of parking, based on real maps and real demand patterns. Our findings suggest that small carriers take up a substantial space in the city, and increase the duration of stops while parking at various locations for parcel delivery. In this context, the city would benefit greatly from a market scheme, in which small carriers cannot deliver goods to end-customers, far more than moving between complete consolidation and a few reasonably large carriers.

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1 Introduction

Increasing internet trade, coupled with growing populations, leads to more and more package deliveries in urban areas (Savelsbergh & Van Woensel 2016). These trends, however, do not just bring more deliveries but also more delivery companies competing on speed and quality for market shares, resulting in the emergence of a more competitive and dynamic delivery landscape (Allen et al. 2021). The phenomenon of 'uberification' within the market amplifies this further, as it promotes the widespread adoption of on-demand, technology-driven service models that enable individuals to engage in delivery services (Zhou & Wan 2022). As a result, more delivery vehicles drive in cities and occupy road space while carrying loads less than vehicle capacities on longer than necessary routes. Consequently, the contribution of urban freight transport to various challenges of public authorities (e.g., traffic congestion, occupied road space, noise pollution) inevitably increase (Fulzele & Shankar 2022).

Neghabadi et al. (2019) distinguish between two classes of policy measures in addressing these challenges. The first class of measures is defined as solutions that are driven by private carriers and are based on carrier cooperation. These solutions require substantial support from the public sector to succeed. Among these, urban consolidation centers (UCCs) are one of the most widely studied solutions in the literature and are also one of the most applied in practice. UCCs are logistics facilities to store, sort, and consolidate inbound freight flow from different carriers to achieve optimized outbound flow (Bektaş et al. 2017, Jamili et al. 2022). Consolidation achieves a reduced number of delivery vehicles driving in cities, leading to higher utilization of vehicle capacities, shorter routes and stopping times, and fewer stops (Roche-Cerasi 2012). The second class of policy measures is regulations imposed by local authorities to restrict carriers' access to urban areas. To name a few, these regulations include time window restrictions, city toll schemes, vehicle size or type limitations, and zero-emission zones. Some of these regulations may also result in consolidation, but this is not the primary objective. Consolidation in this case is not achieved by cooperation, as in UCCs, but through carriers' compliance with regulations. Implementing such regulations is a daunting task due to the non-overlapping interests of interacting stakeholders. For instance, while reducing congestion and emissions is aligned with the goals of local authorities, it is not a primary concern for carriers.

Despite the benefits that UCCs offer, a majority of the projects fail to achieve success in practice (Deng et al. 2021). Quak & de Koster (2009) report that over half of the 100 consolidation initiatives fail during implementation. Dablanc et al. (2011) verify the same and indicate that less than ten consolidation projects have survived among 150 projects in Europe. One of the main reasons for this failure lies in UCCs' financial performance (Paddeu et al. 2018, Giampoldaki et al. 2023). These centers are driven initially by public money to encourage consolidation among carriers. However, once the public money dries up and carriers are expected to pay, participation in UCCs diminishes and eventually fails as it becomes no longer attractive (Friedrich 2022). In this regard, Bruni et al. (2024) point out that one of the primary factors contributing to the infeasibility of these centers is the disparity between the operational costs and the revenue generated from using these centers. Similarly, Dablanc (2005) asserts that service fees charged to carriers are so high that carriers opt for subcontracting to small third-party carriers instead of using UCCs. Thus, while substantial public funding covers these differences as a subsidy during the initial experimental phase, these centers struggle to function autonomously after the experiment (Ciardiello et al. 2023). This dilemma is more troublesome in small cities since the level of freight throughput for consolidation is limited, and hence it is harder to justify lower fees given the high establishment and operational costs of UCCs. Allen & Huschebeck (2006) claim that these costly infrastructure-led solutions are often unlikely to be viable in small cities unless such facilities are already in place.

Imposing restrictions on carriers' access to urban areas is, therefore, a more appropriate policy measure in small cities for consolidating goods. In order to implement such restrictions, concerned regulatory bodies have to rely either on try-and-see approaches (e.g., pilot studies), whose results are only known ex-post and can potentially reduce the belief in facilitating consolidation, or on research studies conducted for other cities, where extrapolation might not produce reasonably robust answers due to different city characteristics. Consider, for instance, the dynamics of large cities featuring a two-echelon distribution system, where research is often concentrated. This setup contrasts with that of smaller cities, which employ a one-level distribution scheme and lack the intermediary satellite infrastructure that provides an additional layer of sorting and consolidating goods. Even within smaller cities, significant variations in road network configurations, stemming from features such as a complicated topography, medieval structure, geographical layout and traffic patterns, can pose different implications regarding consolidation and the associated freight regulations required to facilitate it. For instance, in areas characterized by a network of narrow roads that leads to increased traffic congestion and where shortage of parking spaces results in unauthorized parking and roadblocks, authorities may favor increased consolidation to reduce such effects. Conversely, in areas with a network layout featuring efficient traffic distribution and ample parking availability, authorities may find it acceptable to opt for less consolidation to keep and encourage competition among carriers as long as their impacts on the environment align with the city landscape. Moreover, the structure of the freight market may vary from one city to another. For instance, in some cities, carriers prioritize direct deliveries to end-customers, while in others, individuals may need to retrieve their items from designated collection points. Therefore, it becomes imperative for authorities to be able to quantify the effects of varying consolidation levels for their own urban environments and configurations.

Norway is a country with a complicated geographical landscape composed of many logistically challenging small cities. Bjørgen et al. (2021) assert that Norwegian cities in general have low urban density, resulting in vehicle dependency for passenger and freight transport. Commercial transport comprises 30% of all urban transport in Norway (Ministry of Transport and Communication 2017) and is one of the significant challenges for authorities. Despite the need, Bjørgen et al. (2019) highlight the absence of urban freight strategies in various Norwegian cities. Bergen, the second largest city in Norway, is one of them. In addition to being medieval, Bergen is one of Norway's most mountainous and hilly cities. The city center is composed of many one-way streets, which are often narrow. The authorities are committed to preserve the medieval structure of the city, including its ancient road network, which was not designed to accommodate vehicles like delivery vans. In this regard, the street pattern of the city center is intentionally designed to discourage vehicular traffic, wherein a single incorrect turn could necessitate retracing one's path to reach the intended destination. Accordingly, two locations that appear close to each other on the map may result in a long drive by a vehicle. Hence, walking from one point to another in the center may be faster than driving. Moreover, parking is often restricted in residential areas and there are limited parking spots reserved for delivery vehicles. While authorities have regulated passenger transport heavily, they have left freight transport to the private sector, whose impact is growing progressively in the city. The influence of the latter within the city landscape has catalyzed an interest among authorities to undertake measures that mitigate its escalating impacts. In response, we partner with local authorities in Bergen and propose a modeling framework tailored for authorities in smaller cities, which can adapt diverse road network configurations through data integration, to quantitatively assess varying levels of consolidation within the freight transport market of Bergen.

The impacts of freight transport on city livability are reflected in driven distance as well as the number and duration of stops. Improving these metrics would consequently reduce the burden of freight transport. As mentioned earlier, employing regulatory tools is an appropriate approach for reducing the effect of freight in small cities, and regulations can at the same time induce consolidation. However, which regulatory tools to employ for achieving consolidation may change over time as technology moves forward and brings additional tools and capabilities to support policy making. Besides, this is more of a political decision. In this regard, identifying what to achieve with regulatory tools, rather than which ones to employ, is more important in guiding authorities. Therefore, our objective is not to analyze specific freight regulations to achieve consolidation, but identify, through a case study, important consolidation effects that can inform policy-making. In light of this, this paper strives to answer the following research questions.

- What is the value of consolidation from the authorities' perspective in terms of driven distance as well as the number and duration of stops?
- How does varying carrier numbers and sizes in the freight transport market influence the urban environment?
- Is there a big gain in achieving a complete consolidation over having a few reasonably large carriers?
- Is, and if so how, the increasing number of small carriers causing problems for cities?

To address these questions, we do not plan consolidation for carriers, but we use their routing models as micro models to answer macro questions for authorities. This enables us to mimic the operations of carriers at a holistic level while capturing the broader perspective of authorities. As an example, while the time it takes to serve a customer once a vehicle is parked is an operational concern for carriers in their route planning, this is a measure for authorities to assess both the duration and frequency of carriers' parking in order to gain insights into their curb occupancy. To this end, we propose a routing-based framework as a policy guidance tool and use data from Bergen, Norway.

The contribution of this paper is two-fold. First, we provide a modeling framework designed for small city authorities, allowing them to evaluate the effects of freight consolidation by incorporating their city's road network configurations and freight demand patterns. Second, we conduct a comprehensive computational study with real data collected from Bergen, where we obtain insights on the value of consolidation for city livability from the perspective of authorities. In light of these, we provide the following avenues to exploit our work in academic and practical contexts.

- The framework has enabled us to actively engage in discussions with authorities in Bergen. Our research demonstrates that routing models can serve as a facilitator for strategic-level dialogues and can be leveraged beyond their typical use in operational contexts within the literature.
- Small city authorities can adopt the framework to understand the effect of consolidation on city livability and prioritize what is essential to achieve for their regulatory decisions by quantitatively assessing different levels of consolidation.

The paper is organized as follows. The related literature is presented in Section 2. Section 3 describes the problem statement. The routing-based policy framework and the corresponding model formulations are presented in Section 4. Section 5 introduces the case study and the data. The results of the computational study are presented and analyzed in Section 6. Section 7 concludes the paper.

2 Related literature

Challenges in urban freight transport have fueled a variety of studies in operations research and transportation science (Crainic et al. 2020). One of the research streams, in this regard, has focused on collaborative transport, including UCCs, which can reduce the negative impacts of freight distribution in urban areas. While some of these studies focus mainly on carriers' operations (e.g., Amiri & Farvaresh 2023), others focus on interactions between different stakeholders and their impacts on the system (e.g., van Heeswijk et al. 2020). In this section, we focus on the latter, from which one can obtain implications for authorities. While here we explore the nature of the problem and provide qualitative insights, the choice of methodology and related approaches in the literature are discussed in Section 4. For an overview of urban collaborative transport, we refer the readers to a survey by Cleophas et al. (2019).

2.1 Urban consolidation centers

Although we emphasized that UCCs often fail due to their poor financial performance, a number of efforts have been deployed to achieve financial viability. We, therefore, review the literature discussing how to overcome these challenges. As UCCs are not the only way to achieve consolidation, the conclusions and inferences drawn from this literature are informative for consolidation.

van Heeswijk et al. (2019), for instance, develop an agent-based simulation to generate insights on sustainable UCCs. The authors define various schemes, constructed by combining different administrative policies and cost settings, and test these on multiple stakeholders through their simulations. Specifically, they apply their model in Copenhagen based on available data in the literature for different stakeholders (carriers, receivers, UCC, and municipality). They assert that UCCs are doomed to fail without supportive measures from a purely financial standpoint. In this regard, they show that temporary subsidies and zone-access fees are effective measures in achieving profitable UCCs, where the system might operate without external funds if a certain level of freight throughput is achieved. The authors, however, do not claim viability for all UCCs in practice and stress that achieving financial stability is highly challenging. The analysis in Mepparambath et al. (2021) also addresses the importance of achieving a certain level of freight throughput, albeit with a focus on environmental benefits. The authors highlight that there is a critical level of participation required in the UCC scheme, defined by the number of retailers joining the initiative, to see a reduction in freight trips within a retail district. The extent of this reduction depends on the location of the UCC, whether it lies within or outside the district, with the former showing lower responsiveness to increasing participation levels in trip reduction. The authors also point out that while greater consolidation through the UCC does lead to benefits, there is a point where the additional benefits become less significant as consolidation increases further. Achieving a certain freight throughput level is, therefore, a critical aspect for authorities to establish financially viable and environmentally friendly UCCs. Supportive measures are also suggested by Kin et al. (2018). The authors develop a mathematical model and examine different distribution set-ups for delivering fast-moving consumer goods in a megacity. They argue that greater restrictions imposed by authorities (e.g., narrow time windows), coupled with a higher volume of consolidated freight, may improve the viability of UCCs. In another study, Elbert & Friedrich (2018) explore the impact of urban access regulations on the cost attractiveness of UCCs. The authors apply an agent-based simulation model on a case inspired by the Frankfurt Rhine-Main area. Since the region does not have a real-world UCC, the authors base their simulation on cost factors and data obtained from the literature. They argue that shortened time windows affect carriers' operations to a large extent and increase the cost attractiveness of a UCC. However, they highlight the difficulty of finding a setting where all carriers benefit from the center. Another intriguing analysis of achieving financial viability can be found in van Heeswijk et al. (2020). The authors utilize an agent-based simulation to evaluate the impacts of company-driven initiatives (e.g., optimized routing, collaboration) and administrative policies (e.g., time windows, zone access fees) on multiple stakeholders based on aggregated data from the literature. They show that UCCs are unlikely to achieve long-term financial viability, even with the most supportive administrative measures (e.g., carrier subsidies and time windows), mainly due to high handling costs but also to some extent inadequate level of freight throughput. They, however, perform a back-casting experiment (while allowing exploration outside the data boundaries) and illustrate that financially viable UCCs may exist, but only for schemes where operating costs are lower than what is suggested in the literature. Specifically, they assert that lowering handling cost to €1.5/m3 (the lower bound of the aggregated data is €3.45/m3), decreasing the range of the carrier prices between €11- €17 per stop (the range of the aggregated data is €12- €18 per stop), and increasing temporary carrier subsidies to 30% would yield a viable case. In contrast to this study, where carriers have the option to transship all or none of their deliveries to UCC at each decision epoch, Friedrich & Elbert (2022) introduce the aspect of cherry-picking specific customer requests for direct delivery and then determining whether to transship the remaining customer requests to a UCC. While analyzing the operations of UCCs together with different city toll regulations, the authors illustrate that the utilization of UCC is closely tied to pricing schemes, indicating that a competitive level is essential to incentivize carriers. Nevertheless, they argue that setting a low price to use the UCC that attracts many carriers may not yield profitability of the UCC. Hence, administrative measures may be required to subsidize UCC operations to facilitate competitive pricing. In brief, the literature suggests that achieving financially viable UCCs is highly challenging, but that lowering operational costs, increasing the level of freight throughput, and introducing administrative policies as supportive measures may lead to viable systems. More studies on these aspects can be found in Tamagawa et al. (2010), Van Duin et al. (2010), and Wangapisit et al. (2014).

Such ex-ante studies, however, often assume a greater number of carriers utilizing the system than there actually is (Quak 2008). For instance, Takahashi et al. (2004), in their simulations, assume that carriers fully cooperate with the consolidation center, although they find that only a limited number of carriers use the system in practice. While the main reason for this may lie in the financial unviability of UCCs, carriers' beliefs about the system are likely to contribute. For instance, Schoemaker (2002), in an ex-post study, highlights that carriers consider supportive administrative policies as unfair measures to keep unprofitable UCCs alive rather than making the city more livable. Also, the author emphasizes that carriers often consider UCCs as competitors, reducing their willingness to cooperate. Modeling such beliefs, however, is often not possible. In this regard, ex-ante studies conducted for such complicated systems may have difficulties in obtaining implementable insights while examining conditions that may not occur in practice. In conjunction with this, it is often not possible to know a variety of input data for a non-existing facility, which leads authors to rely on available data in the literature. However, although this approach might provide precise results for these given data points, the insights may remain impractical due to, for instance, changing (or different) economic conditions and cost overruns in constructions. Hence, advising authorities on establishing a consolidation center based on an estimation of how much it would cost to build and run might pose practical challenges. More importantly, the conditions suggested for viable UCCs by the reviewed literature in large cities are unlikely to be achieved in small cities due to the limited volume of freight throughput, which also leaves limited room to reduce operational costs.

2.2 Urban freight regulations

Aside from the context of supporting UCCs, freight transport regulations are also analyzed individually to control the distribution flows in urban areas. Dablanc (2007) highlights that time windows and vehicle restrictions are the most commonly used policy measures in practice. While both measures aim to improve the livability and attractiveness of cities, Quak & de Koster (2009) show that these can come at the expense of environmental challenges. The authors illustrate, through case studies in the Netherlands, that these policy measures increase emissions and traveled distance. In their study, they focus purely on retailers' perspectives and do not explicitly incorporate the objectives of local authorities. The latter is addressed by Akyol & De Koster (2013), in which the authors propose a framework based on data envelopment analysis and apply it to a case study of Dutch retail organizations. While modeling and quantifying the trade-offs between different objectives of stakeholders, they analyze and show the possibility of identifying time window policies that satisfy environmental sustainability, distribution efficiency, and the authorities' objectives. In another study, Akyol & De Koster (2018) develop a cooperative game-theoretic approach to obtain superior time windows, compared to the ones presently in use, by establishing horizontal cooperation between cities to determine joint time windows. Through a case study in Netherlands, comprising three cities and three fashion retail organizations, the authors illustrate the possibility to find better time windows that improve the city satisfactions, while having minimal influence on the operational effectiveness of the retail companies. Time windows policies are also utilized to motivate carriers in adopting electrical vehicles. For instance, diesel vehicles are restricted to enter city centers at certain times of the day in numerous Italian cities (Franceschetti et al. 2017). Although such measures may contribute to environmental performance, they do not impact congestion and illegal parking of delivery vehicles. A recent line of research has focused on the latter. In this regard, Chiara et al. (2020) formulate a policy-sensitive parking choice model for carriers and derive policy implications on how to operate parking infrastructures and mitigate illegal parking in Singapore. The study conducted by Kalahasthi et al. (2022) analyze parking patterns in urban freight loading zones by simultaneously considering vehicle arrival rates and parking durations. The authors provide a tool for planning and allocation of such zones, deriving policy insights into optimal location, quantity, and capacity as well as in freight regulations like time-limit restrictions. Zero-emission zones (e.g., Lurkin et al. 2021), congestion and emission pricing (e.g., Chen et al. 2018, Zhang et al. 2015), and toll schemes (e.g., Perera et al. 2021) are other types of measures available to local authorities. We refer the readers to a survey by Holguín-Veras et al. (2020) for an overview of the public-sector initiatives on urban freight management.

An intriguing policy measure related to our study is the load factor restrictions, which aim to reduce the number of delivery vehicles based on a minimum load factor. Jensen (2000), in this regard, highlights a scheme in Copenhagen, where a so-called "green certificate" was granted to carriers whose vehicle utilization was at least 60% on average over three months and whose vehicle engines were younger than eight years. Carriers were obliged to send a report to authorities every three months, which was used for inspections and crosschecks in the field. Despite the satisfaction of the carriers and the positive results, the scheme was discontinued due to a law breach resulting from reserving loading zones exclusively to certificate holders. While the violation may have been addressed by authorities, the required physical control of the scheme, coupled with its impact on increased congestion, reduced its appeal. Such obstacles, however, may be tackled with new and emerging technologies (Savelsbergh & Van Woensel

2016). For example, having real-time data on how full the carriers' vehicles are may eliminate the required physical control and the corresponding congestion issues encountered in Copenhagen's certification scheme. Such real-time data could also enable authorities to introduce a gradual toll scheme, where any carrier could deliver goods but would have to pay high toll fees for inefficient operations. While these kinds of measures, as technology moves forward, can enable consolidation among carriers, it is prudent to also realize what can be achieved with them in order to guide authorities.

3 Problem description

We consider a local authority operating in a small city. The authority would like to estimate the impact of consolidating freight transport in the city in terms of distance driven by parcel carriers as well as the number and duration of their stops. This estimation requires mimicking the daily operations of carriers on a holistic level, while capturing sufficient operational details to drive strategic regulatory decisions. In this regard, we initially define the operations of a single carrier from the perspective of the authority as follows. We assume that all carriers operate as described, but they differ from each other in terms of size.

A carrier serves a set of buildings I, also referred to as customers and/or collection points. An unlimited number of delivery vehicles with a capacity of $Q^{vehicle}$ is available at the depot $\{0\}$ to satisfy the daily demand of each building $i \in I$, denoted by $d_i^{building}$ and refers to the number of packages. The carrier establishes routes to serve the buildings. In this regard, the carrier initially groups the buildings into a set of clusters K, where each building $i \in I$ is assigned exactly to one cluster. The purpose of the clustering is to serve nearby buildings on foot after parking the vehicle at a location within the cluster. Therefore, to be classified in the same cluster, the walking distance $c_{ij}^{walking}$ between building $i \in I$ and building $j \in I$ must lay within a walking threshold, $c^{threshold}$.

Table 1: Selection criteria of parking spots

Criteria	**Selection process**
Building requiring multiple visits	Parking spot is selected at the building requiring the most visits
Multiple buildings requiring equal visits	Random selection among these buildings
Each building requires only a single visit	Random selection

Another criterion in determining clusters is the number of times a courier needs to visit a building. There is a maximum package capacity, $Q^{courier}$, that the courier can carry on each trip. Hence, the courier may have to visit some buildings more than once. In this context, the location where the vehicle will be parked is of importance. The scarcity of parking spaces for freight transport in the city leads to carriers stopping at various locations as needed. Therefore, we assume that one of the buildings in each cluster is assigned as the designated parking spot and the selection is made according to the definitions provided in Table 1.

We note that if the courier has to visit a building more than a certain number of times, then another building that requires the same number of visits (or more) cannot be in the same cluster

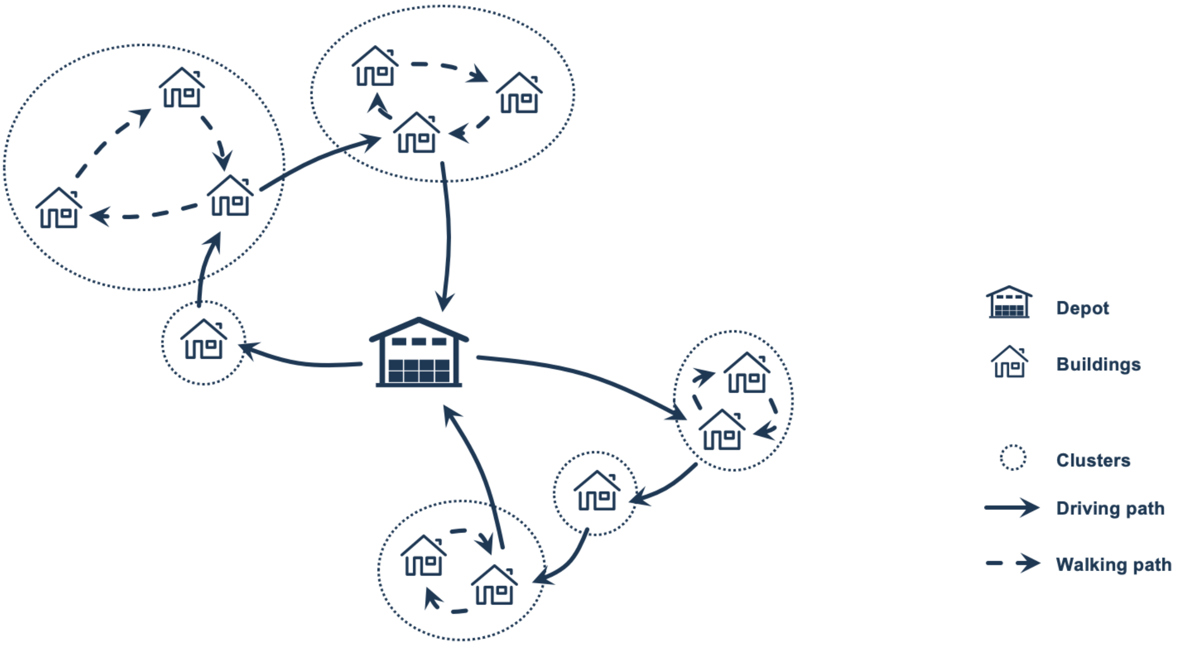

Figure 1: Illustration of carriers' operations

as this building. The rationale for this is that instead of having to walk to and from another location extensively, the courier opts to park the vehicle close to the building in question and provide the service from there. Consequent parking location of each cluster is represented by the set P, where $|P|$ is equal to the number of clusters, $|K|$.

The vehicle capacity possesses the last criterion in identifying the clusters such that the demand of each cluster $k \in K$, which is denoted by $d_k^{cluster}$ and refers to the aggregated demand of buildings in that cluster, cannot exceed the vehicle capacity. In some cases, the demand at a collection point may be greater than the vehicle capacity. In such situations, the carrier satisfies the demand by visiting the collection point with a full load. Any remaining demand at the location is included in cluster generation with other requests. These rules provide the basis for defining the operations of a carrier at a micro-level for the macro perspective of the authority.

Based on the generated clusters and parking decisions, let $G = (V, A)$ be a complete directed graph with V as the set of nodes, defined by the depot and parking locations $(\{0\} \cup P)$, and A as the set of arcs. A distance measure is associated with each arch $(i, j) \in A$, where $c_{ij}^{driving}$ refers to driving distance between node $i \in V$ and node $j \in V$. The carrier generates routes that start and end at the depot and involve visiting each cluster once, via their designated parking spot, while respecting the vehicle capacity. The carrier, in this regard, minimizes the driven distance. Once the vehicles arrive at the designated parking spots, the couriers follow the routes designed by the carrier to deliver the packages on foot. Depending on the number of packages and carrying capacity, the couriers may have to make multiple trips.

On the basis of these consecutive operations carried out by each carrier, as illustrated in Figure 1, the authority would like to assess the impact of consolidation by analyzing the structure of the freight transport market. More specifically, by varying the number and size of carriers, which reflects different degrees of consolidation, the authority would like to understand the distance driven by carriers as well as the number and duration of their stops. In this regard, while the number of stops is defined by the total number of clusters that carriers generate for their operations, driven distance is specified by their route length. We consider the following three components to estimate the duration of stops, which refers to the time spent in all clusters. The first component is the duration of time to off-load packages. This is calculated by adding a fixed amount of time needed for setting up the off-loading procedure (including the time to park the vehicle) to a variable amount of time required to off-load the packages, which is dependent on the number of packages being delivered. The second component is the time required for the courier to walk to and from the buildings, which is calculated by the traveled walking distance and the average walking speed. The last component is the required time to deliver packages to customers and is calculated based on the total number of visits to buildings and the average service time per building.

4 Routing-based policy guidance framework

A substantial share of the studies covered in the literature review utilize simulation-oriented approaches or game theory to examine stakeholders' perspectives within the last mile delivery. This choice is motivated by realizing the interaction between the decisions made by different parties in the value chain. For instance, in analyzing the UCC scheme, carriers have the options of either directly delivering parcels to end-customers or routing them to a UCC for subsequent distribution. In this regard, the strategic and tactical decisions of authorities and the UCC operator influence this decision-making process for carriers. While vehicle routing models are commonly employed to model the operational decisions, the dynamics between the stakeholders are analyzed through simulation-based studies aimed at capturing the interactions. As an example, in the reviewed study conducted by van Heeswijk et al. (2020), the authors address the strategic, tactical, and operational dimensions of their problem through an agent-based simulation method. Specifically, strategic decisions concerning the establishment of supportive administrative policies for the UCC are predetermined by authorities and remain fixed throughout the simulation, spanning multiple years. Tactical decisions on subsidies and cost determination for the UCC are made by authorities and the operator on a monthly basis, respectively. Consequently, carriers make their tactical decision between direct delivery and outsourcing to the UCC. Daily operational decisions of dispatching and routing are then made by carriers and the operator upon receipt of parcel orders from shippers, utilizing vehicle routing models for optimization. In this regard, the simulation serves as a powerful tool for analyzing and capturing the interactions among the stakeholders.

In contrast to these approaches, which mainly focus on capturing the voluntary participation of carriers and the feasibility aspect of achieving sustainable UCC schemes, our problem centers on the strategic regulatory aspect that carriers must comply with. Specifically, our problem setting revolves around informing policymakers on how the parcel delivery landscape can be structured in order to improve city livability. Accordingly, we analyze potential parcel delivery landscapes, characterized by differing degrees of consolidation, to assess their impact on the urban environment. These landscapes need not be modeled as strategic decisions; instead, they can be externally defined as market structures. In this regard, the operational aspects of carriers can be represented within each structure through vehicle routing models, providing insights for authorities when making strategic decisions regarding consolidation. As previously mentioned, our objective is not to analyze specific freight regulations for consolidation, but rather to recognize important consolidation effects that can contribute to policy-making decisions. The approach adopted in this study relies on this and involves employing routing models to conduct the aforementioned analysis. Furthermore, in addition to addressing the nature of our problem, reducing the required technical steps can bring practical benefits, considering that the tool can be employed by authorities in their decision-making processes.

In light of these, we introduce a three-stage routing-based framework to address the given problem. The framework, while inspired by initiatives that integrate walking and driving for optimized last-mile delivery for carriers, differs by adopting a broader strategic perspective tailored for authorities. To illustrate this perspective, we will cover some initiatives that integrate walking as a mode of transport into delivery operations. For instance, Nguyên et al. (2019) employ a cluster-first route-second approach to optimize last mile delivery using a combination of walking and driving. Clusters are determined in advance and serves as input data for the routing model. The model then determines the optimal paths for both walking and driving simultaneously by designating a certain customer location within each cluster as a parking slot. Martinez-Sykora et al. (2020), on the other hand, tackle a similar issue but without assuming any predetermined clusters. Instead, the optimal walking paths naturally form the clusters. Despite being theoretically optimal, however, such approaches may encounter practical hurdles. For instance, the chosen customer location might not be available for parking upon the courier's arrival, requiring detours to locate an alternative and to proceed to the next customer. In this regard, the study conducted by Le Colleter et al. (2023) removes the assumption of selecting certain customer locations as parking slots. The authors require couriers to stop at designated parking spaces or loading zones for subsequent on-foot delivery. This approach, however, remains feasible in situations where there is a large availability of parking areas, such as in large cities.

As previously highlighted, however, small cities pose challenges as they typically have few parking options available, resulting in couriers stopping wherever they can. Therefore, optimizing the locations where a courier stops in such cities, be it at a customer's location or a parking spot, may underestimate the effects of the delivery process on city livability, particularly in driven distance, from the perspective of authorities. More importantly, determining precise stopping points is a detailed operational concern in order to identify optimal walking and driving paths during the delivery process. Our emphasis, however, is not directed towards identifying operationally optimal paths. Rather, our focus is on capturing strategic measures to provide insights for authorities in enhancing small city livability. For instance, while the integration of walking into carriers' route planning aims to improve delivery completion within a shorter time frame, authorities consider walking as a means to measure the duration of vehicle occupancy along the curbside when parked. Thus, our adoption of walking as a mode of transport does not focus on capturing granular details, such as identifying the optimal parking spots and subsequently generating the optimal paths, but rather on measuring the effects of delivery operations on city livability.

Given these considerations, although we mimic carriers' underlying operations using vehicle routing models, these serve as strategic tools in our approach. As such, the macro regulatory perspectives are drawn from routing models that are grounded in the micro-level behaviors of carriers. This, in fact, has enabled us to leverage these models as a *"tool to talk"* during our discussions with authorities.

The following subsections outline the stages of the framework to capture the given measures, which are cluster generation, vehicle routing, and courier delivery.

4.1 Cluster generation

Clusters are generated by using three criteria, namely the walking distance threshold between any two buildings, the maximum number of allowed visits to a single building, and the capacity of the vehicle. An integer linear programming model is formulated as follows.

Sets

I: set of all buildings
$K = \{1, \ldots, |I|\}$: set of all potential clusters (each building can form a singleton)

Parameters

$d_i^{building}$: demand of building $i \in I$
$Q^{vehicle}$: vehicle capacity as the maximum number of packages
$r_{i,j}$: equal to 1 if buildings $i \in I$ and $j \in I$ are allowed to belong to the same cluster, 0 otherwise

Decision variables

$x_{i,k} \in \{0, 1\}$: 1 if $i \in I$ is assigned to a cluster $k \in K$, 0 otherwise
$y_k \in \{0, 1\}$: 1 if cluster $k \in K$ has at least 1 building assigned, 0 otherwise

Objective function

$$\min \sum_{k \in K} y_k \tag{1}$$

Constraints

$$\sum_{k \in K} x_{i,k} = 1 \qquad \forall i \in I \tag{2}$$

$$y_k \geq x_{i,k} \qquad \forall i \in I,\, \forall k \in K \tag{3}$$

$$x_{i,k} + x_{j,k} \leq 1 + r_{i,j} \qquad \forall i \in I,\, \forall j \in I,\, \forall k \in K \tag{4}$$

$$\sum_{i \in i} d_i^{building} \cdot x_{i,k} \leq Q^{vehicle} \qquad \forall k \in K \tag{5}$$

$$x, y \in \{0, 1\} \tag{6}$$

The objective function (1) minimizes the total number of clusters. Constraints (2) ensure that each building is assigned exactly to one cluster. Constraints (3) establish the logical relationship between variables $x_{i,k}$ and y_k. Constraints (4) make sure that two buildings cannot be assigned to the same cluster under two conditions: if they require more visits than the maximum allowed or if the distance between them exceeds the predefined walking threshold. The values of the parameter $r_{i,j}$ are set to 0 when one of these conditions are met, and to 1 otherwise. Constraints (5) assure that the total demand of a cluster cannot be greater than the vehicle capacity.

The solution of the model provides a list of clusters along with the buildings they contain. For each cluster, a building is designated as a parking spot based on the rules given in the problem statement.

4.2 Vehicle routing

A capacitated vehicle routing problem (CVRP) is formulated such that the parking spot of each cluster is visited once while respecting the capacity of the vehicles. The mixed integer programming model for the CVRP is presented below.

Sets

P: set of parking spots, one for each cluster $k \in K$
V: union set of depot $\{0\}$ and P
A: set of all arcs

Parameters

$c_{i,j}^{driving}$: driving distance from the depot or the parking spot $i \in P$ to the depot or the parking spot $j \in P$
$d_i^{cluster}$: aggregate demand of buildings in cluster with parking spot $i \in V$, where $d_0^{cluster} = 0$
$Q^{vehicle}$: vehicle capacity as the maximum number of packages (as in cluster generation)

Variables

$x_{i,j}^{driving} \in \{0,1\}$: 1 if there is a vehicle driving from the depot or the parking spot $i \in P$ to the depot or the parking spot $j \in P$, 0 otherwise
$l_{i,j}^{driving} \in \{0,1,\ldots\}$: the number of packages delivered on the route after stopping at the parking spot $i \in P$ and before reaching parking spot $j \in P$

Objective function

$$\min \sum_{(i,j)\in A} c_{i,j}^{driving} \cdot x_{i,j}^{driving} \tag{7}$$

Constraints

$$\begin{aligned}
&\sum_{j\in V: i\neq j} x_{i,j}^{driving} = 1 && \forall i \in P && (8)\\
&\sum_{j\in V: i\neq j} x_{i,j}^{driving} = \sum_{j\in V: i\neq j} x_{j,i}^{driving} && \forall i \in V && (9)\\
&l_{i,j}^{driving} \leq (Q^{vehicle} - d_j^{cluster}) \cdot x_{i,j}^{driving} && \forall i \in P, j \in V : i \neq j && (10)\\
&l_{i,j}^{driving} \geq d_i^{cluster} \cdot x_{i,j}^{driving} && \forall i \in P, j \in V : i \neq j && (11)\\
&\sum_{i\in P} l_{i,0}^{driving} = \sum_{i\in P} d_i^{cluster} && && (12)\\
&\sum_{j\in V: j\neq i} l_{i,j}^{driving} - \sum_{j\in V: j\neq i} l_{j,i}^{driving} = d_i^{cluster} && \forall i \in P && (13)\\
&x^{driving} \in \{0,1\}, l^{driving} \geq 0 && && (14)
\end{aligned}$$

The objective function (7) minimizes the total driving distance between clusters. Constraints (8) make sure that each parking spot is visited exactly once. Constraints (9) ensure that vehicles depart from the nodes where they arrive. Constraints (10-13) are capacity-bounding constraints.

4.3 Courier delivery

The courier delivery uses the CVRP formulation defined in (7-14) such that the courier visits each apartment within a cluster while respecting its maximum carrying capacity. The description of the sets, parameters, and variables are given as follows, while following the same notations of the model. Parameters and variable superscripts are adjusted accordingly.

Sets

P: set of all buildings within the current cluster except the building visited by a vehicle, which is denoted by $\{0\}$
V: set of all buildings within the current cluster
A: set of all arcs

Parameters

$c_{i,j}^{walking}$: walking distance from building $i \in V$ to the building $j \in V$
$d_i^{building}$: demand of building $i \in V$ in the current cluster. The demand of the building visited by the vehicle is served prior to commencing the walking route (i.e., $d_0^{building} = 0$)
$Q^{courier}$: courier capacity as the maximum number of packages (as in cluster generation)

Variables

$x_{i,j}^{walking} \in \{0, 1\}$: 1 if the courier walks from building $i \in V$ to building $j \in V$, 0 otherwise
$l_{i,j}^{walking} \in \{0, 1, \dots\}$: the number of packages served by the courier on his path after serving the demand of building $i \in P$ and before visiting building $j \in P$

5 Urban freight transport in Bergen, Norway

Bergen is a medieval Norwegian city with a road network characterized by winding roads and steep inclines. The majority of the roads follow the natural contours of the mountains, making navigation rather challenging for drivers. Moreover, due to topography, the narrow and often one-way streets result in long drives as well as congestion. As an example, consider the distance between two buildings in Figure 2. Although it is a short distance on foot, a driver has to follow a long and rather congested path due to the network structure.

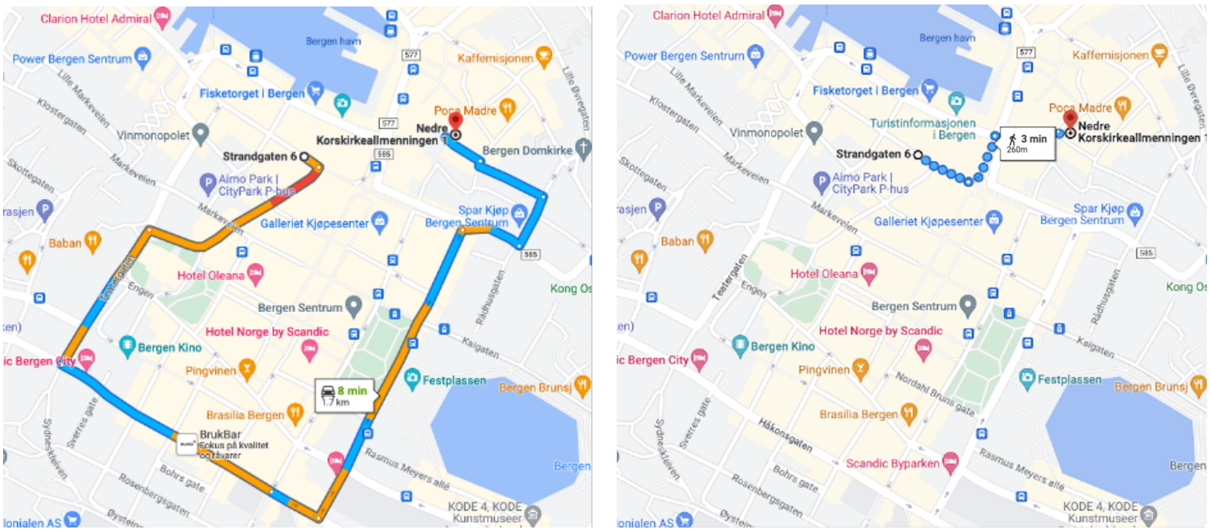

Figure 2: Driving (left) and walking (right) in the city center (Google Maps)

As previously emphasized, urban freight transport comprises a significant portion of all urban transport throughout Norway (Ministry of Transport and Communication 2017) and Bergen is not an exception. The authorities, however, have left the market to the private sector and have not regulated freight transport. While the majority of the distribution has been conducted by a small number of large carriers, the number of emerging small carriers has been growing progressively in the city. As of January 2023, 434 carriers, providing road-based services, are registered in the records of Bergen municipality, of which only 17 have more than 20 employees (Proff 2023). To provide a point of reference, 335 of these carriers were in operation by the end of 2020. These growing numbers of small carriers, however, deliver only a handful of packages per trip and do not benefit from economies of scale as large carriers do. As a result, their operations bring further inefficiencies to the freight market and hamper the livability within the city. It is noteworthy that these carriers deliver directly to customers and do not utilize collection points like the large operators. As they do not have enough volume to consolidate, there is no difference between serving the customer directly or from the collection points from their operational perspective. The latter mode, however, is the main distribution channel in Norway and consists of places such as grocery stores, shopping malls, and convenience stores. Large carriers consolidate several packages that require delivery to a specific region and transport them to a collection point within the area, where customers retrieve their packages.

Considering their growth potential prompted by uberification and internet trade, we believe that it is essential for the authorities to examine how these small carriers are affecting the city. In this regard, we assess the current market structure of parcel distribution and conduct a comprehensive analysis to compare it with potential market structures that can be achieved. These potential structures vary in terms of the number and size of carriers involved, representing different levels of consolidation. We provide a more detailed explanation of the market structures following the description of the data.

5.1 Data description

We define the road network topology of Bergen, both for driving and walking, based on the data we gather from the National Road Database administrated by the Norwegian Public Roads Administration[1]. We pull the links of each road in Bergen as well as the corresponding objects and restrictions (e.g., directions, one-way streets, no turn or entry restrictions, and roadblocks) from the database and transform them into applicable formats for our models. We focus on the central parts of the city and define its boundaries according to the postcode classifications of the Norwegian Mapping and Cadastre Authority[2]. We identify the locations of all buildings residing within this boundary, which we collect from the database of the mapping authority. We then connect these buildings with our road network and generate the map of central locations in Bergen, which we illustrate in Figure 3. The red ellipse outlines the city center.

We also obtain real freight patterns and volumes of a major carrier in Norway, namely PostNord[3], for Bergen. The carrier distributes packages of individuals and companies, and resembles a perfect consolidator. While the carrier delivers most of its packages through collection points, it also delivers a significant portion directly. We, therefore, assume that the distribution patterns for both delivery modes are typical for all other carriers.

The data received from PostNord includes the weekly distribution of the carrier in 2020 for each postal code. We initially estimate the average daily distribution of the carrier from the weekly distributed volume. As the pattern is attached to postcodes, we break it down by address

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[1] https://api.vegdata.no

[2] https://www.kartverket.nol/api-og-data/eiendomsdata

[3] https://www.postnord.no/en

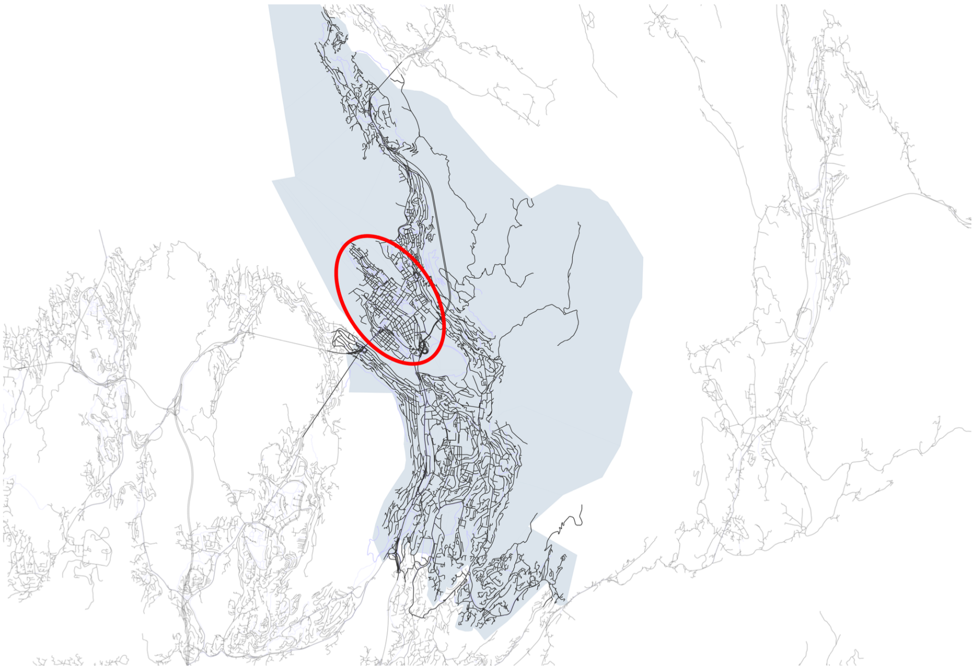

Figure 3: Map of Bergen (highlighted region indicates the central locations in Bergen, the city center is displayed with a red ellipse)

level based on the estimated population of each building in Bergen from Fang & Opedal (2020) and, consequently, derive the proportion of each building receiving packages per day. Based on these proportions and the market share we believe PostNord has, we define the daily parcel distribution in Bergen, corresponding to 6000 packages, and generate instances accordingly.

Each instance includes a list of buildings, along with the number of packages requested in each building. We implement Dijkstra's shortest path algorithm to generate two distance matrices for each instance, one for driving distances (asymmetrical) and the other for walking (symmetrical). The list of buildings also includes a depot, which is in an area next to Bergen's main bus and train stations. Most of the transport infrastructure in the city converges towards these stations, which have been the main point of operations for large carriers. Unlike large carriers, small carriers do not require a depot and their operational locations are widely unknown. However, we assume that they initiate their operations from the same region as the large carriers. Other parameters include the capacities of vehicles and couriers, set to 200 and 5 packages respectively. Furthermore, while the walking threshold between any two buildings is chosen as 100 meters, the maximum number of allowed visits to a single building is set to two trips, excluding the building which is designated as the parking spot. 75% of the packages are assumed to be distributed through collection points, whereas the remaining portion is delivered directly to customers. Also, setting up the off-loading procedure (including the parking time) is assumed to be 2 minutes per stop, while the time required to unload each package is set to 30 seconds. The service time per building is set to 1.5 minutes and the average walking speed is set to 4.5 km/h. These figures for estimating the duration of stops are derived from a field trip we conducted in the city center of Bergen, in collaboration with local authorities, to observe the freight delivery processes.

5.2 Market structures

Three market structures are defined to analyze the freight distribution in Bergen. The detailed explanations of these structures are described as follows.

5.2.1 Current market with small and large carriers

As previously emphasized, the majority of freight distribution in Bergen is done by a handful of large operators, with small carriers also holding a share in the market. These small carriers, however, are not as efficient as the large ones due to the limited volumes they deliver. It is, therefore, prudent to understand how these carriers affect the city in terms of road space and stops. In this regard, we study the following setting.

Table 2: Market shares of small and large carriers

	Carrier A	Carrier B	Carrier C	Carrier D	Carrier E	Carrier F	Small carriers
Market shares	34%	25%	9%	8%	7%	7%	10%

We assume that 10% of the freight market in Bergen is shared among small local carriers, whereas the remaining 90% is captured by six large carriers. There is, however, no available information on how many small carriers there are conducting parcel delivery or how many packages they deliver. Therefore, instead of making a guesstimate, we analyze how distance and stop measures would increase as the number of small carriers increases, which represents what we are facing today with the increasing uberification and internet trade. In this context, we vary the number of small carriers sharing 10% of the market share equally between 25 and 100 carriers. Table 2 illustrates our assumption on the market shares of the parcel carriers, in which large carriers are denoted by letters. The largest two carriers operate primarily through collection points, while the remaining large carriers have a mix of the two delivery modes. Small carriers, on the other hand, serve their customers directly.

5.2.2 Competitive market with large carriers

We study a competitive market that only consists of large carriers. We examine the impact of the following two changes by establishing two potential market setups. The initial setup prohibits small carriers from delivering goods directly to end-customers and considers a setting where the market share of the small carriers is distributed among the large ones based on their respective market shares. The second setup, on the other hand, realizes a distribution setting where two to three reasonably large carriers share the freight market equally. We analyze these setups to provide insights to policymakers regarding the importance of understanding how variations in carrier numbers and sizes within the freight market affect city livability in comparison to the current market landscape. By doing so, we assist authorities in identifying what is essential to prioritize in their regulatory decisions. For instance, they might consider implementing criteria-based schemes to regulate carrier operations based on their size and consolidation efficiency.

5.2.3 Completely consolidated market with a single carrier

A complete consolidation forms our last market structure. We analyze a single carrier serving all customers within the city. This potential setup also facilitates the identification of the maximal impact of consolidating goods within the urban environment.

In addition, to capture the future growth in parcel deliveries, we also examine each structure while the total freight volume in the city increases by 25% and 50%.

6 Computational study

In this section, we present our computational experiments for analyzing and comparing the given market structures in Section 5.2. We initially describe the solution procedure in Section 6.1. While the results and comparisons are presented in Section 6.2, the managerial insights are highlighted in Section 6.3.

6.1 Solution procedure

The cluster generation and vehicle routing models described in Section 4.1 and Section 4.2, respectively, require computational times when attempting to solve carrier instances, involving a large number of delivery locations, using commercial solvers. We, therefore, adopt heuristics for these two models in our computations. Specifically, we utilize the state-of-art hybrid genetic search algorithm proposed by Vidal (2022) for CVRP. We choose to employ this as it is a specialized algorithm tailored to this problem class, capable of providing high-quality and robust solutions for instances involving up to 1,000 customers. We construct a cluster generation algorithm accommodating the walking distance threshold between any two buildings, the maximum number of allowed visits to a single building, and the capacity of the vehicle. The order of buildings in clustering is of importance and, therefore, we sort the buildings based on their demand, considering possible parking spaces as initial inputs for the clusters. These algorithms and the CVRP model for the courier delivery are implemented in Python and the latter is solved by using Gurobi.

The solution procedure is outlined as follows and remains consistent across all market structures: To begin, the clustering algorithm is applied to the customers of each carrier in the market to identify clusters. Following this, we utilize the rules detailed in Table 1 to assign a parking spot for each identified cluster. We then employ the hybrid genetic search algorithm to optimize the driving paths of each carrier, generating a sequence of trips that include parking spots and the depot. Finally, we use Gurobi to identify the walking routes for couriers within each cluster of the carriers.

Table 3: Operational results of the small carriers in the current market with small and large carriers

Number of small carriers	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips	Number of packages
25	539.6	826.8	38.9	25.0	607.8
50	569.6	1178.3	39.8	50.0	607.8
75	582.0	1433.5	40.0	75.0	607.8
100	587.2	1664.3	40.2	100.0	607.8

6.2 Results

6.2.1 Current market with small and large carriers

Table 3 summarizes the operations of small carriers in the current market in terms of driven distance as well as the number and duration of stops, which are used to measure city livability from the perspective of authorities. Four settings are showcased, in which the 10% of the market share is distributed equally among 25, 50, 75, and 100 small carriers. The analysis consists of five operational days for each setting. The variations between the daily results are minimal and, therefore, we base our analysis on the average.

Table 4: Operational results of the large carriers in the current market with small and large carriers

Carrier	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips	Number of packages
A	154.6	131.8	37.0	11.0	2020.3
B	120.2	109.4	27.3	8.0	1496.3
C	155.8	98.7	17.7	3.0	563.8
D	123.8	88.7	14.3	3.0	488.0
E	77.2	70.4	10.0	3.0	411.6
F	77.6	71.4	10.0	3.0	412.4

The results highlight that, whether the corresponding market is divided between 25 or 100 small carriers, the total number of stops is approximately the same as the total number of packages to be delivered. The customers that small carriers need to serve per day are spread across different parts of the city and, therefore, carriers mostly serve one package per stop. The situation, however, is different for large carriers. As shown in Table 4, each large carrier has a lower number of stops compared to small carriers combined, even if they carry more packages alone. The obvious reason for this is that, owing to the large number of packages they deliver, these carriers can either consolidate packages at a building level (including the collection points) or serve customers that are in close proximity from each other. While this results in a higher average duration of stop per cluster, the total duration of stops is lower than the combined operations of small carriers as seen in Table 3 and Table 4. The consolidation effect naturally

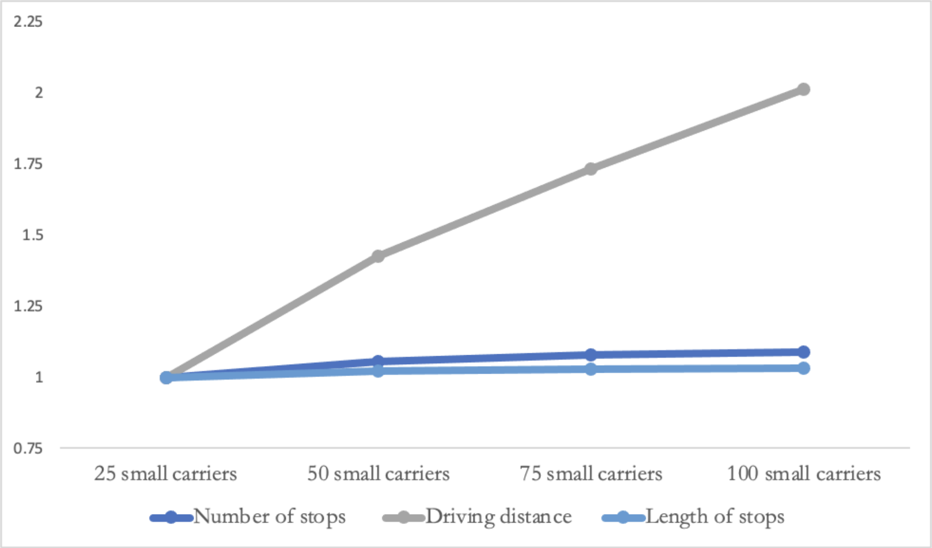

Figure 4: Comparison of the average daily operational results for the market share served by different number of small carriers (relative to the market with 25 small carriers)

translates into driven distance as well. Despite carrying a volume that is only one-third of what the market leader has, small carriers together travel more distance in comparison to the leader. In this regard, as seen in Figure 4, the more smaller carriers there are, the worse the situation is. Although the total number and duration of stops of small carriers are approximately the same in each setting (since the consolidation options are limited), the total driven distance increases as the number of small carriers grows. The reason for the latter can be observed in Figure 5, where we visualize the routes taken by a small carrier within the following two market structures: one with 25 small carriers and another with 100 small carriers. Despite the difference

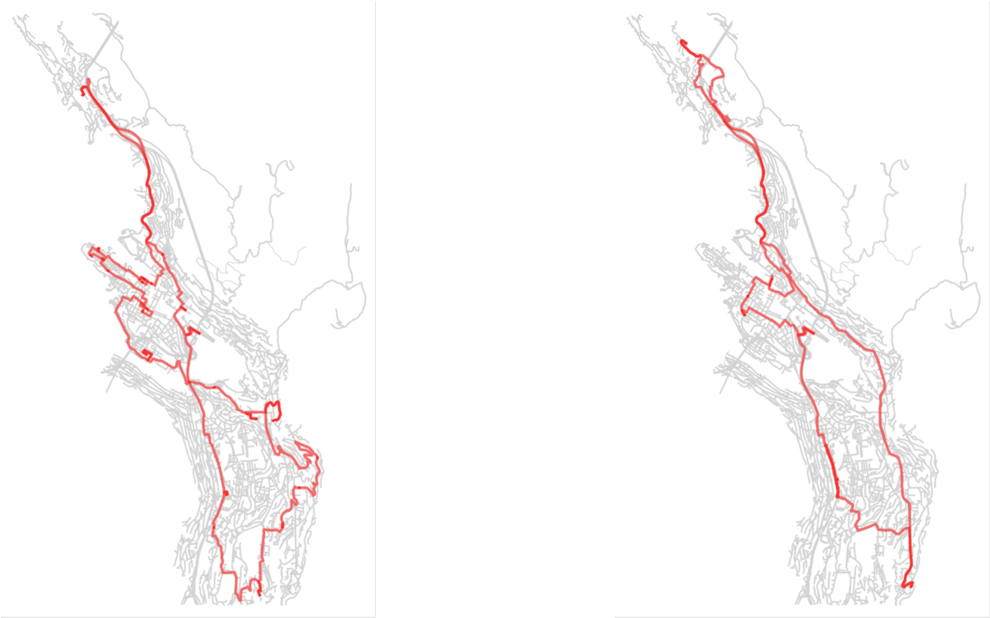

Figure 5: Routes covered by a typical small carrier in the market with 25 small carriers (left) and 100 small carriers (right)

in the number of packages they deliver, where the small carrier in the former setting delivers 24 packages and the one in the latter setting delivers 6, both carriers follow similar paths and cover approximately the same locations. The operational differences between the market leader and 25 small carriers in terms of driven distance and stops per package are shown in Figure 6.

Figure 6: Average daily operational results of the market leader and 25 small carriers per package in the current market with ongoing uberification

6.2.2 Competitive market with large carriers

We initially analyze the setting where the share of small carriers is distributed to large ones based on their market shares on direct deliveries. Table 5 provides the corresponding share of each carrier.

Table 5: Shares of the six large carriers in the competitive market

	Carrier A	Carrier B	Carrier C	Carrier D	Carrier E	Carrier F
Market shares	36.5%	26.7%	11.5%	9.7%	7.8%	7.8%

The comparison between the competitive market with large carriers and the current market with 25 small carriers is illustrated in Figure 7. While the number and duration of stops are decreased by 20.9% and 6.6% respectively, the total driving distance is reduced by 52.8%. There are two major reasons behind this drastic reduction in the driven distance. First, some of the additional deliveries from small carriers are located in the existing clusters of the large operators (some are even served to the same buildings) and, therefore, the distance driven earlier to serve these deliveries is avoided. Although this translates into a longer duration of stops for these clusters, the fewer stops reduces the total amount of time needed for setting up the off-loading procedure and, consequently, the total duration of stops. Second, some of the remaining additional deliveries are destined for locations that are in close proximity to the existing clusters of the large carriers. Hence, these packages are served with only minor changes

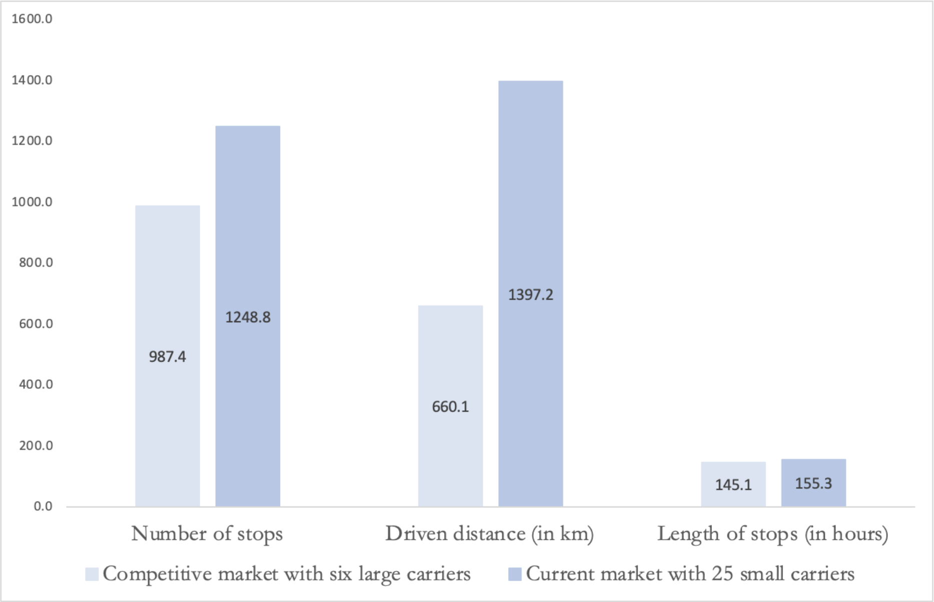

Figure 7: Comparison between competitive market with large carriers and current market with 25 small carriers

to existing routes. This can be observed in Figure 8, where we present the route of a large carrier before (left image) and after (right image) the distribution of small carrier deliveries to large carriers. The additional deliveries either intersect with the initial route of the large carrier or can be incorporated into the large carrier's route with only minor adjustments. The visualization also illustrates that, due to the available consolidation opportunities, the large carrier can design a route tailored to serve a specific area within the city. Achieving region-specific routes, resulting from consolidation, reduces the number of carriers passing through the

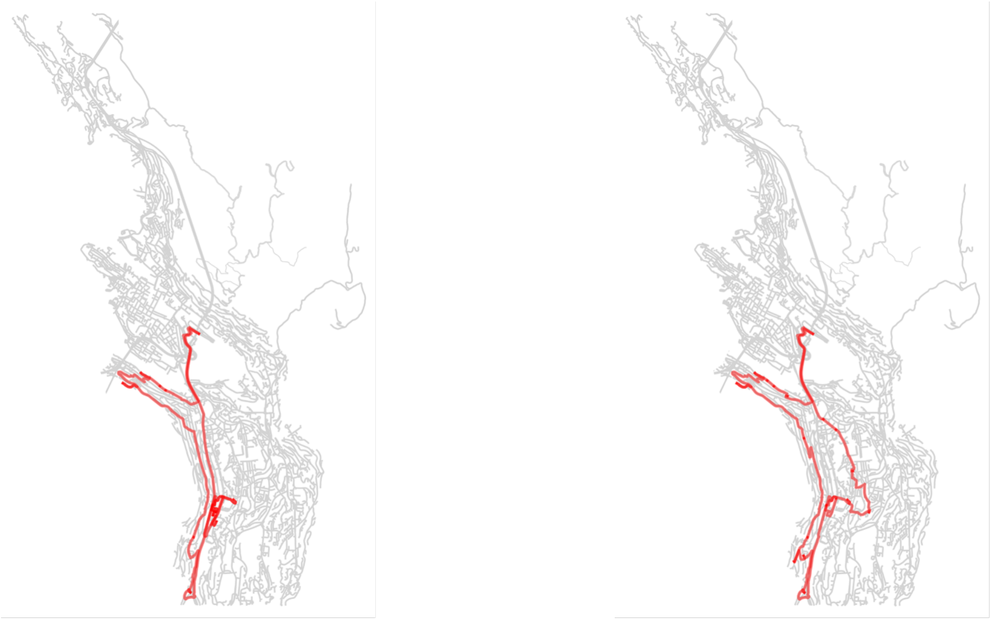

Figure 8: The route of a large carrier before (left) and after (right) the distribution of small carrier deliveries to large carriers

city center, aligning with the objective of the authorities in Bergen to allocate more space for pedestrians on the narrow roads of the downtown area. As previously illustrated in Figure 6, small carriers pass through the city center while serving customers distributed across the city. Accordingly, a growing number of small carriers results in increased volume of freight traffic passing through the city center.

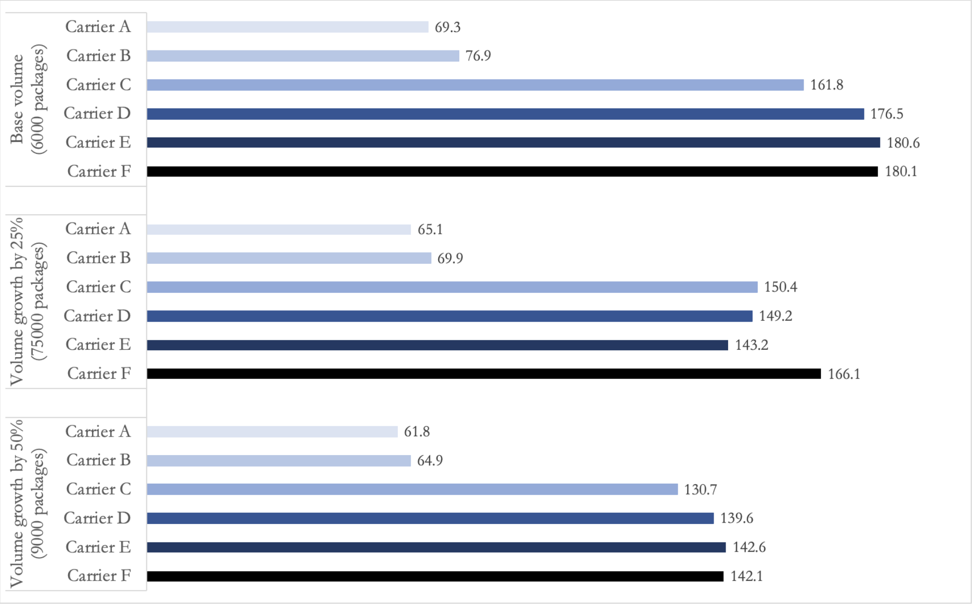

Figure 9: Driven distance per package for each carrier in the competitive market with six large carriers

As the parcel volume grows in the city, the total driven distance and stops per package reduces. Specifically, we observe that the driven distance per package decreases by 10.2% when the volume increases by 25.0%, whereas the number and duration of stops reduce by 6.0% and 1.5%. Meanwhile, when the volume increases by 50.0%, these metrics reduce by 17.3%, 10.5%, and 2.8%, respectively. Figure 9 highlights the driven distance per package for each carrier. Carriers A and B consolidate the bulk of their deliveries for collection points, resulting in significantly less driven distance per package than other carriers. As the volume grows, the remaining carriers deliver more packages and achieve higher degree of consolidation as well as more efficient routes. Although their driven distance per package reduces, it is considerably higher than that of carriers A and B as a result of their limited presence at the collection points.

The complicated road network of Bergen's city center also plays a role in reducing the livability of the city. Large carriers handle a substantial number of packages destined for the city center and operate under the complexities of intricate traffic patterns and narrow one-way streets, which pose unique challenges compared to smaller carriers handling only a limited number of packages in the city center. Consequently, even within a market shared by only six large carriers, we observe the emergence of long and convoluted routes caused by topography and political decisions. This is exemplified in Figure 10, which displays several routes taken by the carriers within the city center.

The overall life quality in the city can, therefore, improve further as the degree of consolida-

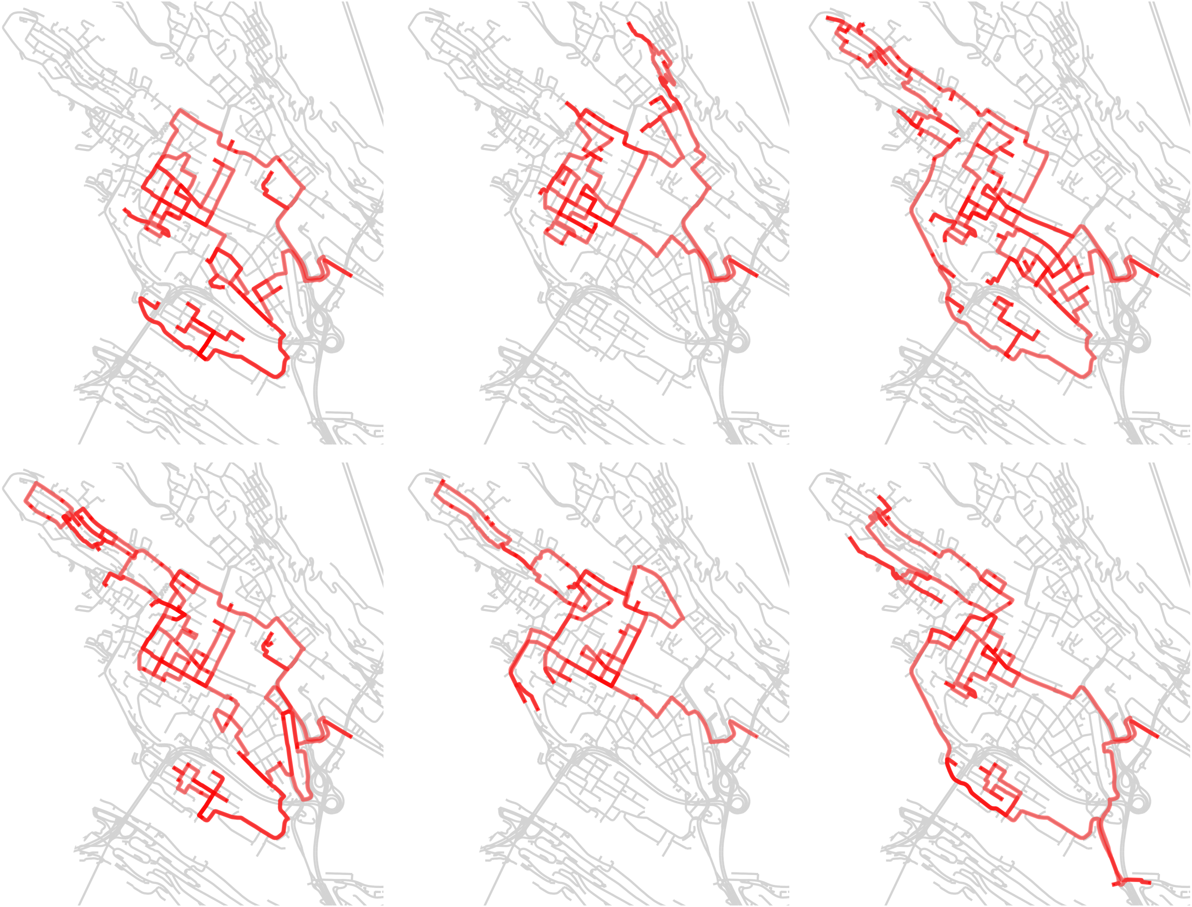

Figure 10: Downtown routes covered by the six large carriers of the competitive market

tion increases in the market. In comparison to the market led by six carriers, there is an average reduction of 41.3% in driving distance in the two carrier scheme, accompanied by a reduction of 31.7% and 18.7% in the number and duration of stops, respectively. For the market with three carriers, the differences are 29.6%, 20.5%, and 13.6% respectively. The underlying reason for this is that although the six carriers have considerable distribution volumes, the market has an opportunity for more efficient consolidation and shorter routes as these carriers serve customers in similar (or exact same) locations and even on each other's routes. Figure 11 presents the comparison of the market led by two and six carriers. As a result of a higher degree of consolidation and more efficient routes, reflected by the number of stops and driven distance, respectively, distance and stops metrics drastically reduce.

6.2.3 Completely consolidated market with a single carrier

A complete consolidation scheme, by definition, provides the most effective market structure for a city's livability in terms of driven distance as well as the number and duration of stops. In this regard, in comparison to the market with two carriers, the scheme on average reduces the driven distance as well as the number and duration of stops by 18.6%, 23.8%, and 5.1% respectively. Comparing the market led by a single carrier, which needs 14 trips to serve the packages, to the market led by two carriers, requiring 15 trips, we find that despite a similar number of trips

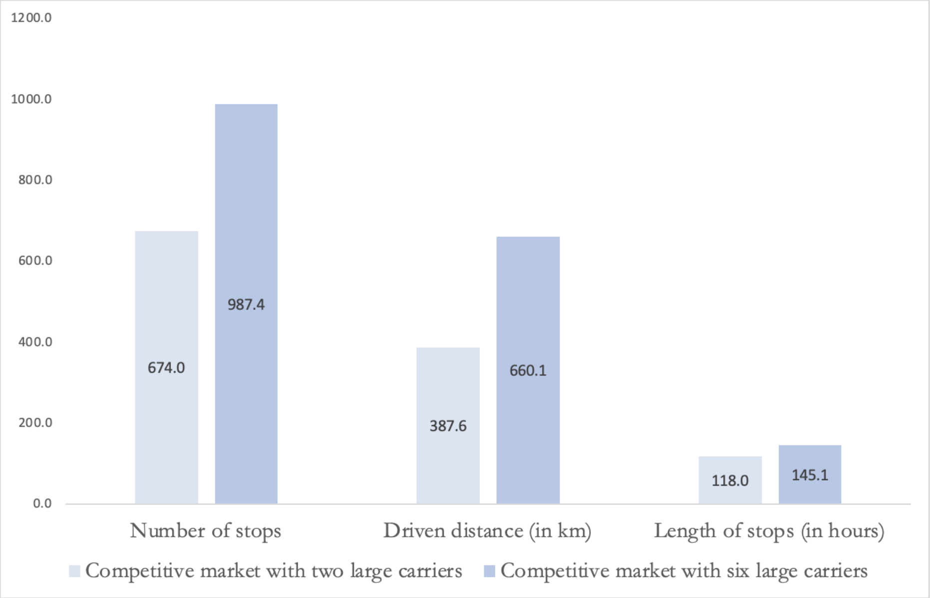

Figure 11: Comparison between the competitive market with two and six large carriers for a day

and near-full vans, the former exhibits a more efficient consolidation scheme. Consequently, it achieves shorter routes and stopping times, and fewer stops. We, however, observe that the percentage gap on driven distance per package between the complete consolidation and the market led by a reasonably few large carriers reduces slightly when the total parcel volume in the city increases, as shown in Figure 12.

Furthermore, a higher degree of consolidation results in the creation of shorter and more compact routes in the city center. In comparison to Figure 10, which displays longer and

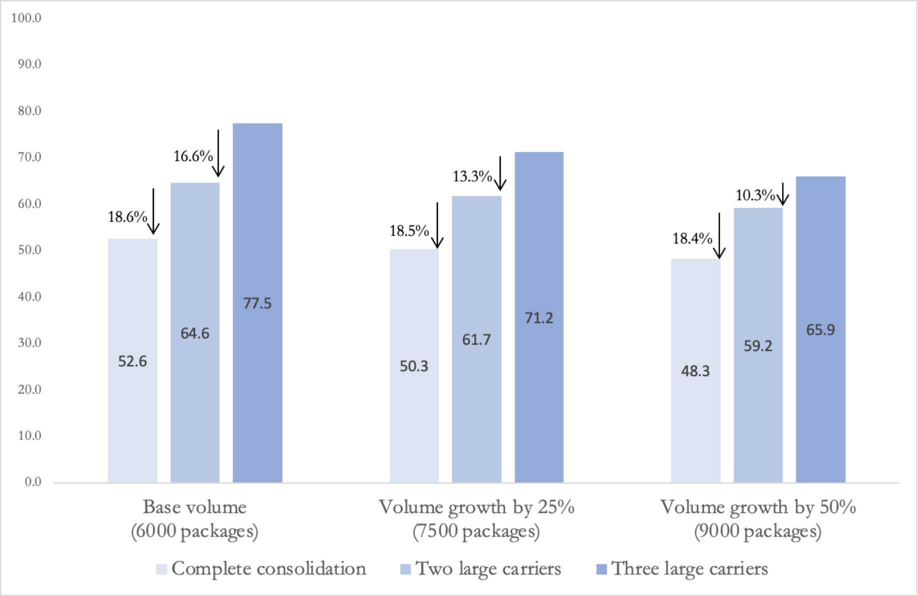

Figure 12: Differences in driven distance between complete consolidation and a few reasonably large carriers as the number of packages increases

inefficient routes traversed in the city center within the market shared by six large carriers, Figure 13 illustrates that increased consolidation leads to shorter routes that are tailored to accommodate the intricate road network of the city center.

Figure 14 illustrates the operational results of each market structure. The numerical results are provided in Appendix A.

Figure 13: Downtown routes covered by the single carrier of the completely consolidated market

6.2.4 Remarks

In our analysis, we assumed certain values for the walking threshold as well as for the vehicle and courier capacities. We, therefore, performed sensitivity analyses for these parameters, considering the baseline volume as our reference. We examined three different settings: one where the walking threshold is increased to 150 meters, another where the vehicle capacity is increased to 300 packages, and a third where the courier capacity is increased to 10 packages. We do not observe any significant changes conflicting with the insights previously derived. For instance, increasing the walking threshold to 150 meters does not affect the driven distance significantly, as the extra walking distance covered by the courier does not result in significant routing changes. As expected, the number of stops reduces and the distance traveled by the courier increases for some clusters. Although this means longer stopping times for some clusters, the total duration of stops remains approximately the same as a result of fewer stops. The results

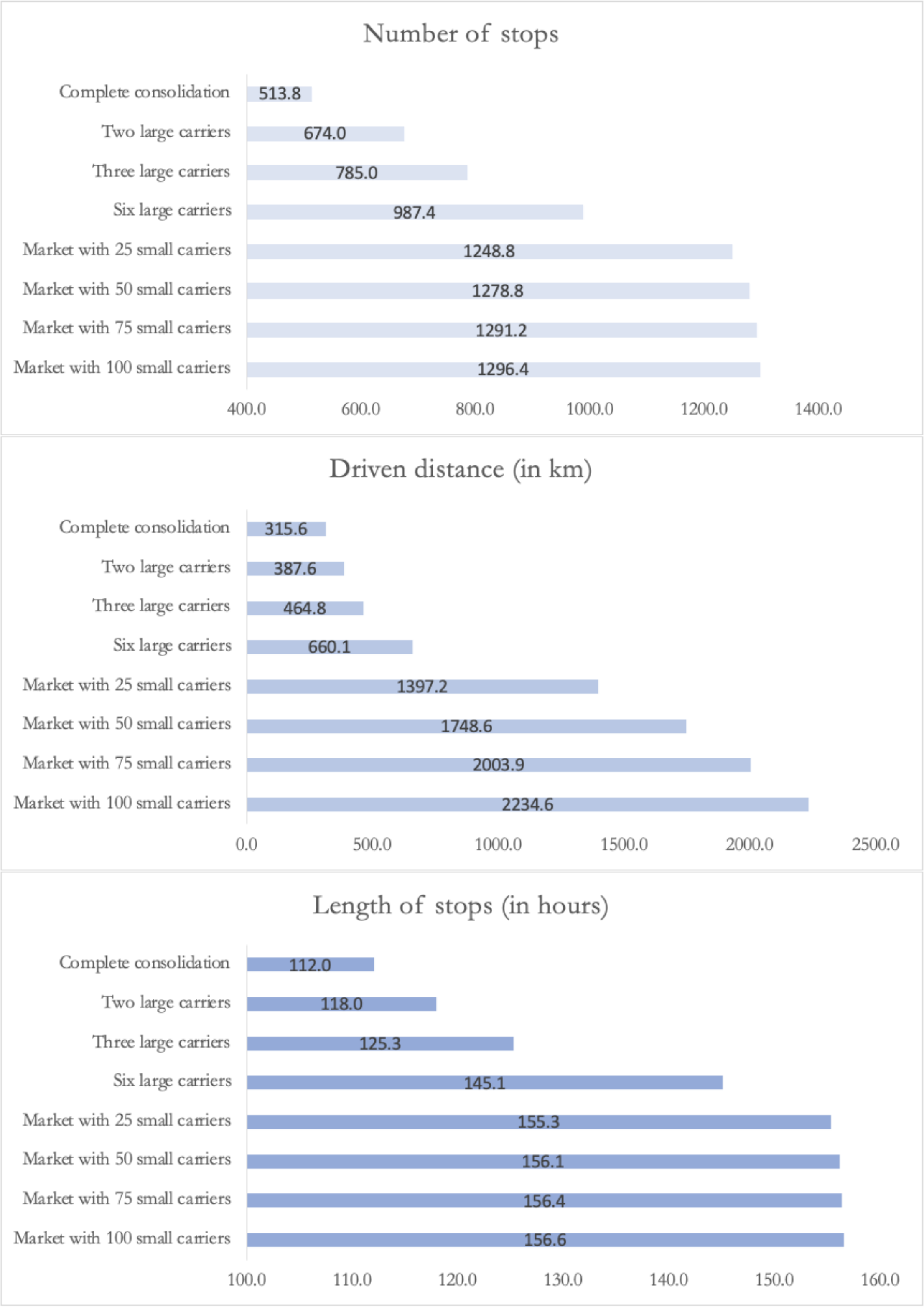

Figure 14: Operational results of the market structures

of these three settings are presented in Appendix B.

Furthermore, in our analysis, we assumed a higher proportion of deliveries through collection points compared to direct deliveries to represent the parcel distribution in Bergen. We, therefore, also analyze a day when the market is divided equally between the modes of direct delivery and delivery through collection points. We assume that carriers have the same market shares as in Table 1. The large carriers, naturally, drive more distance and stop more often as they perform more direct deliveries in this setting. Even in this case, however, the impact of small carriers on the city is significantly higher than the large carriers and our insights into the parcel market remain valid. The serious consequences of small carriers on city livability, therefore, should likely be on the radar of authorities in numerous other small cities. The corresponding results are provided in Appendix C.

Last, we analyzed a setting where carriers operate in two distinct time periods per day to provide a rough insight on the adoption of time windows. Each demand is fulfilled in one of these time periods and the customers decide in which time period the demand is met, unless they require their shipments to be delivered through a collection point. Therefore, the carrier might serve the same building twice per day. We assumed that direct shipments to customers are evenly distributed between the two time periods. The results highlight that the percentage gap in driven distance per package between the complete consolidation and the market with two carriers has increased substantially. The underlying reason is that although the two carriers have a large number of packages to deliver, the consolidation effect is weakened as carriers have to comply with the time periods at which their customers request their packages. We present the results in Appendix D.

6.3 Managerial insights

In this section, we summarize the managerial insights obtained from our study and computational experiments. We will begin by outlining insights that have broader applicability beyond our case study.

- Vehicle routing models can offer capabilities beyond merely capturing operational details; they can also be leveraged to provide strategic insights. In our collaboration with the authorities, we utilized these models strategically to discuss the impact of freight consolidation on city livability.

- We have observed that supporting authorities' decision-making processes, rather than interfering with them, leads to tangible benefits in gaining their cooperation. Given the complex nature of political factors involved, focusing on what needs to be achieved instead of recommending specific actions facilitates a smoother exchange of information.

The insights gathered from our case study are summarized as follows.

- Small carriers drastically increase the driven distance as well as the number and duration of stops. In particular, prohibiting them to deliver to end-customers reduces the driven distance by 52.8%. The ongoing uberification is fueling these effects even further. While increasing the number of small carriers from 25 to 50 results in an additional distance increase by 42.5%, increasing it to 100 small carriers leads to a distance increase by

101.3%. As revealed through the sensitivity analysis, the impacts of these carriers should also be taken into consideration by other small city authorities.

- While local authorities may intentionally choose to implement measures to deter driving in specific areas, they should recognize that this could result in delivery vehicles taking unconventional routes, extending their driven distances beyond what would occur in the absence of such strategies. Therefore, in conjunction with such policies, the consolidation aspect of deliveries should be considered within these areas to enhance city livability.
- Although the complete consolidation scheme provides the best alternative for parcel delivery, a market scheme where small carriers cannot deliver to end-customers yields a much greater gain than moving between complete consolidation and reasonably large two to three carriers. Small carriers are subject to inefficient routes and underutilized vehicles. Consolidating their deliveries brings greater benefits compared to consolidating a few large carriers into one, since the latter typically operate with already efficient structures.
- As the number of packages increases, the operational gap between the complete consolidation scheme and the market operated by a reasonably few large carriers slightly reduces. This arises because as consolidation intensifies, the advantages it offers diminish in significance, leading to a case where a market run by two or three carriers experiencing growing parcel volumes gradually tends towards the operations of a market with a single carrier. Additionally, the driven distance as well as the number and duration of stops reduce per package when the parcel volume grows.
- As a result of increased internet trade and a more demanding customer base that expects and is willing to pay for faster deliveries, carriers offer different time intervals to serve their customers. This, however, comes at the expense of reducing the livability in cities by weakening the consolidation effect. In this regard, time windows are expensive for city livability and the necessity of accommodating such customer requests has to be discussed in small cities with challenging networks.

7 Concluding remarks

In this paper, we proposed a routing-based policy guidance framework to assess the market structure of freight transport in small cities and understand the value of consolidation from the perspective of authorities. To this end, we analyzed several market structures for improving city livability in terms of driven distance as well as the number and duration of stops based on real maps and real demand patterns from Bergen, Norway. The results show that small carriers take up a lot of space in the city, while also stopping at various locations and increasing the duration of stops. In this context, we observe that the gain of setting up a market structure where these small companies cannot deliver to the end-customers is greater than moving between complete consolidation and a few reasonably large carriers.

Before concluding, we provide directions for further research and reflect on limitations of our study. The duration of stops is an important measure for these cities as a result of narrow one-way streets. Although consolidation would reduce the duration of stops to a certain level, a substantial time would still be spent at the curb. Devising strategies to reduce this time in small cities could be a direction of research. For instance, instead of a driver, another delivery personnel may distribute the packages to customers once a driver arrives in an area and hands over the packages to the personnel. In this setting, the delivery personnel would be able to cover longer distances compared to what the driver can cover on foot. This would not only result in shorter stopping times but would also result in fewer stops of vehicles. Authorities in Bergen, for instance, are currently considering a policy to use bicycles for last-mile delivery. The feasibility, the required business model, and the impact of such a setting could be the subject of research for such cities. Another line of research could explore the city livability in the context of different product categories. Our study delved into the parcel market, but further research could offer strategic insights to authorities by examining other market segments through the lens of consolidation. In addressing the limitations of our study, we acknowledge the use of PostNord's distribution pattern as a proxy for other carriers. While gathering data from additional parcel carriers presents practical challenges, incorporating such data into our study has the potential to enhance the robustness of our experimental outcomes.

Acknowledgments

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Appendices

Appendix A

Table A1: Operational results of the current market with small and large carriers (including the parcel volume growth by 25% and 50%)

with number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	6000.0	1248.8	1397.2	155.3	56.0
	7500.0	1499.0	1544.3	192.6	63.0
	9000.0	1755.0	1707.9	236.6	71.0
50	6000.0	1278.8	1748.6	156.1	81.0
	7500.0	1545.0	1931.6	194.1	88.0
	9000.0	1817.0	2128.2	238.7	96.0
75	6000.0	1291.2	2003.9	156.4	106.0
	7500.0	1410.0	2243.4	194.3	113.0
	9000.0	1846.0	2467.1	239.3	121.0
100	6000.0	1296.4	2234.6	156.6	131.0
	7500.0	1585.0	2486.0	194.3	138.0
	9000.0	1553.0	2720.1	239.0	146.0

Table A2: Operational results of the competitive market led by six large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2171.8	216.4	150.5	43.7	11.4
B	1597.2	162.4	122.7	32.0	8.6
C	715.4	219.8	115.7	24.6	4.0
D	589.0	171.4	104.0	19.1	3.0
E	461.6	108.6	83.4	12.8	3.0
F	465.0	108.8	83.8	12.8	3.0
Total	6000.0	987.4	660.1	145.1	33.0

Table A3: Operational results of the competitive market led by six large carriers, where parcel volume grows by 25% and 50%

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2710.0	258.0	176.5	54.1	15.0
	3251.0	296.0	200.8	64.5	17.0
B	1993.0	186.0	139.4	39.7	10.0
	2389.0	226.0	155.2	47.1	13.0
C	900.0	266.0	135.3	30.7	5.0
	1082.0	294.0	141.4	35.4	6.0
D	740.0	195.0	110.4	22.8	4.0
	889.0	230.0	124.1	27.7	5.0
E	578.0	119.0	82.8	15.4	3.0
	693.0	136.0	98.9	18.4	4.0
F	579.0	136.0	96.2	16.2	3.0
	696.0	144.0	98.9	18.5	4.0
Total	7500.0	1160.0	740.6	178.8	40.0
	9000.0	1326.0	819.2	211.6	49.0

Table A4: Operational results of the competitive market led by two to three large carriers

Number of large carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
2	6000.0	674.0	387.6	118.0	32.0
3	6000.0	785.0	464.8	125.3	32.2

Table A5: Operational results of the completely consolidated market led by a single carrier

Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
6000.0	513.8	315.6	112.0	31.0

Table A6: Operational results of the single and a reasonably few large carriers, where parcel volume grows by 25% and 50%

Number of large carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
1	7500.0	625.0	377.4	142.5	38.0
	9000.0	680.0	434.3	166.7	46.0
2	7500.0	816.0	463.0	153.9	40.0
	9000.0	914.0	532.5	186.2	46.0
3	7500.0	1385.0	534.1	150.5	39.0
	9000.0	1599.0	593.4	180.2	48.0

Appendix B1: Increasing the walking threshold to 150 meters

Table B1.1: Operational results of the small carriers in the current market with small and large carriers

Number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	607.8	516.3	822.7	39.3	25.0
50	607.8	548.7	1176.4	39.8	50.0
75	607.8	568.0	1412.2	40.2	75.0
100	607.8	576.7	1637.5	40.1	100.0

Table B1.2: Operational results of the large carriers in the current market with small and large carriers

Carrier	Number of packages	Driven distance stops	Duration of stops (km)	Number of (h)	Number of trips
A	2020.3	134.0	129.6	37.4	11.0
B	1496.3	105.7	107.5	27.6	8.0
C	563.8	134.3	93.9	17.9	3.0
D	488.0	110.0	86.5	14.5	3.0
E	411.6	70.7	68.1	10.1	3.0
F	412.4	72.3	70.4	10.1	3.0

Table B1.3: Operational results of the current market with small and large carriers

with number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	6000.0	1143.3	1378.7	156.9	56.0
50	6000.0	1175.7	1732.4	157.4	81.0
75	6000.0	1195.0	1968.2	157.8	106.0
100	6000.0	1203.7	2193.5	157.7	131.0

Table B1.4: Operational results of the competitive market led by six large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2171.8	184.7	147.0	44.1	11.4
B	1597.2	138.3	120.9	32.2	8.6
C	715.4	187.0	110.6	23.2	4.0
D	589.0	146.3	99.2	19.4	3.0
E	461.6	98.3	82.4	13.0	3.0
F	465.0	100.3	82.7	13.0	3.0
Total	6000.0	855.0	642.7	146.8	33.0

Table B1.5: Operational results of the competitive market led by two to three large carriers

Number of large carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
2	6000.0	569.7	380.5	112.8	32.0
3	6000.0	661.3	457.7	119.1	32.2

Table B1.6: Operational results of the completely consolidated market led by a single carrier

Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
423.7	309.8	111.9	31.0	6000.0

Appendix B2: Increasing the vehicle capacity to 300 packages

Table B2.1: Operational results of the small carriers in the current market with small and large carriers

Number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	607.8	539.6	805.9	38.9	25.0
50	607.8	569.6	1143.8	39.8	50.0
75	607.8	582.0	1417.2	40.0	75.0
100	607.8	587.2	1629.8	40.2	100.0

Table B2.2: Operational results of the large carriers in the current market with small and large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2020.3	154.6	112.5	37.0	7.0
B	1496.3	120.2	97.6	27.3	5.0
C	563.8	155.8	93.0	17.7	2.0
D	488.0	123.8	86.7	14.3	2.0
E	411.6	77.2	66.7	10.0	2.0
F	412.4	77.6	68.7	10.0	2.0

Table B2.3: Operational results of the current market with small and large carriers

with number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	6000.0	1248.8	1331.2	155.3	45.0
50	6000.0	1278.8	1669.1	156.1	70.0
75	6000.0	1291.2	1942.4	156.4	105.0
100	6000.0	1296.4	2155.0	156.6	120.0

Table B2.4: Operational results of the competitive market led by six large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2171.8	216.4	131.1	43.7	8.0
B	1597.2	162.4	110.8	32.0	6.0
C	715.4	219.8	112.5	24.6	3.0
D	589.0	171.4	99.4	19.1	2.0
E	461.6	108.6	81.3	12.8	2.0
F	465.0	108.8	81.4	12.8	2.0
Total	6000.0	987.4	616.5	145.1	23.0

Table B2.5: Operational results of the competitive market led by two to three large carriers

Number of large carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
2	6000.0	674.0	339.1	118.0	20.7
3	6000.0	785.0	417.1	125.3	21.0

Table B2.6: Operational results of the completely consolidated market led by a single carrier

Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
6000.0	513.8	255.1	112.0	21.0

Appendix B3: Increasing the courier capacity to 10 packages

Table B3.1: Operational results of the small carriers in the current market with small and large carriers

Number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	607.8	539.6	826.8	38.9	25.0
50	607.8	569.6	1178.3	39.8	50.0
75	607.8	582.0	1433.5	40.0	75.0
100	607.8	587.2	1664.3	40.2	100.0

Table B3.2: Operational results of the large carriers in the current market with small and large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2020.3	154.6	131.8	37.0	11.0
B	1496.3	120.2	109.4	27.3	8.0
C	563.8	155.8	98.7	17.6	3.0
D	488.0	123.8	88.7	14.2	3.0
E	411.6	77.2	70.4	10.0	3.0
F	412.4	77.6	71.4	10.0	3.0

Table B3.3: Operational results of the current market with small and large carriers

with number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	6000.0	1248.8	1397.2	155.1	56.0
50	6000.0	1278.8	1748.6	155.9	81.0
75	6000.0	1291.2	2003.9	156.2	106.0
100	6000.0	1296.4	2234.6	156.4	131.0

Table B3.4: Operational results of the competitive market led by six large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2171.8	216.4	150.5	43.6	11.4
B	1597.2	162.4	122.7	31.8	8.6
C	715.4	219.8	115.7	24.5	4.0
D	589.0	171.4	104.0	19.0	3.0
E	461.6	108.6	83.4	12.8	3.0
F	465.0	108.8	83.8	12.8	3.0
Total	6000.0	987.4	660.1	144.4	33.0

Table B3.5: Operational results of the competitive market led by two to three large carriers

Number of large carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
2	6000.0	674.0	387.6	116.6	32.0
3	6000.0	785.0	464.8	124.3	32.2

Table B3.6: Operational results of the completely consolidated market led by a single carrier

Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
6000.0	513.8	315.6	110.4	31.0

Appendix C: Operating under the equal market shares of direct delivery and delivery through collection points

Table C1: Operational results of the small carriers in the current market with small and large carriers

Number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	598.0	537.0	819.2	38.5	25.0
50	598.0	572.0	1220.2	39.8	50.0
75	598.0	571.0	1449.3	40.0	75.0
100	589.0	589.0	1693.6	39.9	100.0

Table C2: Operational results of the large carriers in the current market with small and large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2041.0	384.0	185.2	54.4	11.0
B	1501.0	290.0	148.6	41.4	8.0
C	569.0	209.0	111.5	21.2	3.0
D	480.0	176.0	102.0	17.8	3.0
E	405.0	137.0	96.5	13.8	3.0
F	406.0	128.0	83.9	13.6	3.0

Table C3: Operational results of the current market with small and large carriers

with number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	6000.0	1861.0	1546.9	200.5	56.0
50	6000.0	1896.0	1947.9	201.8	81.0
75	6000.0	1895.0	2177.0	201.9	106.0
100	6000.0	1913.0	2421.3	201.9	131.0

Table C4: Operational results of the competitive market led by six large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2190.0	417.0	192.6	59.7	11.0
B	1600.0	314.0	155.8	44.2	9.0
C	718.0	259.0	124.2	27.8	4.0
D	579.0	213.0	110.8	22.3	3.0
E	454.0	161.0	104.2	16.3	3.0
F	459.0	147.0	95.3	15.8	3.0
Total	6000.0	1511.0	782.8	186.1	33.0

Table C5: Operational results of the competitive market led by two to three large carriers

Number of large carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
2	6000.0	1020.0	448.9	149.7	30.0
3	6000.0	1192.0	539.6	160.7	32.0

Table C6: Operational results of the completely consolidated market led by a single carrier

Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
6000.0	739.0	337.2	134.6	31.0

Appendix D: Operating under two distinct time periods

Table D1: Operational results of the small carriers in the current market with small and large carriers

Number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	607.8	570.7	1156.9	39.5	50.0
50	607.8	583.0	1648.3	39.8	100.0
75	607.8	592.3	1962.3	40.0	150.0
100	607.8	596.7	2177.2	40.2	200.0

Table D2: Operational results of the large carriers in the current market with small and large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2020.3	201.0	178.9	39.1	12.0
B	1496.3	156.0	154.8	28.9	8.0
C	563.8	199.3	152.2	19.5	4.0
D	488.0	160.0	140.6	15.8	4.0
E	411.6	103.7	115.8	11.1	4.0
F	412.4	105.3	117.1	11.2	4.0

Table D3: Operational results of the current market with small and large carriers

with number of small carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
25	6000.0	1496.0	2016.4	165.3	86.0
50	6000.0	1508.3	2507.7	165.5	136.0
75	6000.0	1517.7	2821.7	165.7	186.0
100	6000.0	1522.0	3036.6	165.9	236.0

Table D4: Operational results of the competitive market led by six large carriers

Carrier	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
A	2171.8	280.7	207.1	46.8	12.0
B	1597.2	210.3	173.9	34.1	9
C	715.4	275.0	177.4	27.0	4.0
D	589.0	218.0	157.9	21.3	4.0
E	461.6	134.7	128.8	13.8	4.0
F	465.0	141.0	134.2	14.3	4.0
Total	6000.0	1456.4	1003.7	161.8	36.8

Table D5: Operational results of the competitive market led by two to three large carriers

Number of large carriers	Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
2	6000.0	865.0	526.3	130.4	32.0
3	6000.0	1003.7	647.4	139.2	31.6

Table D6: Operational results of the completely consolidated market led by a single carrier

Number of packages	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips
6000.0	677.7	390.1	117.1	32.0

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Paper II

Disconnecting a city centre to prevent through traffic: An a priori evaluation with a focus on freight transport*

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Abstract

There has been a growing interest from public authorities around the world in implementing measures aimed at preventing through traffic in city centres and establishing car-free zones. One of these initiatives has recently been proposed by the City of Bergen, aiming to zone the city centre in such a way that, in the long run, only public transport and emergency vehicles can pass through. While the zoning is primarily focused on mobility to make the city centre more attractive to residents by reducing traffic and parking, its effects on freight delivery in relation to city livability is not thoroughly discussed. This paper investigates the implications of this zoning decision on freight transport, offering authorities a broader understanding of its impact through the utilization of clustering and routing models of freight carriers at a holistic level. Our analysis reveals that alongside the anticipated increase in total driving for freight deliveries throughout the city, there would also be a rise in traffic within the city centre itself, which may not have been intended or expected. As a remedy, we analyse the effect of introducing a micro-hub for consolidation, and bicycles for the last mile delivery, another policy that is presently being considered by the city. Our study highlights the importance of integrating freight transport into decision-making processes from the initial stages, rather than treating it as a secondary concern relative to mobility.

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1 Introduction

Public authorities utilize regulatory measures to enhance the quality of life for their residents. These measures primarily focus on addressing key societal facets, including public safety, environmental protection, and the development of infrastructure and transport. One of these regulations advocates the establishment of car-free zones and prevention of through traffic in the city centre, enabling the promotion of public transport and the development of pedestrian-friendly areas. While these measures trace their origins back to the 1960s and 1970s (Nieuwenhuijsen et al. 2019), they have recently attracted renewed interest from city planners (Aumann et al. 2023). For instance, authorities in Lisbon proposed a three-months trial period during the summer of 2023 to ban cars from driving through the city centre (Municipality of Lisbon 2023). Another example lies in Barcelona, where policymakers established the concept of super blocks in 2016 in order to preserve the interior areas of the streets for pedestrians and cyclists (Nieuwenhuijsen & Khreis 2016). Although these initiatives are geared towards providing more space to pedestrians and improving city livability, measuring their overall impact remains a challenging endeavour for authorities. Several businesses in Paris, for instance, raised their concerns on banning non-essential traffic passing through central districts from 2024, stressing that this would reduce their commercial activities (O'Sullivan 2022). The same has been reported in Madrid, where multiple retail associations claimed that their businesses are affected by the car ban policy (O'Sullivan 2019). Although the newly elected policymakers at that time, who had a different political agenda than the previous ones, planned to rescind the ban, the residents of Madrid backlashed the decision, ultimately leading the authorities to re-evaluate their call (O'Sullivan 2019). These dilemmas, as a result, suggest that the controversial nature of such vehicle restriction policies necessitates the need for conducting thorough ex-ante evaluations in order to gain a deeper insight into their overall impact. Moreover, such evaluations would enable authorities to not only identify and communicate the potential impacts of their proposed regulations, but also to proactively address any concerns that may arise well in advance of their implementation.

In this study, we look into a regulatory measure designed by the authorities in Bergen, a small medieval city in Norway, to disconnect the city centre in order to prevent through traffic. The authorities have decided to divide the city centre into three distinct traffic zones and redirect the traffic from one zone to another towards the major roads outside the boundaries of the city centre. One of the reasons for the decision lies in Bergen's challenging network in the downtown area, where the present-day transport infrastructure is built around the traditional narrow alleyways connecting streets and stone pavement. The medieval structure and layout of the city present obstacles to expand the road infrastructure within the centre. The authorities, consequently, aim to redirect inner-city traffic to the well-developed major roads located outside the downtown area. In this regard, the overall goal is to reduce city centre traffic, by forbidding through traffic, except for public transport and emergency vehicles. The disconnection, coupled with the topography of Bergen, also leads to the emergence of a car-free zone in the downtown core.

Although the disconnection decision is primarily focused on mobility, one of its noteworthy consequences is its impact on urban freight transport, which becomes more and more challenging to manage as a result of growing population and internet trade. The need for faster deliveries, fewer items per delivery, and higher delivery failures increase the number of required trips. Currently, delivering to various buildings requires delivery vans to pass through the city centre. Imposing traffic zones forces delivery vehicles to move around the downtown area every time they need to enter a new zone, increasing the overall distance driven, and thereby worsening their impacts on traffic and congestion. While it is foreseen that the overall distance covered for freight deliveries will increase as a result of the traffic zones, it may not be apparent that this will also lead to a rise in driven distance within the city centre. In this paper, therefore, we study the impact of the zoning decision on freight transport in Bergen and provide an a priori analysis to guide authorities in gaining a more comprehensive understanding of the overall impacts of their zoning. We, additionally, assess the potential impacts of implementing a micro-hub for consolidation and bicycles for the last mile delivery, which is another policy under consideration by local authorities. Introducing a micro-hub gains greater relevance in the lights of the city's traffic zoning policy, which can be considered as a means to mitigate the unintended effects of the planned regulation on freight transport.

The contribution of this paper is two-fold. First, we assess the zoning decision of authorities in Bergen to prevent through traffic in the city centre, noting that similar versions of this policy have recently gained significant attention from authorities worldwide, with a particular emphasis on the impact of freight transport on city livability, while quantifying both the intended and unintended effects on driven distance. Second, we evaluate the viability of the concept of bicycle delivery with micro-hub consolidation as a potential solution to address the challenges arising from traffic zones.

The paper is organized as follows. The literature review is presented in Section 2. The problem description is provided in Section 3. While Section 4 describes the methodology, related data is presented in Section 5. Section 6 presents the analysis and discusses policy implications on enhancing city livability. Section 7 concludes the paper.

2 Literature review

Policies aimed at promoting sustainable mobility practices have been introduced in numerous cities across the world (Gallo & Marinelli 2020). However, there is limited exploration of the broader effects of these policies on various aspects of urban life. Many of these policies aimed at improving urban traffic prioritize mobility but often overlook the implications for freight delivery. Certain parking regulations established within the city, for instance, often originate from passenger-centric models and can have unintended negative consequences on freight transport dynamics (Jaller et al. 2013). Furthermore, the introduction of congestion pricing policies coupled with designated time windows for deliveries serves to alleviate urban traffic congestion. While this approach can lead to reduced traffic within the city, it can concurrently escalate issues for freight carriers (Holguín-Veras et al. 2006).

The car-free zone policies possess similar effects. As noted by Agatz et al. (2020), although this type of initiatives improves the overall livability of cities, it can negatively impact the supply of goods. The measure would ultimately worsen the impact of freight transport on livability. Although the regulation may actually have an overall positive effect, it would possess negative outcomes from the freight transport side. Despite its potential negative consequences, however, the impacts of such policies on freight transport have received limited attention from the scientific community (Verlinde & Macharis 2016). Among the studies carried out, Muñuzuri et al. (2013) simulate the effects of pedestrianization on freight deliveries in Seville from the viewpoint of congestion, parking space occupation, and route duration. Although the study addresses the blocking of a specific street, rather than our focal interest in completely disconnecting the city centre, the authors show that the congestion levels are reduced in the area of concern. However, the through traffic was redirected to surrounding streets, resulting in a substantial increase in congestion within these areas. In another paper, the impacts of a car-free city centre on freight deliveries are examined by Hagen et al. (2020) through a qualitative study in Oslo. The authors conduct a comprehensive survey, in which freight drivers express the increased difficulty in delivering goods to the city centre as a result of the shift in driving patterns. Moreover, drivers highlight that this shift leads to longer delivery route durations and heightened parking difficulties, which, in turn, implies an increased burden of freight transport on urban areas.

Another impact of pedestrianization on freight transport lies in modal shift, where the utilization of small capacity vehicles together with an urban consolidation centre serves as one of the compelling examples for parcel delivery (Verlinde & Macharis 2016). Such large centres, however, are often unviable in small cities (Allen & Huschebeck 2006). This is primarily due to the city's sparse demand patterns and relatively low volumes of goods transport. Moreover, previous research indicates instances where these centres struggle due to limited profitability, reliance on public subsidies (Katsela et al. 2022), issues with delivery service levels (Lagorio et al. 2016), and suboptimal long-term operational models (Van Rooijen & Quak 2010). A micro-hub with cross-docking can be an alternative, which can handle consolidation with minimal inventory building. These are smaller warehouses established within the city limits where the goods are transhipped from heavy commercial vehicles to last-mile distribution vehicles (De Marco et al. 2018). While most studies discuss the validity of micro-hubs in delivery operations ((e.g., Hribernik et al. 2020, Katsela et al. 2022)), these facilities also reduce congestion and minimize emissions (Browne et al. 2005). Moreover, due to their size advantage, these can be placed close to the demand locations within the city. As a result, the consolidation of shipments from diverse private carriers and the streamlining of their last-mile deliveries hold the potential to reduce congestion and emissions within urban areas.Among small capacity vehicles to establish this modal shift, utilization of cargo bikes is a promising solution for the last mile delivery. Cargo bikes have been suggested as effective means of freight delivery in many cities like New York (Conway et al. 2012), Seoul (Lee et al. 2019), and São Paulo (Ormond et al. 2019). They are also widely adopted across numerous European cities (Elbert & Friedrich 2020, Seidlová & Ledvinová 2020) as an ecologically sound logistics solution. A multitude of case studies conducted in various urban centres have explored the integration of cargo bikes for improved last-mile delivery through micro-hubs, as exemplified in both large cities, like Paris (Robichet et al. 2022), and small cities like Padova (Ceccato et al. 2023). In contrast to conventional delivery vans, cargo bikes offer a range of advantages. For instance, Hagen et al. (2013) highlight several benefits of cargo bikes based on an exploratory case study conducted in Rio de Janeiro. These benefits include reduced operational costs, positive environmental impacts, decreased infrastructure expenditures, and heightened safety levels. Moreover, a case study conducted in Berlin illustrates that cargo bikes can reduce the overall delivery distance by up to 48% (Gruber et al. 2013,0).

3 Problem description

Bergen City Council decided to implement a traffic plan (Matre 2023) for the central area of the city. The primary objective of this plan is to offer traffic solutions that reduce car congestion within the city centre, subsequently prioritizing pedestrian activity, cycling, and public transport. The city's goal is to redirect a significant portion of its downtown traffic away from the city centre, primarily utilizing tunnels and the surrounding roads. The traffic plan puts forth a long-term solution centred around segmenting the city centre into various traffic zones. In this strategy, the central city ring, as highlighted in orange in Figure 1, would be entirely closed to through traffic in the long run, requiring vehicles to use the designated entry and exit roads indicated as the purple roads in Figure 1.

Due to the topography of the city, the city centre is divided into three distinct zones: Sentrum Nord, Sandviken, and Sentrum Sør, as illustrated in Figure 1. Delivery vehicles should enter the inner ring through the nearest zone. Therefore, in our analysis, the delivery locations in the inner ring are assigned to the closest zone. The division of the city into zones will increase the overall delivery distance as the vehicles will need to travel around the city centre in order to enter each zone and perform the delivery. As the aim of the traffic plan is to make the city centre less crowded with vehicles and more pedestrian friendly, increased traffic outside the city centre is an expected outcome. Our goal is to estimate the distance travelled by the delivery vans within city zones, as the regulatory bodies are mainly concerned about the traffic within the city centre.

Accordingly, based on this traffic zone policy, we evaluate two distinct cases, one referring to the current state of the city without the presence of the traffic zones, which we describe as the without zone case, and another referring to the city with the designated traffic zones, which we define as the with zone case. For each case, we examine parcel deliveries carried out by freight carriers with differing market shares. In this regard, we mimic the actions of parcel carriers and evaluate their operations in order to estimate their impact on city livability. Driven distance, in this context, is the key metric in assessing the impact of the traffic zones on freight transport.

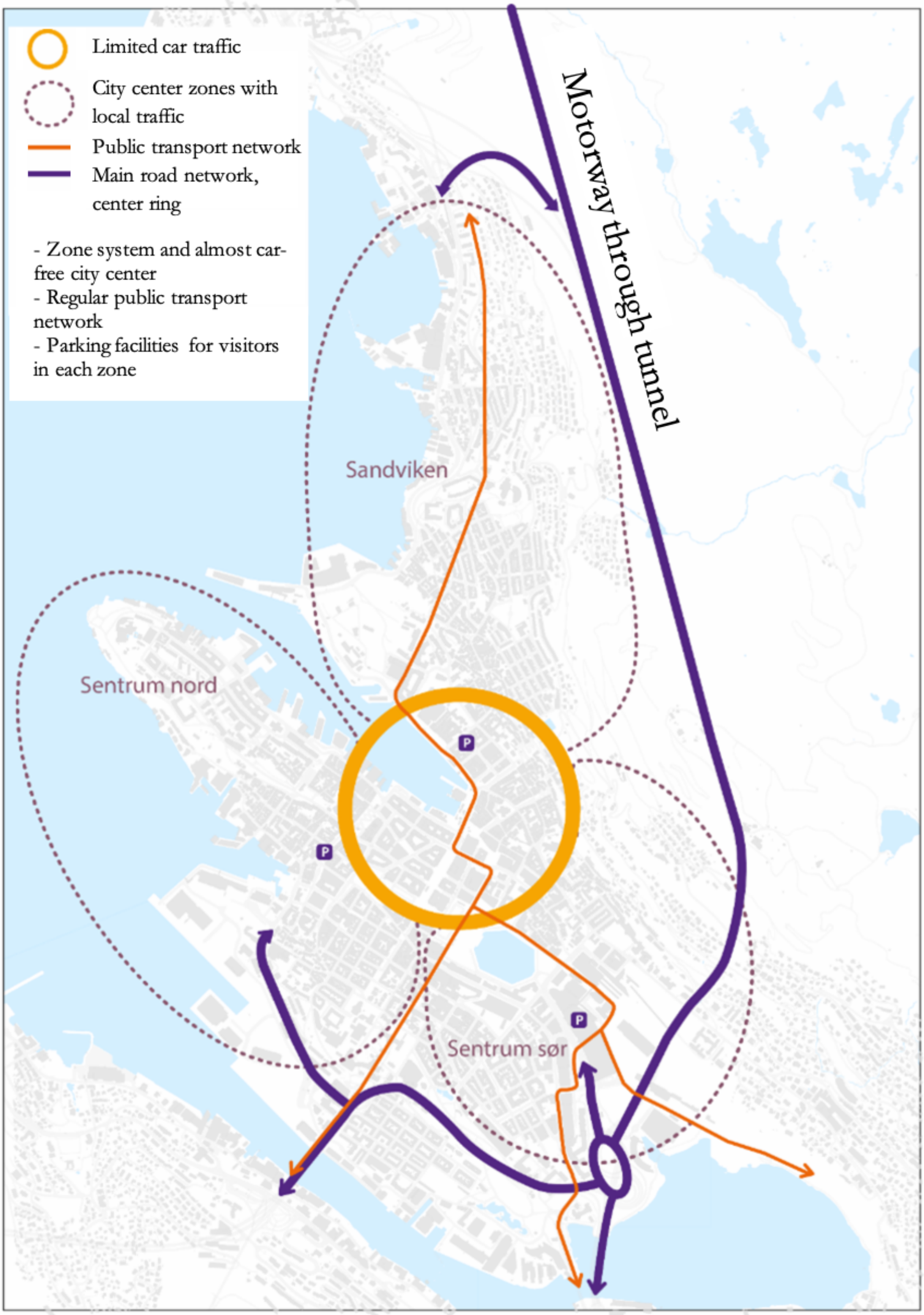

Figure 1: Traffic zones

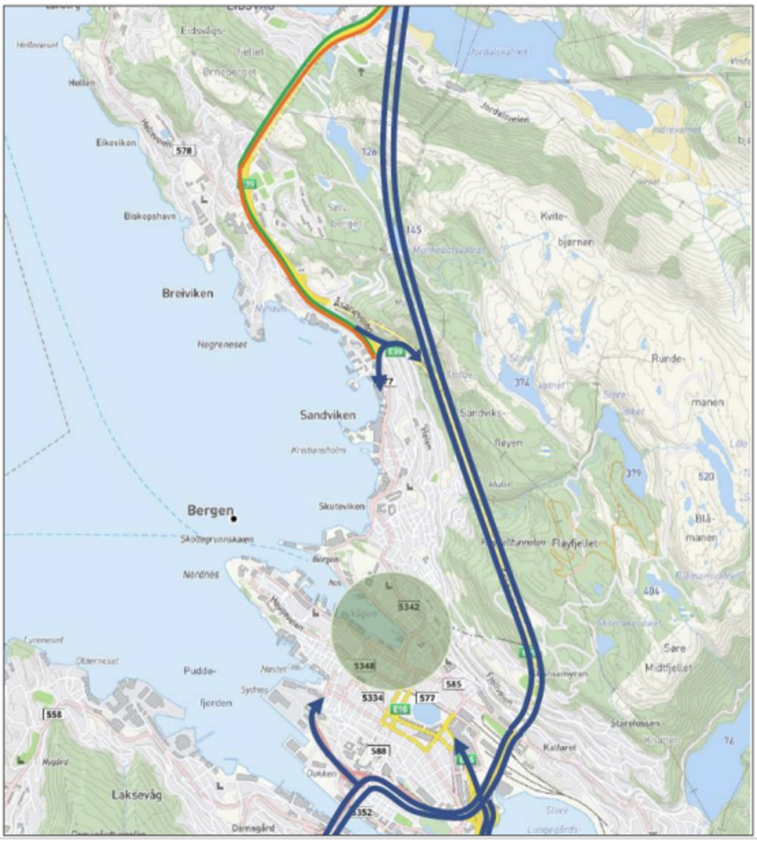

Figure 2: Entrances to the city centre

Carriers begin their routes from depots and enter the city centre via one of the three possible roads. As depicted in Figure 2, the unique geography of Bergen's city centre features three primary entrance points: two major bridges located to the south and a road originating from the north. Carriers choose an entrance/exit point corresponding to their depot location outside the centre. These points mark the starting and ending point for tracking the distance travelled.

Demands of each carrier are distributed among buildings within the city. These collection points are locations like grocery stores or supermarkets, where the final receivers for the parcels can collect their consignments. Given the higher concentration of parcel orders directed to collection points, their demand outweighs that of individual buildings. Building locations, on the other hand, are often closely clustered in the city centre, enabling delivery vans to park near a building and complete deliveries to nearby buildings on foot. While observing the operations of the carriers during a field trip, we observed that the couriers tend to stop near the building with the greatest number of parcel deliveries compared to neighbouring buildings. In our experiments, we assume that a courier can carry a certain number of package deliveries on foot. However, if a building exhibits a demand exceeding this threshold, the courier typically opts to drive directly to that location for delivery, recognizing the efficiency gains in doing so. In this regard, each carrier forms distinct clusters driven by their demand distribution and geographical proximity of the buildings. Once these clusters are formed, carriers generate their driving routes to perform deliveries while visiting each of these clusters once and respecting vehicle capacity. Additionally, walking routes are established within each cluster for the courier in order to deliver the packages on-foot.

4 Methodology

The problem described in the preceding section requires the employment of clustering and vehicle routing models of carriers. We, however, do not utilise these models as a way to plan delivery processes for carriers but instead as a tool to generate strategic insights for authorities.

As an example, carriers employ these models to determine the optimal walking and driving routes for their delivery services. However, our emphasis does not lie in pinpointing the operationally optimal solutions, but in extracting strategic insights for authorities by imitating the carriers' operations. In this regard, we mimic the actions of carriers on a holistic level through these models, while gaining sufficient operational details for authorities to estimate the impact of traffic zoning on city livability in relation to freight transport. While we anticipate that the actual and optimised routes would not coincide precisely, as our procedure focuses on gaining strategic insights through sufficient operational details, we have observed that the routes generated through this approach aligns with the delivery plan of a major carrier in Norway, presented as routing sequences of postal codes.

We initially utilise clustering to identify groups of buildings that can be served by couriers on foot. Along with centroid distance, our clustering methodology integrates inter-building walking distances, package demands per building, the courier's capacity, and the selection of the centroid building based on demand considerations. We use a modified hub location problem to identify the clusters. The selection of clusters adheres to specific conditions aimed at optimising the delivery operations:

- Proximity constraint: All buildings within a cluster must be situated within a close proximity of each other, aligning with a reasonable walking range for the courier.
- High demand building: Each cluster can accommodate at most one building with a demand exceeding the courier's carrying capacity. Given the courier's capacity to manage packages per walking trip, the buildings with higher demand are strategically chosen as the building which the courier parks the vehicle near to. This approach minimizes the need for multiple trips to the same building.
- Capacity limit: The cumulative demand of buildings within a cluster should not surpass the capacity of the assigned delivery van. Each cluster is exclusively served by a single delivery vehicle, necessitating that the combined demand of buildings remains within the vehicle's capacity.
- Exclusive assignment: Each building can only be assigned once within a given cluster for a particular carrier. This ensures that buildings are not redundantly included in multiple clusters.

Clustering Model (Z1)

Sets

N: set of buildings

Parameters

q_i: number of packages to be delivered to building $i \in N$ (demand of the building)
Q_v: capacity of the vehicle

Q_C: maximum number of packages a courier can handle while walking
$d^w_{i,j}$: walking distance between buildings i and j
M: a large number equal to the maximum distance $(\max[d^w_{i,j}],\ i, j \in A]$
D: the walking distance limit between any two buildings

Variables

$x_{i,j} \in \{0, 1\}$: 1 if building j is connected to building i, 0 otherwise
$y_i \in \{0, 1\}$: 1 if courier parks near to building i, 0 otherwise

Objective function

$$\min \sum_{i \in N} y_i \tag{1}$$

Constraints

$$\sum_{i \in N} x_{i,j} = 1 \qquad \forall j \in N \tag{2}$$

$$\sum_{j \in N} x_{i,j} \leq |N| \cdot y_i \qquad \forall i \in N \tag{3}$$

$$\sum_{j \in N} x_{i,j} \cdot q_j \leq Q_v \qquad \forall i \in N \tag{4}$$

$$x_{i,j} \cdot q_j \leq y_i \cdot q_i \qquad \forall i, j \in N \tag{5}$$

$$x_{i,j} \cdot q_j \leq Q_c \qquad \forall i, j \in N : i \neq j \tag{6}$$

$$d^w_{i,j} - M \cdot (2 - x_{k,i} - x_{k,j}) \leq D \qquad \forall i, j, k \in N \tag{7}$$

$$x_{i,j} \in \{0, 1\}, y_i \in \{0, 1\} \tag{8}$$

Model Z1 describes our clustering approach. Consider a graph $G = (N, A)$, where N represents the set of buildings, including the collection points, within the city centre and the set A represents the arc connections between them. The buildings in each cluster are connected to a single building, near which the delivery van will be parked. This building, which we denote as the visited building, has more package deliveries than other buildings in the cluster. The objective function (1) minimizes the number of visited buildings, thereby minimizing the total number of clusters. The visited building along with the connected buildings forms a cluster. Constraints (2) ensure that every building is connected to at most one building. Constraints (3) determine whether a building is a visited building or not. Constraints (4) ensure the total demand of the buildings within a cluster is lower than the capacity of the van. Constraints (5) ensure that the building selected as the visited building has the highest number of deliveries compared to the rest in the cluster. Constraints (6) enforce each cluster to accommodate at most one building with a demand exceeding the courier's carrying capacity. This building can only be the one designated as the visited building. Constraints (7) limit the distance between any two buildings within the cluster.

The number of variables in model Z1 can explode if we consider all building combinations in set N. We generate variable $x_{i,j}$ only for those building pairs, whose inter building distance is less than the distance limit ($d^{w}_{i,j} \leq D$) and the demand of building j is less than or equal to courier's carrying capacity. This approach satisfies Constraints (6) and Constraints (7), enabling us to omit them from our model formulation.

Subsequently, we utilize capacitated vehicle routing problem (CVRP) to mimic the operations of carriers. Our approach adopts two distinct CVRP models, one to identify delivery van routes and another to determine courier walking routes within clusters. These are used to generate both driving and walking routes for the with and without zone cases. Model Z2 describes the CVRP formulation we employed from Toth & Vigo (2014) to identify the routes of the delivery vans. The set and parameters of the model differ when determining the walking routes of the couriers, and these will be explained after describing the CVRP formulation below.

CVRP Model (Z2)

Sets

V: set of locations of visited buildings and entrance/exit to the city centre

Parameters

$d^{d}_{i,j}$: driving distance between nodes i and j in V
K: maximum number of vehicles

Variables

$x_{i,j} \in \{0,1\}$: 1 if location i is visited immediately after j, 0 otherwise

Objective function

$$\min \sum_{i \in V} \sum_{j \in V} d^{d}_{i,j} \cdot x_{i,j} \tag{9}$$

Constraints

$$\sum_{i \in V} x_{i,j} = 1 \qquad \forall j \in V \setminus \{0\} \tag{10}$$

$$\sum_{j \in V} x_{i,j} = 1 \qquad \forall i \in V \setminus \{0\} \tag{11}$$

$$\sum_{i \in V} x_{i,0} \leq K \tag{12}$$

$$\sum_{j \in V} x_{0,j} \leq K \tag{13}$$

$$\sum_{i \notin S} \sum_{j \in S} x_{i,j} \geq r(S) \qquad \forall S \subset V \setminus \{0\}, S \neq \phi \tag{14}$$

$$x_{i,j} \in \{0,1\} \tag{15}$$

The objective of the model is to minimize the total distance travelled. We define a set V to include the entrances to the city centre utilized by a given carrier as well as the visited buildings within each cluster. Location $0 \in V$ represents the starting and ending location for the vehicles. The parameter $d^d_{i,j}$ represents the driving distance between locations in set V. Distance $d^d_{i,j}$ is different between the with and without zone cases, as the former considers additional inter zone distances.

Constraints (10) and (11) ensure that every building in the set V is served once. Constraints (12) and (13) ensure that at most K vehicles are used. The constraints also confirm that the vehicles start from the location of the city entrance used by the carrier and return back to the same by the end of the trip. Constraints (14) fulfil both subtour elimination and capacity constraints. In this regard, given a subset of $S \subset V$, the function $r(S)$ provides the minimum number of vehicle routes required to serve buildings in S. This ensures that no subtour exits and routes start and end at the chosen entry point.

The model remains the same while identifying the walking routes and is employed for each cluster separately. The set V, in this case, represents the buildings within a cluster. The visited building in that cluster becomes the starting and ending location represented by $0 \in V$. Additionally, walking distance $d^w_{i,j}$ is considered in the model in the place of driving distance $d^d_{i,j}$. K is set to the number of buildings in the visited cluster, providing the upper limit on the number of walking routes possible. Furthermore, in this setting, $r(S)$ represents the minimum number of trips needed to serve buildings within a cluster.

5 Data

We gathered parcel demand data from one of the major package delivery firms in Bergen, namely PostNord[1]. The data provided contains the carrier's weekly parcel distribution volume in Bergen for each postal code throughout the year 2020. Almost all deliveries are business-to-customer shipments. The majority of these shipments are designated for collection points,

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[1] https://www.postnord.no/en

with a significant portion also being delivered directly. The former is the main distribution channel in Norway, composed of locations such as grocery stores and shopping malls as previously described. The carrier's primary operation is centred on the delivery of parcels for both individuals and businesses, representing the characteristics of a perfect consolidator. Therefore, we assume that the distribution patterns for both modes of delivery are representative for other carriers.

We implemented the following procedure to mimic the parcel delivery landscape in Bergen. Initially, we estimate the average daily distribution of the company from the weekly distribution data. Since the pattern is associated with individual postcodes, we analyse it at an address level, considering the locations of all buildings and their postcodes from the Norwegian Mapping and Cadastre Authority[2] and the estimated population of each building in Fang & Opedal (2020). We then calculate the proportion of each building receiving a package per day. Using these proportions and our assumed market share of PostNord, we define the daily parcel distribution in the city centre of Bergen, comprising approximately 2600 packages destined for delivery close to 500 buildings.

We gathered data from OpenStreetMaps[3], a widely utilized mapping reference, to obtain both driving and walking distances between buildings. Driving distances are used to determine the routes of the delivery vans, while walking distances are utilized to identify the courier's on-foot trips. The distances are computed as the shortest paths between buildings through the roads and the paths available in the road network. In the case of driving distance, road network with both one-way and two-way streets are considered. When computing walking distance, all pathways within the network are taken into account, including narrow paths, staircases, and roads. Directional restrictions are not considered in this case, as walking is not subject to directional limitations. Dijkstra's algorithm is used to find the shortest paths. The distances are computed between the buildings as well as with the entrances to the city centre.

The estimated distances vary between the cases we considered for our study. More specifically, the driving distances between the with and without zone cases differ due to the introduced zones. Distances between buildings and entrances are determined using the shortest paths in the without zone case, whereas additional distances related to moving between zones are accounted for in the with zone case. Moreover, in the with zone case, distinct road entrances are allocated for each zone, in which each of these have regulated entry and exit points, as provided in Figure 1.

Most of the delivery vehicles used by the carriers are of similar sizes and, therefore, we assume the same capacity for all the vehicles irrespective of the carriers, allowing up to 200 packages. We also assume that couriers can carry a maximum of 5 packages at a time. While carriers' operations are subject to varying conditions of packages such as different sizes and weights, we assume uniformity of packages as our focus relies on strategic insights and not granular operational details. In this regard, we assume average package size and weight, defined by the number of packages a vehicle and a courier can accommodate.

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[2] https://www.kartverket.nol/api-og-data/eiendomsdata

[3] https://www.openstreetmap.org

As previously described, walking distance is a criterion in clustering buildings. A courier, while making deliveries, might walk a considerable distance once parked in one area, but their coverage may be limited in another, resulting in shorter distances travelled. The courier's preferences may also play a role in this, as evidenced by observations in the field. However, as we are interested in capturing strategic insights, we assume a certain walking distance threshold between any two buildings, specifically 100 meters, in the clustering procedure to mimic carriers' operations.

We take six unique market scenarios into consideration in our study, comprising both small and large carriers. These carriers operate independently, possessing distinct demand distribution patterns and vehicle fleets tailored for deliveries. In the current market landscape, large carriers utilize both collection points and direct delivery, whereas small carriers perform direct delivery mode only. We assume that approximately 90% of parcel delivery demands in Bergen are met by major carriers, while the remaining 10% are served by numerous small-scale individual businesses. This is grounded in the current delivery market landscape in Bergen, where large carriers dominate the market, leaving only a minor share to small carriers. There are no concrete facts available on market shares. In examining the operations of large carriers, we analyse two market potentials: one that includes 90% of the demand spread across six carriers, and the other involving three carriers. The rationale behind this lies in understanding the market dynamics between varying numbers of large carriers, recognizing the impact of consolidation under traffic zones. In this regard, while the six large carrier scenario represents the current market landscape for parcel delivery, the three large carrier scenario defines the setting to realize the effect of consolidation under traffic zones. Regarding the operations of small carriers, their size remains unknown. Therefore, instead of making speculative guesses, we explore scenarios with varying numbers of carriers, specifically 25, 50, and 100.

Table 1: Analysed scenarios of the freight transport market

	Number of large carriers	Average demand of large carriers (number of packages)	Number of small carriers	Average demand of small carriers (number of packages)
Scenario 1	3	780	25	10
Scenario 2	3	780	50	5
Scenario 3	3	780	100	3
Scenario 4	6	390	25	10
Scenario 5	6	390	50	5
Scenario 6	6	390	100	3

Considering these, we examine the dynamics across scenarios involving three to six major carriers and between 25 and 100 small carriers. These market scenarios and the corresponding distribution of demands for both small and large carriers are detailed in Table 1. It is worth noting that, while the number of large and small carriers changes across market scenarios, their combined market share remains constant. Changes in market share between large and small carriers would alter the distribution between direct deliveries and deliveries through collection points, deviating from reflecting the current delivery market landscape in Bergen.

6 Results

Based on the clustering and routing models provided in Section 4, each market scenario specified in Table 1 is constructed as follows. Each carrier forms distinct clusters through model Z1, while the driving and walking routes are determined by using model Z2. We use only the visited buildings of each cluster while identifying the driving routes. Within each cluster, on the other hand, we utilize model Z2 to find the walking routes of the courier between the buildings of the corresponding cluster.

Due to the large number of buildings in our study, model Z2 cannot be solved exactly, while using a commercial solver, to identify the distance driven by carriers. Therefore, we adopt the Hybrid Genetic Search algorithm (Vidal 2022) to estimate the routes of delivery vans. Exact methods for model Z2, on the other hand, are used to solve the walking routes of the courier inside the clusters. The models were executed on an 8-core machine with 16 GB of RAM. We implemented our models in Python 3.7 and used Gurobi 12.6 as the linear programming solver. Our results and corresponding insights are described as follows.

The total driven distance by the carriers within the defined six market scenarios are illustrated in Figure 3 for both the with and without zone cases. As expected, the zoning decision results in an overall increase in driven distance for all the six market scenarios. The primary reason for this increment lies in the shift of carriers' driving patterns, in which their vans need to utilize tunnels and major roads to navigate between the traffic zones. The comparison between the with and without zone cases illustrates that the increment in driven distance occurs mainly from the operations of small carriers. While, for instance, the distance driven by 25 small carriers in Scenario 1 increases by 62% with the introduction of traffic zones, the increment is only 1.8% for the three large carriers. The reason behind this difference lies in the operational differences of these carriers. The number of packages that small carriers need to

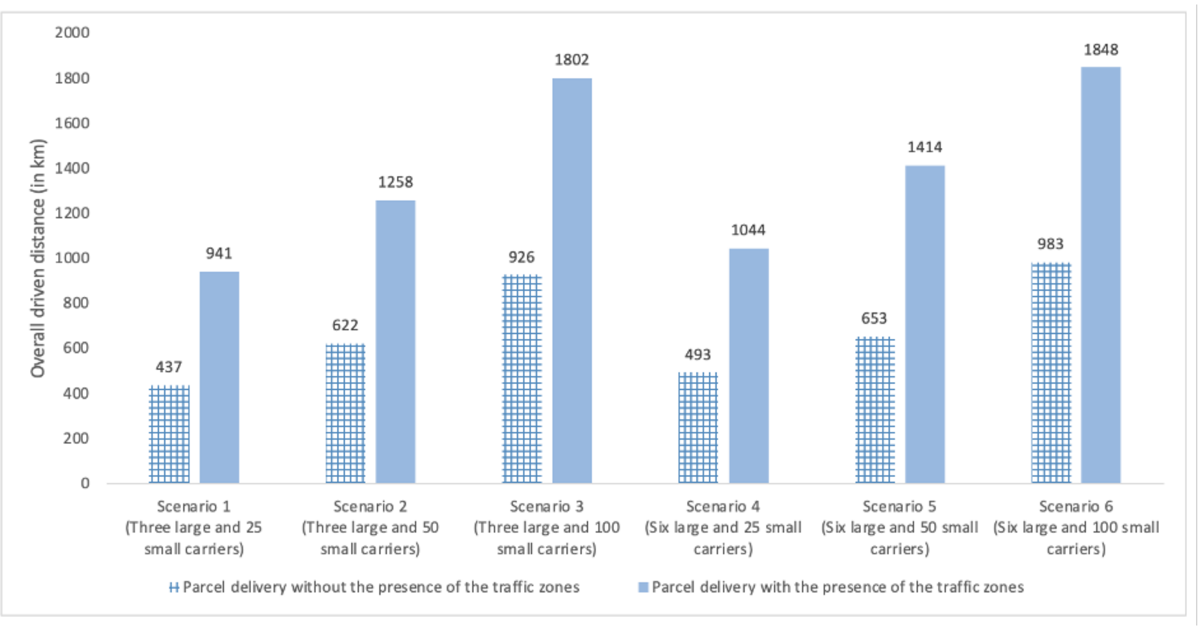

Figure 3: Total driving distance for the delivery vans in the with and without zone cases

deliver are relatively small and the destinations of these packages are sparsely distributed in different parts of the city. Hence, in the without zone case, these small carriers pass through the city centre as this provides the shortest path to reach the next customer. With the introduced traffic zones, however, through traffic is prohibited and, therefore, these carriers are diverted to tunnels and roads that lie on the outskirts of the city. This situation, however, is different for large carriers. These carriers serve a large number of packages and are able to utilize collection points for their operations. As a result, they are able to achieve routes that concentrate on specific areas, resulting from consolidation. The introduction of traffic zones, therefore, does not impact their operations too much, as their routes align well with these zones. However, as the number of large carriers increases in the market, as analysed in Scenarios 4-6, the distance driven by these carriers between with and without zones increases by 12.7% as a result of the weakened consolidation effect. The impact of traffic zones on driven distance intensifies further as the number of small carriers grows in the freight market as well. More specifically, we notice that the disconnection decision increases the driven distance by 42% when the number of small carriers increases from 25 to 100.

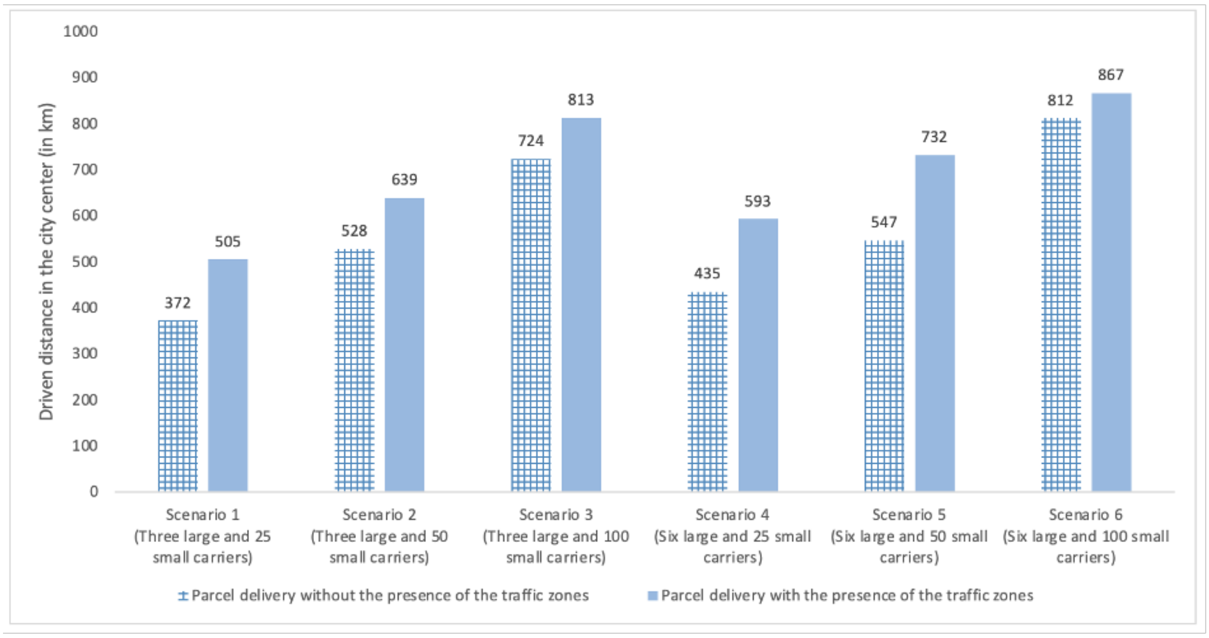

Figure 4: Total driving distance in the city centre for the delivery vans in the with and without zone cases

The effect of the zoning decision on the driven distance within the city centre, however, is not reduced as one might expect. As illustrated in Figure 4, the total driven distance within the city centre increases in all the six market scenarios between 7% and 35%. Although the through traffic is prohibited, particularly the small carriers end up driving longer within the city centre in order to enter and exit the traffic zones. The deliveries that occur within individual traffic zones require carriers to change their driving patterns as a result of the disconnection, resulting in increased distances driven within these zones. This is exemplified in Figure 5, in which the introduced zones force carriers to drive longer in order to serve customers from specific entry points designated by the traffic zones as depicted in the right image, while in the prior situation the carrier could drive in between as illustrated in the left image.

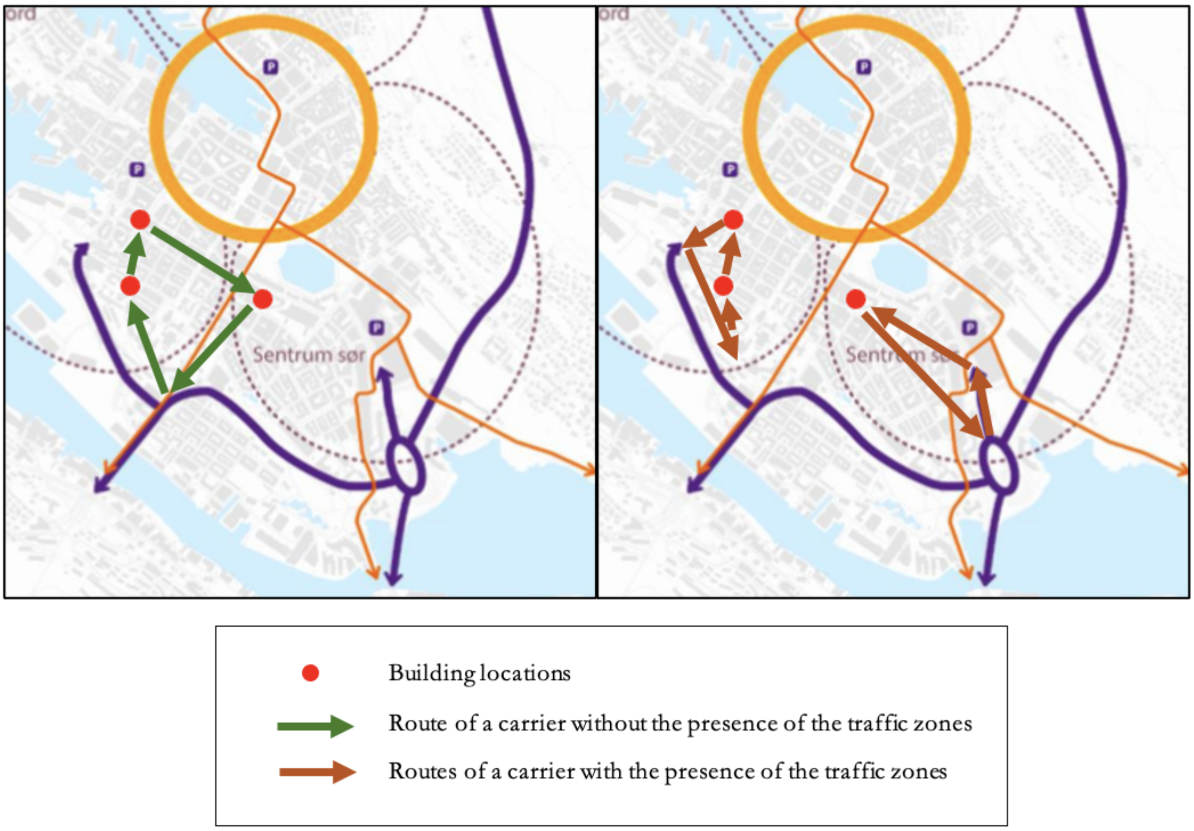

Figure 5: Example routes of a carrier without (left figure) and with (right figure) zones

6.1 Micro-hub consolidation with cargo bike delivery

The authorities in Bergen, in a separate planning, consider implementing a micro-hub for consolidation and cargo bikes for the last mile delivery. Despite the fact that Bergen as a whole is hilly, the city centre is flat. The nature of this policy may not only prevent the additional burden created by the zoning decision but may also reduce the effects of freight transport on city livability in terms of the number and duration of stops. For instance, the utilization of cargo bikes can significantly enhance the efficiency of freight distribution, while taking up less road space and contributing to a more environmentally friendly city. Therefore, we also analyse the impact of this separate plan as a potential remedy to overcome the challenges caused by the zoning. This system, in fact, aligns with the traffic zone policy aimed at creating a city centre that is more conducive to biking and pedestrian activities.

The analysis requires the establishment of a micro-hub. The city council considers Bergen railway yard as a potential location. This location, as shown in Figure 6, is a crossroads for the major roads linking the traffic zones and is convenient for carriers to transport parcels from their depots directly to the micro-hub without entering the city centre. More specifically, while carriers located in the northern side of the town can utilize the tunnel, carriers located in the southern part can use the major roads to reach the micro-hub. Although this location is convenient for carriers to deliver their parcels for consolidation, it possesses challenges in

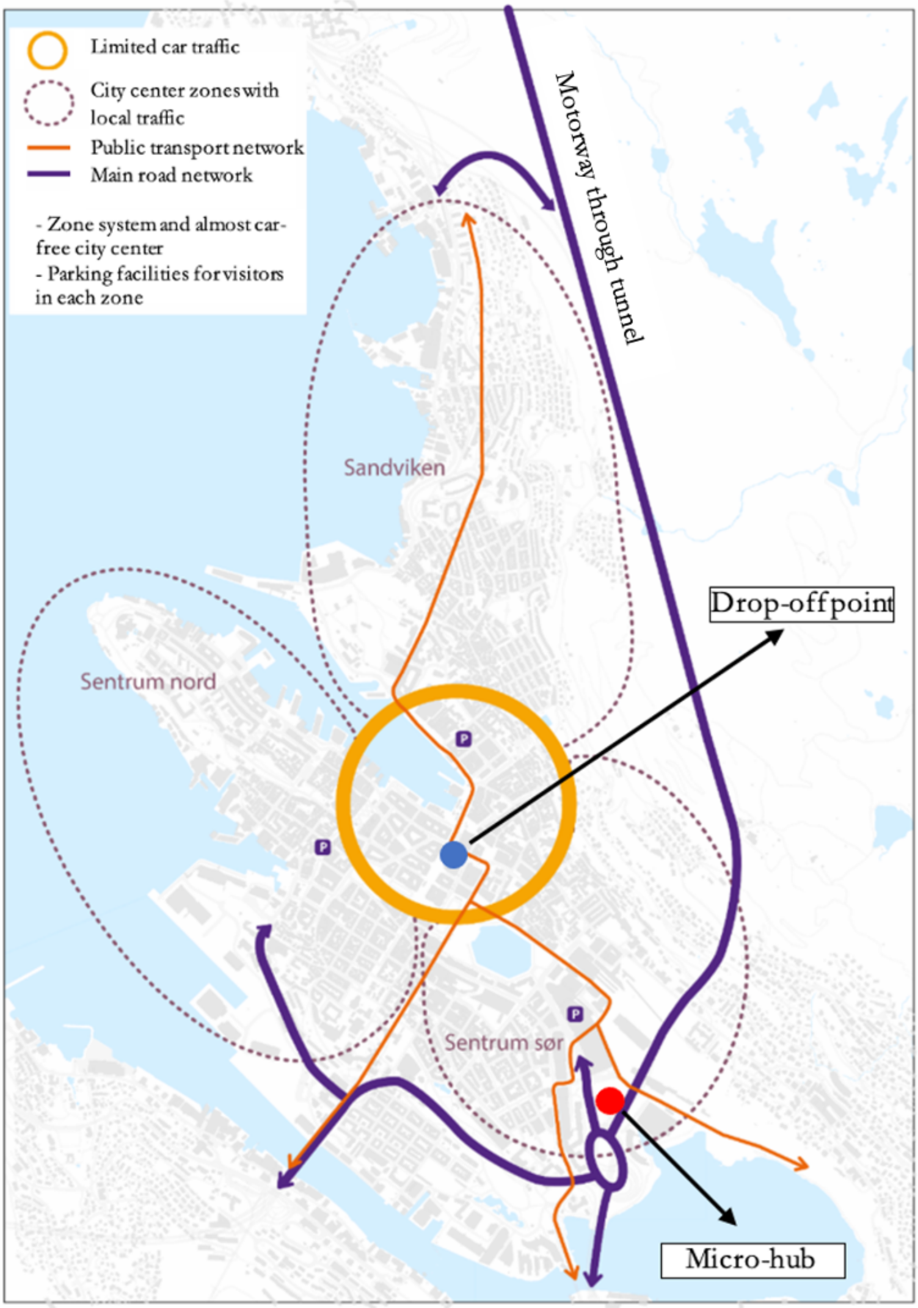

Figure 6: Locations of the micro-hub and drop-off point

performing the last mile delivery with cargo bikes due to the long distances between the micro-hub and the northern parts of the city centre. We, therefore, consider a drop-off point, where a portion of the consolidated goods, which we refer to as cargo boxes, are transferred from the micro-hub with vans for the last mile delivery. As illustrated in Figure 6, the drop-off point is located in the inner ring of the zoning plan. In this system, while the buildings closer to the micro-hub, within a 2 km radius, are served with cargo bikes from the hub, the remaining buildings are served from the drop-off point. We assume that each cargo bike can carry a single cargo box, amounting to 10 packages.

This business model has been discussed with the local authorities in Bergen and is considered as a potential setup. It is, however, worth noting that it is not the business model that we are interested in analysing, but the impacts of having one for the overall goal.

The operations of cargo bike deliveries, both from the micro-hub and through the drop-off point, can be mimicked through the CVRP model (Z2) presented in Section 4. These operations differ from the previously analysed delivery van case in the sense that they do not involve an initial clustering process. Specifically, as the cargo bikes are not subject to direction restrictions and space constraints, all packages can be delivered directly to each building. In this regard, the solution procedure is structured as follows: Initially, we determine the allocation of customers to be served from either the micro-hub or drop-off point. This allocation provides the driving distance that delivery van(s) must traverse to transfer the shipments from the micro-hub to the drop-off point. Subsequently, we execute model Z2 independently for each location, as their operations are independent from each other. Through this process, we determine the riding distance travelled by cargo bikes from these two locations. In the implementation of the model, the set V denotes the locations of buildings, with the depot uniquely identified as either micro-hub or pick-up point. Specifically, for operations originating from the micro-hub, the warehouse is designated as such, and correspondingly, for operations starting from the drop-off point, the warehouse is denoted accordingly. Additionally, the parameter K, initially representing the maximum number of vehicles, is redefined as the maximum number of cargo bikes. Furthermore, the distances between buildings are measured in terms of bike distance, which are derived from the walking distances by excluding unsuitable paths such as stairs and other non-bike-accessible routes. While the computations are used to identify the total driven bike distances, it also provides insights into the required number of cargo bikes.

Our results highlight that this system significantly reduces the distance covered by delivery vans in the city centre by 84% in comparison to Scenario 1, which has three large and 25 small carriers and has the least total driven distance among all the six market scenarios. The total driven distance that includes the bike trips, on the other hand, increases by 12%. The total increment in driven distance occurs due to the limited capacity of the cargo bikes, however, this would not translate into a negative outcome for city livability due to its environmentally friendly and space-saving nature. The latter, in fact, provides a feature to avoid the number and duration of stops caused by delivery vans. In comparison to the remaining other five market scenarios, the cargo bike solutions provide improvements in driven distance between 4.7% and 53.1%. This can be achieved by employing 17 cargo bikes under the assumption of a shift of eight hours a day, an estimated speed of 5 km/h that accounts for passing through pedestrian zones and traffic lights while utilizing the road network of the vehicles, a service time of 1.5 minutes per building, and approximately 30 seconds handling time per package.

To quantify the benefits of this system in the lights of the number and duration of stops, we utilize the results identified for delivery vans in the previous subsection and compute the following metrics:

- Number of stops: The number of clusters provides the number of stops. A higher number of stops can potentially lead to traffic congestion, particularly in the narrower streets of the city.

- Duration of stops: We assume an average of 2 minutes for the courier to find a parking spot and park the vehicle, a service time of 1.5 minutes per building, and approximately 30 seconds handling time per package to provide a rough estimate on parking duration of the delivery vans. We also consider the walking time the van courier spends delivering packages on foot within each cluster. For estimation we assume an average walking speed of 4.5km/hr. Similar to the increase in the number of stops, a longer duration for each stop results in occupied road space, street congestion and heightened traffic.

Accordingly, we find that around 500 van stops can be avoided with the micro-hub solution, implying up to 58 hours saved stopping time.

7 Concluding Remarks

Conducting an a priori analysis of regulations can provide valuable insights to city administrations, enabling them to anticipate the potential effects of policies and implement corrective measures if adverse outcomes are foreseen. In this study, we conduct an ex-ante evaluation of a traffic zone policy decided by the Bergen City Council with the aim of regulating the downtown traffic. The main focus of the traffic zone policy was to create a more pedestrian-friendly car-free zone at the city centre by diverting traffic to major roads and tunnels outside the centre. Through our analysis, we found that the traffic zones can increase the overall driven distance in the city through different market scenarios.

The crucial finding of our study was that the implementation of traffic zoning did not only increase the overall delivery distance for freight, but also led to a notable rise within the city centre itself, an unintended downside of the traffic zone plan. In this regard, specific entrance and exit roads for each traffic zone have increased the delivery distance as the delivery vans need to travel additional distances within the zones. Moreover, this additional distance tended to escalate with an increase in the number of small parcel carriers sharing the market.

In light of the adverse impact of traffic zones on freight delivery, we examined the potential of a micro-hub consolidation policy proposed by the city to regulate the last mile freight distribution. Considering Bergen's medieval layout with narrow alleys and restricted streets, our findings indicate that implementing a micro-hub with bike delivery can serve as a reliable solution to replace freight delivery vans within the city, especially when the traffic zones are implemented.

As we are focused on examining the impact of the traffic zones on freight transport and offering policy recommendations in this regard, we have not explored private vehicles used for personal purposes to analyse the broader objective of enhancing the city centre's appeal to residents by reducing traffic congestion and parking issues. Restricting their usage could contribute to achieving the overall goal of the authorities despite the increased travel distance caused by freight transport. For instance, the challenges posed by the traffic zones may discourage private vehicle usage, leading to a greater use of public transport and cycling. Additionally, the existing traffic patterns allow private vehicle users to pass through the city centre, even if their destination is beyond it. Implementing traffic zones would prohibit this behaviour. However, we expect private vehicle users, who choose to continue using their vehicles for inter-zonal travel, to increase city centre distances just as for freight. The remaining users travelling between zones might switch to alternative modes of transport, such as walking. The total effect from inter-zonal traffic, therefore, remains uncertain as the current volume of inter-zonal traffic, as well as how many will switch mode, remains unknown. In total, although we foresee that implementing traffic zones would support the overall objectives of the City of Bergen, a thorough analysis is essential before reaching any conclusions.

Before concluding, we reflect on limitations of our study and provide avenues for further research. We have utilized PostNord's distribution pattern as a proxy for other parcel carriers. Although gathering additional data poses practical challenges, integrating them into our study could improve the robustness of our insights. Furthermore, while the routes generated through our approach align with the routing sequence of postal codes provided by a major carrier, the routes observed in the field, especially for the small carriers, may differ from our findings. Our approach prioritises minimising travel distance, but carriers may have additional objectives influencing their routes. Additionally, as previously mentioned, there are no concrete facts available on the market shares of the freight carriers in Bergen. We have, therefore, analysed the impacts of the traffic zones on freight transport under several market scenarios. Gathering the precise shares of the carriers would enhance our analysis by presenting a more realistic representation of the operations. Although this would lead to more concrete values for the analysed metrics in distance and stop measures, in our view, we believe that the insights gained through our study remain valid. As observed, the small carriers are the primary contributors to the increased distance travelled within the city centre in the presence of traffic zones due to their limited consolidation options and inefficient routes. The growing trend of internet trade and the ongoing "uberification", which enables individuals to engage in delivery services, would further expand the small carriers in the freight market. Consequently, this expansion would intensify the proportion of inefficient routes within the city, leading to increased distances travelled within the city centre, especially in the presence of traffic zones. We also note that our study focuses on the ex-ante evaluation of a policy, requiring an ex-post evaluation after the implementation to verify the obtained insights. Exploring the inclusion of private vehicles and residents' driving behaviours could serve as avenues for future research to realize the overall objective of the authorities.

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Paper III

E-commerce shipments in an X-minute city: Informing authorities on freight transport through parcel lockers[*]

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Abstract

We discuss the integration of freight deliveries into the concept of an X-minute city. In particular, we explore the adoption of a dense, carrier-agnostic parcel locker network as a relevant business model for e-commerce shipments, aligning with the core principles of enhancing accessibility for residents and reducing reliance on private transport. Our exploration places particular emphasis on freight transport, which cannot be eliminated, unlike residents' trips, and requires a thorough assessment of its environmental impacts. In this regard, we analyse the effects of freight carriers on the livability of an X-minute city and present insights to authorities regarding the dynamics of the delivery operations. By utilising the vehicle routing models of the carriers at a strategical level, we quantify and characterise the effects of parcel lockers on varying sizes of carriers based on a case study in Bergen, Norway. Our findings illustrate that a broad network of parcel lockers would reduce carriers' environmental impacts, measured by their driven distances and the space they occupy on curbs. We observe that while eliminating carriers' failed deliveries brings substantial benefits to the city, a notable portion of this arises from small carriers. In addition, expanding the consolidation range through parcel lockers provides further benefits to the livability, which are driven by the improved efficiency of large carriers. The results point out that enabling small carriers to have access to parcel lockers is one of the key measures in enhancing the livability of an X-minute city, unless further interventions are designed to directly regulate their operations. As small carriers lack the resources to deploy parcel lockers, their failed deliveries are expensive for urban environments.

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1 Introduction

There has been a growing interest among public authorities worldwide to enhance city livability in response to increasing environmental concerns and the need for a sustainable urban development. One of the central concerns in this context lies in reducing the impacts of the transport industry, given that the sector is responsible for nearly a quarter of the global energy-related greenhouse gas emissions and contributes significantly to air and noise pollution in urban areas. Both the 2030 Agenda for Sustainable Development and the Paris Climate Change Agreement consider transport as a vital element and a catalyst in achieving their objectives, prompting policymakers to adopt solutions (e.g., offering incentives to promote electric vehicle adoption) and regulations (e.g., establishing zero-emission zones) to reduce its negative impacts.

The 15-minute city has recently received attention from policymakers, urban designers, and transport planners. The concept is designed with the intention of reducing the negative externalities related to transport, aiming to establish urban areas where residents reach all essential needs and services (such as schools, healthcare centres, grocery shops, parks, and cafes) within 15 minutes walking or cycling (Moreno et al. 2021). By establishing self-sufficient communities, the concept seeks to reduce dependency on private vehicles for daily needs and diminish the challenges of transport, such as emissions and pollution. One of the first notable political initiatives in this context emerged from Anne Hidalgo, the Mayor of Paris, who included the implementation of the 15-minute city concept as part of her re-election campaign in 2020 (Moreno et al. 2021). Similar initiatives have been proposed in other large cities like Barcelona, Dublin, Milan, Lisbon, and Shanghai (Hernandez-Morales 2022, Schauenberg 2023). While the concept initially emerged as an urban planning solution for large cities, Moreno (2021) has emphasised the necessity of extending this approach to include small- to medium-sized cities and rural areas. In this regard, an X-minute city can adapt a different proximity measure while still adhering to the core concept.

Although the advantages of X-minute cities are clear in terms of reduced reliance on private vehicles, the concept may benefit from comprehensive planning that addresses various aspects of urban life other than mobility and its associated services. One such aspect often overlooked in favour of mobility is freight transport. Giuffrida et al. (2024), for instance, emphasise that the concept of X-minute cities should be examined beyond fulfilling daily necessities and services, especially considering the need as well as the growth of e-commerce. The authors argue that the urban planning of X-minute cities should not disregard the importance of accessing urban delivery services, as neglecting this aspect could raise doubts about the viability and effectiveness of the concept. The European Road Transport Research Advisory Council looks into this aspect as well (ERTAC 2023), emphasising the need for a thorough examination of how the concept of X-minute cities can integrate goods distribution. The Council, in fact, frames this aspect as one of the most pressing policy issues regarding the deployment of X-minute cities.

Among various delivery modes of e-commerce shipments, parcel lockers represent a relevant business model for X-minute cities because, as demonstrated by Caspersen et al. (2023), consumers tend to use vehicles less frequently when retrieving goods from parcel lockers compared to other collection points, such as stores and kiosks. These collection points are designed to minimise the distance travelled by freight carriers, allowing customers to complete the final leg of the delivery. Parcel lockers, contrary to other collection points, can be strategically positioned closer to customers, benefiting from their flexibility for easier expansion and deployment in larger quantities. The proximity of parcel lockers to customers, in this regard, plays a decisive role in determining how customers choose to complete the final leg (Iwan et al. 2016), directly impacting the reduction in private vehicle dependency for retrieving shipments. Other factors, such as the convenience of picking up shipments while visiting other destinations, may also contribute to this. In addition to reducing private vehicle dependency, parcel lockers improve the operational efficiencies of freight carriers. While couriers typically cover shorter distances on foot, customers can travel further to collect their packages. By retrieving their shipments through parcel lockers, customers enable carriers to extend delivery range. This reduces both the overall distance driven and the curb space occupied by carriers in urban areas. Moreover, through a broad network expansion, parcel lockers have the potential to replace direct home deliveries, thereby reducing delivery failures and improving city livability by eliminating carriers' additional trips to fulfil deliveries.

Placing parcel lockers in accordance with the X-minute proximity measure may facilitate residents' access to their shipments by walking or cycling, aligning with the core principles of the concept. Although parcel lockers are not typically linked to the concept of X-minute cities in the literature, likely due to their services extending beyond essential goods, they have been extensively studied in other contexts. Designing a network of parcel lockers, for instance, is one such direction. In this regard, researchers analyse the optimal number, size, and locations of parcel lockers to improve delivery efficiency within the last mile. A study conducted by Deutsch & Golany (2018), for instance, formulates an optimisation problem to design the network of a carrier while maximising the carrier's profit. They base customer choices on deterministic preferences, assuming that customers opt for the closest parcel locker while making their orders. As distances increase, the authors assume that fewer customers are willing to utilise parcel lockers, resulting in direct deliveries instead. Another analysis on identifying the locations of such collection points is conducted by Hong et al. (2019). The authors determine their deployment while minimising a carrier's driven distance. Schwerdfeger & Boysen (2020), on the other hand, explore mobile parcel lockers that dynamically adjust their positions and optimise their locations to minimise the number required to serve customers.

While these studies assume that customers choose the closest parcel lockers for picking up their shipments or let carriers select the parcel locker for them, a number of papers integrates customer behaviour into the analysis. The researchers exploiting this direction argue that customers' behaviour are often interpreted probabilistically and may not necessarily favour the most conveniently located lockers. Lin et al. (2020), for instance, conduct an analysis on redesigning a parcel locker network to maximise its overall service, while employing a multinomial logit choice model to integrate probabilistic customer preferences. A similar perspective is adopted by Peppel & Spinler (2022). Their analysis identifies the proportion of customers who prefer parcel locker delivery over direct delivery, while taking into account recipients' utility functions (based on the distance between them and the lockers), and their time spent at home.

Another avenue of research explores the environmental impacts of parcel lockers. In this regard, Lemke et al. (2016) quantify the benefits of parcel lockers on driven distance while mimicking the operations of InPost, one of the major carriers in Poland, and using their real data. The operations of InPost are also analysed by Iwan et al. (2016). The authors show that parcel lockers reduce the number of trips within urban areas as a result of reduced failed deliveries. In another paper, Song et al. (2013) study the impacts of parcel lockers on greenhouse gas emissions. By exploring the operations of nine large carriers in the United Kingdom, the authors quantify the benefits based on the trips conducted by the carriers and the customers. The benefits of parcel lockers on emissions are noted by Peppel & Spinler (2022) as well, who mimic the operations of a large international logistics operator within their study. Pinchasik et al. (2023) report similar insights. The authors illustrate, through the operations of a major carrier (PostNord) in Norway, that emissions and travelled distances are reduced in the presence of parcel lockers by eliminating direct deliveries. The implementation of carrier-agnostic parcel lockers also contributes to reductions in emissions and driven distances within urban areas (e.g., Hohenecker et al. 2021). The adoption of agnostic lockers in the literature, however, remains scarce, with the primary focus being on privately-owned lockers and government-run facilities (Ranjbari et al. 2023). One noteworthy initiative in this regard is the Singapore government's proposal for a 'Locker Alliance', aiming to establish a network of public lockers alongside those of major carriers to enhance last-mile delivery efficiency (Lyu & Teo 2022).

Although the literature highlights that the impacts of parcel lockers are significant, Caspersen et al. (2023) point out that the focus of these examinations has primarily been on their role as a delivery solution, with limited attention paid to their implications for policymakers and transport planners. One of the concerns raised by Caspersen et al. (2023) is the literature's tendency to overlook how authorities might influence or regulate the location, design, and use of parcel lockers for enhanced city livability. This likely stems from the fact that freight carriers expand their parcel locker networks through agreements with private landowners, without requiring approvals from public authorities. The involvement of authorities, however, gains greater relevance within the concept of X-minute cities, since one of the most pressing policy issues discussed earlier lies in integrating goods distribution within this concept, an issue to which parcel lockers offer a fitting solution for e-commerce shipments. Public interventions, in this regard, may take shape through two different phases of the delivery process: one involving the distribution of goods to parcel lockers, carried out by freight carriers, and the other involving their retrieval from these lockers by customers. The interventions of authorities in the latter phase is primarily focused on reducing the distance between parcel lockers and customers. In this regard, regulating parcel lockers to be carrier-agnostic and facilitating carriers' utilisation of public lands for deployment are among the main interventions that would expand the network of parcel lockers, which would, in return, enable residents to access their shipments by walking or cycling. As outlined previously, such broad expansions that reduce the distance to accessing goods has the impact of replacing home deliveries as well.

On the other hand, intervening in the supply side of the operations poses greater difficulties and requires a comprehensive understanding of the delivery dynamics, given that it may involve regulating or influencing the operations of the freight carriers. In this regard, for informed decision-making, authorities have to grasp the dynamics behind the distribution of goods, its impacts on city livability, and the essential measures required for enhancing it. In this paper, therefore, we focus on these aspects and provide authorities with information regarding the distributions of goods in the presence of parcel lockers. This is particularly important because while parcel lockers may eliminate residents' reliance on private vehicles to retrieve their goods, freight transport cannot be replaced and its impacts must be accounted for. Accordingly, we focus on enhancing the livability of X-minute cities and reducing the impacts of freight transport in terms of distance driven by carriers as well as their number and duration of stops. In achieving this, we are not interested in capturing which transport mode customers would choose to complete the final leg and retrieve their shipments; however, we assume that parcel lockers are carrier-agnostic and can be deployed also on public lands, two interventions intended to promote walking among customers by reducing the distance between them and the parcel lockers. A carrier-agnostic setup would also ensure that the carriers do not deploy individual lockers across the city, a practice that has raised growing concerns regarding its impact on the city's aesthetics and its tendency to occupy more space than necessary when a collaborative approach could be adopted.

Several studies, as outlined previously, analyse the impacts of parcel lockers on the environment, yet their focus on large carriers limits their capacity to capture and provide insights to public authorities regarding the broader market dynamics and effects, especially considering the growth of small carriers as a result of the increasing internet trade, and the ongoing uberification that encourages individuals to engage in delivery services. While the focus of the literature on large carriers may be explained by the lack of resources among small carriers to deploy and utilise these lockers by themselves, the establishment of carrier-agnostic parcel lockers would facilitate their utilisation, requiring authorities to realise the implications for all sizes of carriers. In fact, this is important to capture because, as shown in Orhan et al. (2024a), small carriers drastically reduce the livability of cities in urban areas. Accordingly, contrary to the existing literature, we provide information and insights to authorities while also accounting for carriers of varying sizes, offering a holistic view of the market.

In this regard, through a case study, we compare a current delivery market with a potential one that relies on a dense, carrier-agnostic parcel locker network that enables residents to access packages within X minutes. This potential market resembles a scenario for goods distribution within an X-minute city, where all shipments are directed to parcel lockers and residents can retrieve their shipments within walking distances. We characterise and quantify the impacts of utilising parcel lockers for different carrier sizes in terms of distance and stop measures, and assess their broader implications on city livability to inform policymakers. Based on real maps and real demand patterns, we conduct these assessments through a case study in Bergen, Norway.

Our contribution is two-fold. First, we contribute to the ongoing debate on the concept of X-minute cities by extending the concept beyond essential goods and incorporate e-commerce deliveries through parcel lockers, an aspect considered necessary for the deployment of X-minute cities. Second, based on a computational study with real data collected from Bergen, we quantify the benefits of parcel lockers for varying sizes of carriers and provide authorities with the information necessary for informed policy-making decisions to enhance city livability through parcel lockers.

2 Problem statement

We consider a public authority evaluating the potential of the X-minute city concept suited for their urban environment. The authority seeks to understand the utilisation of parcel lockers for delivering e-commerce shipments as part of the concept and to identify their potential involvement, particularly by assessing the impacts of freight carriers on city livability. This requires the authority to compare the current operations of the carriers against the operations where a dense, carrier-agnostic parcel locker network is in place.

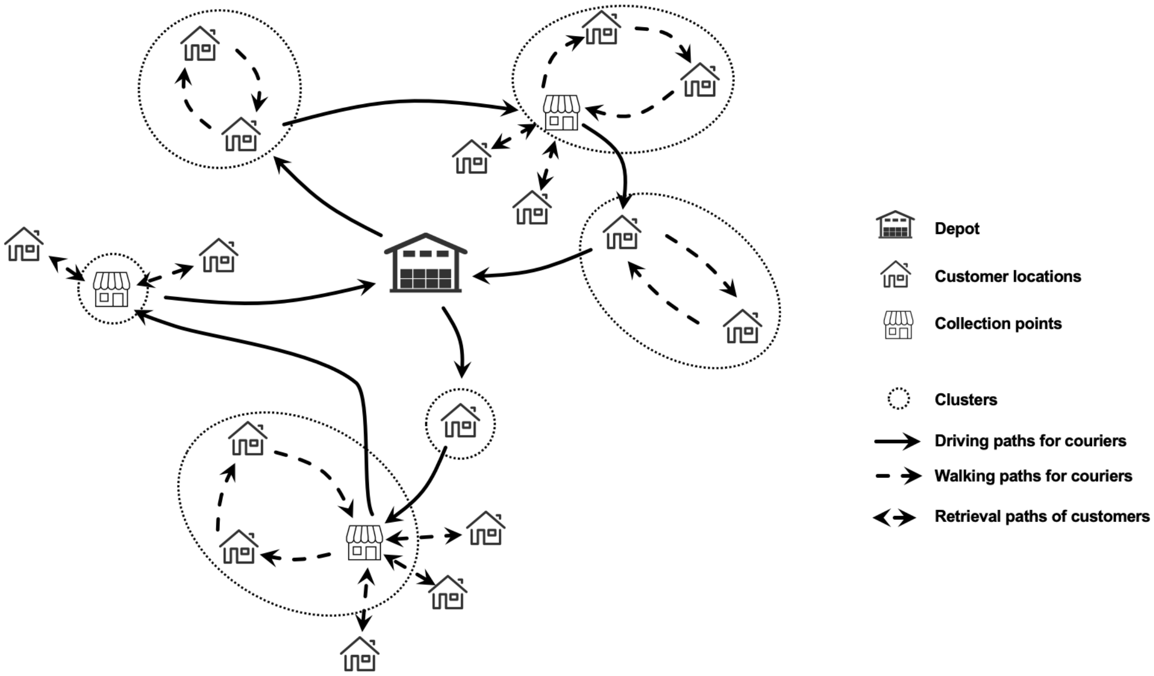

Figure 1: Illustration of the delivery operations in the current market

The current market operates as follows and is illustrated in Figure 1. A number of carriers, holding different market shares, delivers customers' goods to designated locations, which include the buildings where customers requested their shipments as direct deliveries or collection points (such as grocery stores, shopping malls, convenience stores, and parcel lockers) where customers retrieve them at their convenience. Given a set of customers to serve, each carrier plans its services to deliver the goods while minimising the cost, measured by the distance travelled. Accordingly, each carrier assigns their couriers driving routes by clustering nearby customer locations and collection points that can be served on foot. They also designate parking slots for the couriers, which are, in return, used to identify the optimal driving sequence of visits to these parking slots. A building or a collection point where a customer requested the good(s) to may not be situated near to another location that needs be served. In such cases, the courier parks near to this location and delivers the good(s). Alternatively, in cases where multiple customers are clustered together, the courier performs the delivery following an optimal walking sequence to visit each location.

The inclusion of a dense, carrier-agnostic parcel locker network changes the operations of carriers, particularly by replacing direct home deliveries with all shipments directed to parcel lockers. This also eliminates delivery failures, thus reducing the number of shipments handled per day compared to the current market operations. By utilising parcel lockers in their operations, carriers eliminate the need to cluster customers who are geographically close. Instead of walking from one customer to another on foot, as is done in the current delivery operations, shipments are consolidated within the lockers, allowing couriers to park nearby and deliver the goods to these lockers. The routes of the couriers are determined by the optimal driving sequence of visiting the parcel lockers. The operations through the parcel lockers are illustrated in Figure 2.

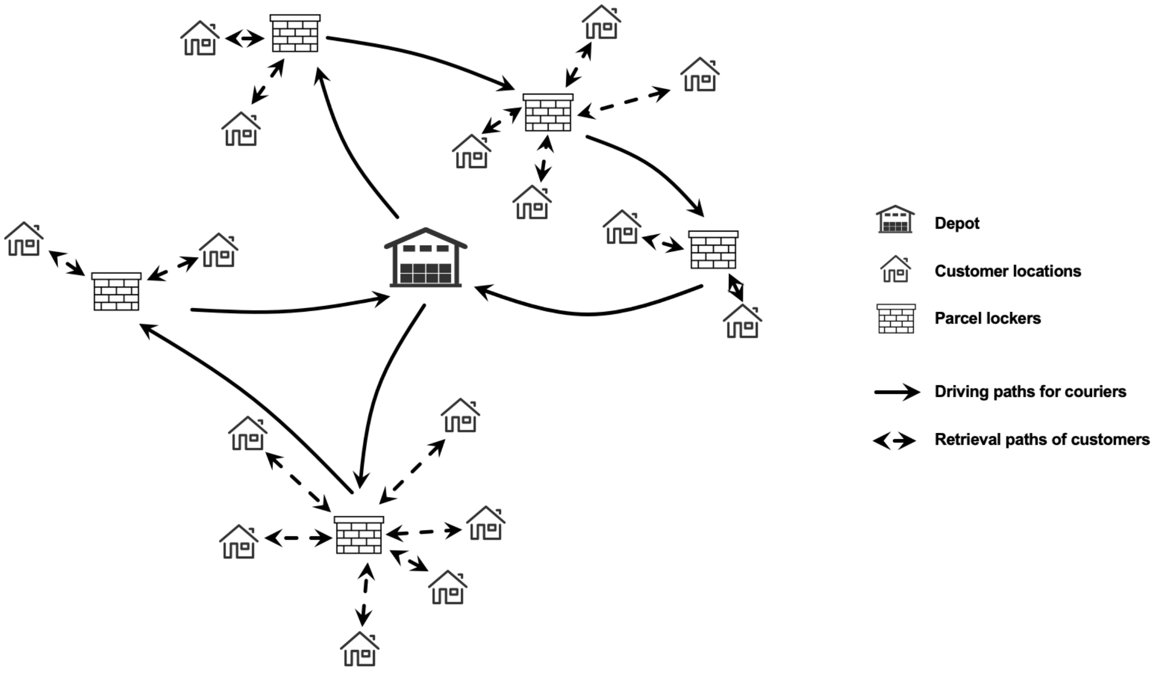

Figure 2: Illustration of the delivery operations in the presence of parcel lockers

The authority is interested in understanding the transition from the current operations to implementing a dense, carrier-agnostic parcel locker network. Their aim is to analyse and characterise the benefits of parcel lockers and to determine whether, and if so, how to regulate carrier operations to improve the livability of their X-minute city, should the concept move forward. The livability is measured by driven distance as well as the number and length of stops, which are calculated as follows. The driven distance, in the current operations, is determined by the optimal route lengths for visiting parking slots. Similarly, the measure is calculated based on the optimal route lengths for visiting parcel lockers when a broad parcel locker network is in place. The total number of stops, on the other hand, depends on the total number of clusters in the current operations, while the measure is determined by the total number of utilised parcel lockers when the operations are conducted through them. Finally, the duration of stops provides a rough estimate on the curb occupancy and is calculated by using the following three components in the current operations.

- Off-loading procedure: A combination of a fixed and a variable time are used to estimate the duration of the off-loading procedure. While the former is calculated by the time required for setting up the off-loading procedure and parking the vehicle, the latter is calculated by the time needed to off-load packages, depending on the quantity to be delivered at each stop.
- Handing over the packages: The time for delivering packages is calculated based on the total number of visits required for each location and the average service time per location.
- Walking in between locations: The time required for the courier to walk to and from buildings and collection points is determined by the distance travelled on foot and the average walking speed.

Contrary to the current operations, the duration of stops is estimated solely based on the first two components when the operations include the parcel locker network. The final component becomes unnecessary since couriers do not travel between locations on foot any longer.

3 Case study

Bergen is a small medieval city in Norway, characterised by its challenging topography that poses difficulties for transport. The city, situated on the coast, has an ancient road network that is designed around the contours of the surrounding mountains, making driving rather difficult. Furthermore, due to the limited available spaces, expanding the road infrastructure is unlikely, particularly within central areas.

Preserving the medieval structure of the city, along with its ancient road network, is a major concern for the authorities in Bergen. In this regard, they are committed to reduce the reliance on vehicles and the impacts of transport within their urban areas. To achieve this, they conduct analyses and tests to implement a range of policies. These, for instance, include establishing a car-free zone through the introduction of traffic zones (Orhan et al. 2024b), changing traffic patterns within the city to discourage driving (Matre 2023), and experimenting with zero-emission zones to reduce the impacts of transport in certain areas (Sweco 2020).

The concept of X-minute cities is a measure that aligns well with the overall objectives of the authorities. Should the concept be adopted, freight transport would be one of the central concepts in the implementation, as the authorities in Bergen increasingly prioritise freight transport within their discussions to mitigate its overall impact. This section presents the data and the methodology adopted in our study to answer the questions highlighted in the problem statement in light of the Bergen case.

3.1 Data and design of the study

The current market in Bergen is dominated by a few large carriers, whereas small ones have a relatively low market share. While 90% of the market is assumed to be operated by six large carriers, the remaining 10% of the market is shared among an unknown number of small carriers. As our reference point, we assume that there are 25 small carriers capturing this share, with each having 0.4% of the market. A higher number of small carriers would result in each one of them delivering fewer packages, leading to less efficient operations and increased impacts on city livability, as shown in Orhan et al. (2024a). Hence, in our analysis, we assume a relatively low number of small carriers as a base for assessing their influence within the market while acknowledging that a larger number would amplify their impacts on city livability. The assumed market shares of large and small carriers are presented in Table 1.

Table 1: Market shares of large and small carriers

	Carrier A	Carrier B	Carrier C	Carrier D	Carrier E	Carrier F	Small carriers
Market shares	34%	25%	9%	8%	7%	7%	10%

The distribution plan of each carrier is based on the data we gathered from PostNord[1], one of the large carriers operating in Norway. The gathered data includes the weekly parcel distribution of the carrier for each postal code of Bergen. It involves mainly the business-to-customer shipments made in 2020, with the majority directed to collection points and a significant portion delivered directly to customers' addresses. As PostNord's business model resembles a consolidator, we assume that its distribution patterns for the two delivery modes, collections points or direct deliveries, act as proxies for other carriers' distribution patterns.

Collection points serve as the main point-of-contact with customers in Norway. While the market share of collection points is assumed to be 75%, the remaining 25% accounts for the share of direct deliveries. The leading two carriers rely on collection points for the majority of their operations, whereas the other large carriers utilise a mix of both delivery modes. Unlike large carriers, the small ones serve their customers directly and do not deliver through the collection points. Given the low number of packages these small carriers handle, which limits their consolidation opportunities, their operations are indifferent between serving their customers directly or through the collection points except for the effects of the failed deliveries.

As the gathered data of PostNord is on a weekly basis and is attached to postal codes, we initially estimate the daily distribution of the carrier and disaggregate it on an address level. In doing so, we utilise the locations of all buildings and their postal codes as well as the estimated population of all buildings in Bergen from Norwegian Mapping and Cadastre Authority[2] and from Fang & Opedal (2020), respectively. Through this procedure, we determine the daily proportion of packages delivered to each building. Utilising this measure along with our assumption of PostNord's market share, we end up with a daily parcel delivery market in Bergen of 6000 package. This represents the current market operations.

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[1] https://www.postnord.no/en

[2] https://www.kartverket.nol/api-og-data/eiendomsdata

The integration of a broad parcel locker network would change this figure by eliminating the delivery failures of the current market operations. We assume that 20% of the direct deliveries fail. Their elimination would reduce the number of packages handled per day in Bergen by 300, which forms 5% of the market. The selection of these reduced packages is determined by carriers' market shares on direct deliveries and the number of packages delivered within each postcode such that postcodes with a higher volume of deliveries would have a greater number of failed deliveries.

As previously discussed, the spread of parcel lockers within X-minute cities would be a key criterion in enabling customers to retrieve their shipments by foot. PostNord concludes that the walking distance for customers to retrieve their goods should be within 300 meters (Hovi & Pinchasik 2023), while several other sources suggest 500 meters as the maximum acceptable distance for walking (Iannaccone et al. 2021, Vakulenko 2023). Framed as the slipper distance, the measure indicates the point at which customers are inclined to switch their transport modes. Considering an average walking speed of 4.5 km/h, a round trip of approximately 10 minutes to receive the goods would satisfy the conditions identified by PostNord, with a maximum of approximately 15 minutes. It is noteworthy that identifying the "X" measure suited for Bergen is not the concern of this paper, since this requires a more thorough analysis while considering various aspects of urban life and freight transport is certainly not a decisive criterion alone. We, however, capture the knowledge of carriers that would prompt customers to utilise parcel lockers while switching to environmentally friendly transport modes, an objective that X-minute cities would like to achieve.

Accordingly, we identify the locations of the parcel lockers. The literature acknowledges that parcel location choices in practice do not follow a single approach due to various factors, such as trade-offs between locational quality and negotiations with landlords, high rental fees in certain locations, compliance with legal regulations, and obstacles arising from limited availability of public space (Pinchasik et al. 2023, Peppel & Spinler 2022, Hadzic et al. 2022). Determining the optimal number and location of parcel lockers, in this regard, may not lead to a practically viable setting, despite being theoretically optimal (Schnieder et al. 2021). As our focus is on providing strategic insights to authorities, we capture the carriers' operations at a sufficient level while adopting a locker network that aligns with the accessibility measures of an X-minute city. In light of this, we employ the following approach and decision rules to determine their locations. Statistics Norway[3] has divided the Norwegian cities into geographical units to derive regional statistics, with the majority including a few hundred residents. We utilise these geographical units in placing the parcel lockers throughout Bergen, while adhering to the conditions suggested by PostNord and the literature. Initially, we gather all possible locations of parcel lockers, including both public and private lands. These include the mapping of existing parcel lockers provided by the three providers (PostNord, Posten Bring, and Instabox), the grocery and convenience stores, the housing cooperatives, the shopping centres, private and public parking locations, public parks, and transport terminals. For each geographical unit, we identify whether any of the mapped locations fall within its boundaries. If such a location

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[3] https://www.ssb.no/en

exists, we designate it as the parcel locker for the unit. In cases where multiple locations are available, we select the one with the shortest average walking distance from all buildings. If, however, no suitable location exists, we identify the buildings within that unit that are beyond the maximum acceptable walking distance and designate the centroid building among them as the parcel locker. Following the allocation, the walking distances to parcel lockers in several geographical units exceeds the given maximum threshold. In such cases, we employ a K-means clustering to partition these geographical units into smaller areas. Subsequently, we apply the same procedure for allocating parcel lockers within these newly defined areas.

Representing market operations through a broad parcel locker network involves a reallocation of the shipments. Given that each customer is within a walking distance to a parcel locker, we operate under the assumption of a deterministic customer preference for direct deliveries, shipping them to parcel lockers where customers have the shortest walking distances. Reallocating the shipments previously retrieved from the collection points to the parcel lockers presents greater difficulties, as customers' shipment decision may change as a result of the broad locker expansion. We distribute the packages of each collection point across all geographical units within the postal codes where the collection points are located. This distribution is done proportionally, taking into account the populations of each unit. We acknowledge two deficiencies within this approach. First, there may be a portion of packages directed to other postal codes based on the behaviours of the customers; however, since we lack such data, this aspect is not accounted for in our study. Second, a collection point may be located within the boundaries of a postal code, but a geographical unit close to that collection point might not fall within the same postal code boundaries. Consequently, this approach may lead to underestimating the volume of some geographical units and overestimating some others. We believe that the implications of excluding these aspects would be minimal for our strategic study objectives and we will return to this discussion following the description of the results.

Once the shipment locations are derived for both operational setups, we identify the driving distances between these locations and the carriers' depots. Initially, we define Bergen's road network topography based on the data we pull from the National Road Database[4] of the Norwegian Public Roads Administration. By connecting all the buildings in Bergen within our road network, we generate our map and run Dijkstra's shortest path algorithm to identify the driving distance between the given locations. Additionally, for the current market operations, we determine the walking distance between the locations since the couriers walk between locations after parking their vehicle within a cluster. As described earlier, we cluster the nearby buildings and collection points within the current market operations. Accordingly, we assume that 100 meters is the walking threshold. We also assume certain parameters to identify the duration of stops, primarily derived from a field trip conducted within a central area of Bergen, together with the authorities, to observe the freight transport. These parameters include the time required for setting up the off-loading procedure along with parking (set at 2 minutes per stop), unloading each package (set at 30 seconds), and handing over the packages (set at 1.5 minutes). Additionally, we assume that the vehicles have a capacity of 200 packages, while

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[4] https://api.vegdata.no

couriers can carry 5 packages at a time while walking during the current market operations. We also assume that parcel lockers do not possess capacity restrictions.

3.2 Methodology

Orhan et al. (2024a) propose a three-stage methodology for small city authorities to derive strategic macro decisions by mimicking the actions of carriers at a micro level. By capturing sufficient operational details of carriers through the adoption of clustering and vehicle routing models, the authors provide a strategic policy guidance tool to authorities. In achieving this, they utilise an integer programming formulation to identify the clusters by ensuring that any two locations that exceed the walking threshold cannot be assigned to the same cluster. Furthermore, they accommodate each cluster to have a maximum of one building that requires couriers to make multiple trips on foot for delivery. This leads couriers to park nearby to these locations and minimise the need for repeated back-and-forth journeys on foot. If such a location within a cluster does not exist, parking selection occurs randomly among the cluster's available locations. This randomness stems from the scarcity of parking spots in Bergen, leading couriers to stop wherever they can. Following the allocation of parking slots for each cluster, a capacitated vehicle routing problem (CVRP) is employed to determine the optimal driving routes. The routes respect the vehicle capacity, require each location to be visited once, and ensure that the routes start and end at the depot. CVRP is also utilised within clusters to determine optimal walking paths, with the parking spot serving as the starting and ending point of the route. We employ this three-stage methodology to analyse the current market operations. We refer the readers to Orhan et al. (2024a) for the formulations of these stages and their corresponding solution procedures.

Contrary to the current market operations, adopting a broad locker network simplifies the operations by utilising only the CVRP formulation to determine the optimal routes for visiting these lockers.

4 Results

We observe that the driven distance as well as the number and duration of stops are reduced when introducing the parcel locker network by 17.0%, 26.6%, and 16.7%, respectively, as illustrated in Figure 3. These reductions occur due to the increased delivery range and the elimination of failed deliveries. Specifically, while couriers are able to cover short distances on foot to consolidate shipments in the current market operations, customers retrieve their own shipments in the presence of parcel lockers, expanding the delivery range for the carriers. Furthermore, carriers no longer need to make trips for failed deliveries, as parcel lockers eliminate these needs. More detailed results of the carriers' operations with and without the presence of the locker network are provided in the Appendix.

Guiding authorities strategically on the delivery dynamics requires an understanding of carriers' micro-behaviour and their impacts in relation to increased delivery range and eliminated deliveries. However, when parcel lockers are in place, the eliminated deliveries are no longer

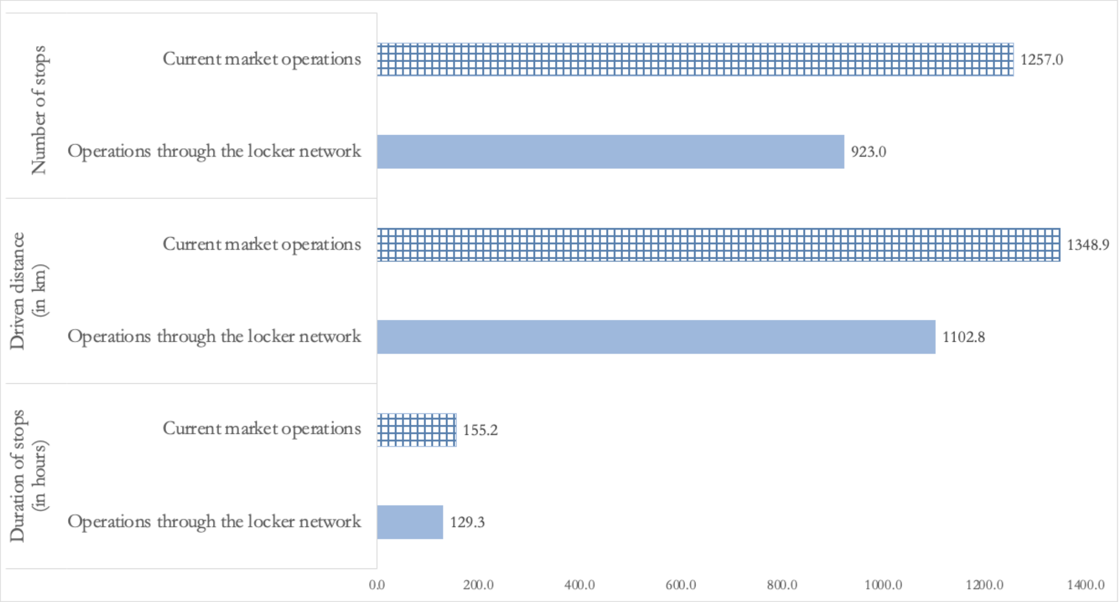

Figure 3: Operational results of the markets with and without the presence of the locker network

part of the operations.Therefore, distinguishing between the impacts of extended delivery range and eliminated deliveries requires an additional step of evaluation. Although this is a marginal detail, we would like to elaborate on this evaluation to clarify how the results are computed. Accordingly, consider a previously failed delivery that requires the fulfilment within today's operations. If this failed delivery falls within a cluster where multiple other shipments exist, then its elimination would not affect the number of stops, as the courier would still need to stop at that cluster to deliver the remaining shipments. Although negligible, the duration of stops would be reduced due to the decreased number of packages to serve within that cluster and the driven distance might be affected, if the parking choice would differ within that cluster. On the other hand, the impacts of eliminating this failure may be significant when it forms a cluster on its own, reducing the need to stop at that location and the time to occupy the curb space. The magnitude of the impact in relation to the driven distance would depend on the distance between the failed delivery location and the nearest other delivery point. In light of this, although parcel lockers would be the cause of eliminating these failed deliveries, the carriers' ability to consolidate their shipments would determine the operational impact of eliminating them. Therefore, the impacts of failed deliveries can be quantified by comparing the current market operations with and without accounting for these failures. Furthermore, the impacts of extended delivery range through parcel lockers can be assessed by comparing the operations with and without the presence of the locker network, while considering the impacts of eliminating failed deliveries. These quantified impacts on the extended delivery range inherently include the effects of changes in shipment locations.

The results illustrate that small carriers are the primary causes of distance and stops measures, both with and without the presence of the locker network. Particularly, while these carriers represent 57.6% of the driven distance in the current market operation, this figure rises to 59.8% in the presence of the parcel locker network. Similarly, while their number and duration of stops accounts for 44.7%, and 25.4%, respectively, of the current market operations, the inclusion of parcel lockers shift these measures to 49.0% and 25.9%. This suggests that while the inclusion of a broad locker network enhances the livability, it also amplifies the relative impact of smaller carriers, as larger ones gain more from this setup.

The current market operations indicate that small carriers typically make only one stop per package, resulting in minimal consolidation of shipments. They frequently occupy curb space to serve individual customers, often located in different parts of the city. These carriers, therefore, navigate through nearly all central areas of the city, as illustrated in Figure 4, leading to a significant increase in total distance travelled throughout the city. The inclusion of a parcel locker network impacts the operations of small carriers mainly through the elimination of failed deliveries. Excluding such deliveries, which are often located a considerable distance away from the remaining shipments, enables carriers to reduce their driving distance by 10.2%. As the excluded deliveries are often the only ones served in their respective clusters, this reduction directly translates into fewer stops and shorter durations as well, particularly by 16.3%, and 12.3%, respectively. The impacts of increased delivery range through parcel lockers, however, have marginal impact on these carriers. Despite the extended range, the benefits remain at 3.7% in driven distance due to limited consolidation options. Accordingly, the number and duration of stops are also reduced by 4.0%, and 3.2%, respectively. We observe that the difference in driven distance may also be impacted by the changes in shipment locations. In some routes where consolidation is absent, the new shipment locations may result in either an increase or decrease in travel distances, while the stop measures remain constant.

The elimination of failed deliveries impacts the operations of large carriers as well, resulting in a reduction of 15.4% in driving distance, 13.2% in the number of stops, and 6.7% in stop

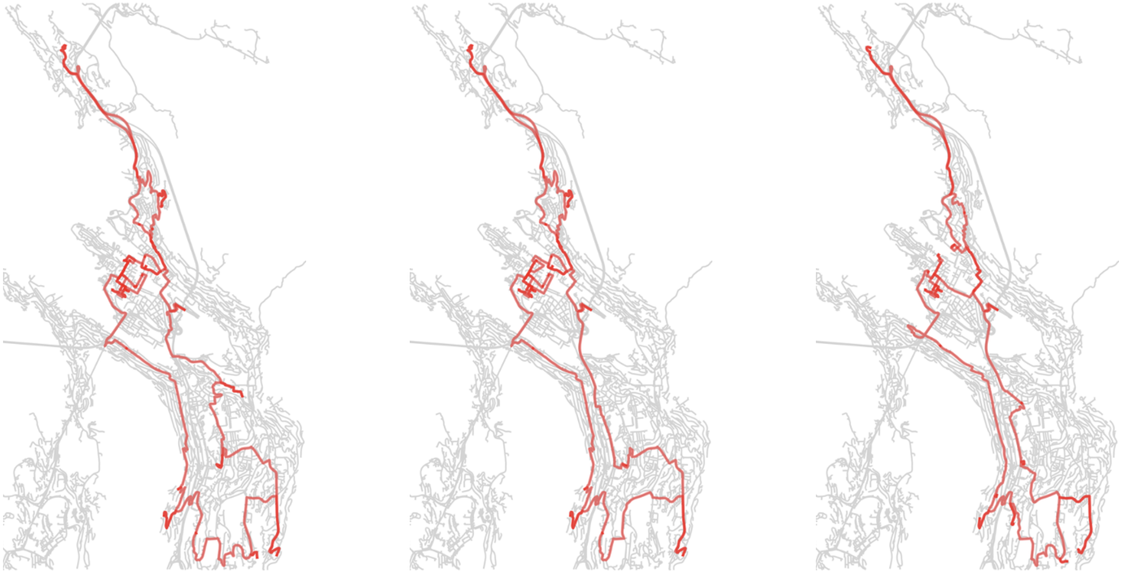

Figure 4: Operations of a small carrier in the current market with the failed deliveries (left figure), in the current market without the failed deliveries (middle figure), in the presence of the parcel locker network (right figure)

duration. It is noteworthy that while the reductions represent a higher percentage compared to those achieved by the small carriers, the absolute impact on small carriers is nearly twice that of the large carriers. Unlike many routes of the small carriers, we observe that some failed deliveries for the large carriers have minimal impact on their operations. This is because these deliveries are within the clusters of the remaining customers, or their removal only results in marginal changes to the delivery plans.

The city also benefits from the impacts gained through extended delivery range, particularly by the large carriers. As these carriers have larger quantity of packages to handle, locating parcel lockers in accordance with the X-minute city concept allows them to enhance their consolidation capabilities. Since these carriers can generate delivery plans for specific geographical areas, as illustrated in Figure 5, the expanded coverage enhances the effectiveness of their regional planning, leveraging consolidation to an even greater extent. This impact is particularly noticeable in terms of stop measures, as certain deliveries are in close proximity to each other. This results in less variation in driving distance compared to stop measures, although still offering considerable benefits. Particularly, while the number and duration of stops are reduced on average by 21.3%, and 12.4%, respectively, the driven distance is reduced by 7.5%. We observe that this situation intensifies in the city centre, where authorities intentionally design traffic patterns to discourage driving. The operations of these carriers in the current market often results in significant detours to reach customers. However, utilising parcel lockers eliminates this issue, making these carriers' routes much smoother and more efficient while making fewer stops along the way. This situation, however, is not observed with the small carriers. They do not encounter the same challenges with the complex traffic patterns that larger carriers do, as they have a limited number of packages to deliver in the city centre.

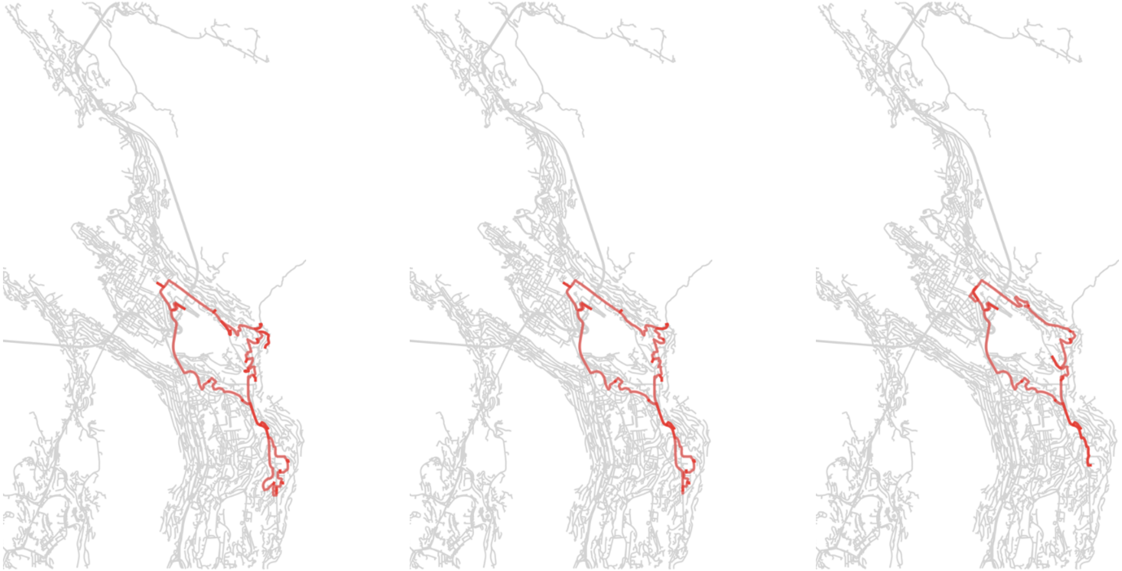

Figure 5: Operations of a large carrier in the current market with the failed deliveries (left figure), in the current market without the failed deliveries (middle figure), in the presence of the parcel locker network (right figure)

4.1 Implications for authorities

Our findings indicate that implementing a broad parcel locker network could improve city livability, particularly by mitigating some of the impacts associated with smaller carriers. Failed deliveries of these carriers impose significant costs on the city, making it necessary to facilitate their access to parcel lockers. This could be achieved by implementing carrier-agnostic parcel lockers, as we have analysed in this study, or by ensuring that smaller carriers can utilise the facilities of larger carriers in case such a setup evolves without maintaining carrier neutrality. This necessity becomes especially apparent if alternative interventions, like those suggested by Orhan et al. (2024a) to regulate the operations of small carriers, such as prohibiting small carriers from delivering within urban areas, are not pursued. We, therefore, highlight that authorities should pay attention to the operations of small carriers while deploying their X-minute city concept.

In line with existing literature, our study reveals the importance of parcel locker proximity to customers, especially for larger carriers, as it extends their delivery range. To facilitate this, policymakers should support carriers by designating public spaces for locker deployment and streamlining legal procedures, both acknowledged in the literature as challenges for carriers. For instance, providing such public spaces strategically, particularly in areas like the city centre of Bergen, would enable carriers to design routes that navigate the complexities, ultimately minimising their overall impact on the city. Implementing such measures would not only enhance carrier consolidation efficiency and reduce their impact on city livability but also ensure that residents have easy access to lockers within walking distance, aligning with the principles of the X-minute city.

Authorities may also intervene by exploring collaborative approaches, not only to enable multiple carriers to utilise parcel lockers but also to enhance carriers' operational efficiency. We observe that a considerable portion of the designated parcel lockers in Bergen are utilised by multiple carriers, while only a handful are exclusively used by one carrier. This indicates that carriers, regardless of their sizes, often visit the same locations to deliver their shipments. Therefore, fostering consolidation among carriers through additional interventions could yield significant benefits for the city, both in terms of distance and stops measures.

5 Concluding remarks

The concept of X-minute cities has received attention by a number of authorities worldwide and its deployment requires further analysis in guiding urban planners. In this study, we explore the freight distribution aspect of this concept, analysing e-commerce shipments while a dense, carrier-agnostic parcel locker network is in place. In this regard, we provide insights to authorities, enabling them to grasp the market dynamics and to identify what are essential to achieve for improving the quality of X-minute cities. Our analysis shows that implementing a broad parcel locker network would enhance the livability by reducing the negative externalities posed by freight carriers. Authorities, to improve livability, should facilitate access to parcel lockers for small carriers, and designate public spaces for locker deployment to reduce the distance between residents and the lockers, thereby increasing delivery ranges for carriers, especially larger ones. Furthermore, they should encourage consolidation among market players to reduce their overall impact on urban areas.

We reflect on directions for future research. Regulating parcel lockers to be carrier-agnostic requires a deep examination of ownership, deployment funding, and maintenance responsibilities. Further research can investigate the implementation process, including considerations such as the appropriate pricing strategies for couriers utilising lockers if authorities are responsible for their deployment. Another potential research direction could involve analysing this setting within different geographical and distributional contexts. Norwegian customers are used to retrieve their shipments from designated collection points, which is the dominant market channel for delivering goods. The implementation of parcel lockers in Bergen leads to the elimination of direct deliveries, although in a market setting where direct deliveries hold a modest market share. In markets where the proportion of direct deliveries is higher, the potential impact of parcel lockers on the livability of cities would be much greater. In this regard, one particular change that we anticipate is the increased impacts of large carriers due to higher proportion of direct deliveries and weaker consolidation options through parcel lockers. While our strategic insights likely extend to other cities, quantitative results would vary and capturing these would be helpful for authorities to make informed decisions regarding their X-minute city concept.

We acknowledge that our work is subject to limitations regarding the absence of certain data. We base the distribution patterns of all carriers on the data we gathered from PostNord. Incorporating patterns from other carriers can validate and improve the robustness of our insights for authorities. Another data limitation arises in the allocation of shipments from collection points to parcel lockers, leading us to have certain assumptions as previously discussed. Although conducting the analysis by capturing the more accurate volumes of parcel lockers would offer a more realistic representation of operations, we believe that this adjustment would minimally affect the objectives of our study. As our focus lies in capturing distance and stop measures to assess livability aspects, discrepancies in parcel locker volume would not lead to substantial changes on the driving sequences. Alterations could occur if the switch would change the goods allocation to vehicles or if new parcel lockers require visits where this was not needed previously. However, given that these shipments are handled by large carriers and their consolidation options enable regional planning, the shift would be handled with minimal adjustments to their delivery plans.

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Appendices

Table A1: Operational results of the large and small carriers in the current market operations

Carrier	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips	Number of packages
A	156.0	132.8	37.2	11.0	2020.0
B	118.0	105.8	27.4	8.0	1496.0
C	155.0	99.2	17.3	3.0	564.0
D	121.0	90.3	14.2	3.0	488.0
E	73.0	67.6	9.9	3.0	412.0
F	71.0	71.7	9.9	3.0	412.0
25 small carriers	563.0	781.5	39.5	25.0	608.0

Table A2: Operational results of the large and small carriers in the presence of the locker network

Carrier	Number of stops	Driven distance (km)	Duration of stops (h)	Number of trips	Number of packages
A	111.0	106.7	33.0	11.0	1975.0
B	81.0	82.5	22.1	8.0	1466.0
C	99.0	74.1	13.0	3.0	519.0
D	78.0	66.1	11.5	3.0	458.0
E	53.0	55.0	8.2	3.0	397.0
F	49.0	58.8	8.1	3.0	397.0
25 small carriers	452.0	659.7	33.5	25.0	488.0

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Paper IV

Multistage vehicle routing with stochastic demand and decision-dependent learning using a single scenario set

with Jaikishan Soman[a], *Benjamin S. Narum*[a], *Feng Guo*[b] *and Stein W. Wallace*[a]

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Abstract

We show to what extent it is possible to formulate multistage vehicle routing problems with uncertain demand and re-routing by repeatedly reusing a single scenario set. Under re-routing, the problem exhibits a decision-dependent information structure where demand is revealed through visiting customers, and we must ensure scenario trees adhere to the underlying information structure. The goal of the paper is not to develop efficient algorithms for such problems, but rather to show what are the necessary requirements on the problems such that a single stage- and state-invariant discretisation of uncertainty (a single scenario set) is sufficient. This extends the realism of stochastic vehicle routing problems by enabling simpler approaches to multistage formulations.

1 Introduction

Models for the vehicle routing problem with stochastic demand (VRPSD) were originally fairly straight-forward extensions of deterministic versions. Typically, such models would produce a route for each vehicle, and the vehicle would follow its route until its capacity was exhausted, return to the depot, and then resume the route where it left off (Bertsimas et al. 1990, Laporte et al. 2002). This strategy allows pre-optimising the route (and observing its cost) as opposed to re-optimising the route each time the vehicle returns to the depot. While pre-optimising the route is formulated as a two-stage stochastic program, re-optimisation at the depot requires a multistage stochastic program. We argue that representing uncertainty in parsimonious ways allows extending the realism of the two-stage VRPSD to its multistage variants in fairly straight-forward ways. Although multistage models are typically more challenging both to formulate and to solve numerically than two-stage models (King & Wallace 2024, Shapiro & Nemirovski 2005), we propose ways to mitigate this complexity by repeatedly re-using a single scenario set to construct a scenario tree and show how such a scenario set can be constructed. Our motivation is to extend VRPSD to incorporate re-routing but the techniques extend to more general setups as well.

We refer to a *route* as a sequence of customers. Exhausting the capacity may cause additional detours to the depot between customers. For VRPSD, there are three ways of determining routes (Dror et al. 1989): (i) pre-optimising the route before visiting any customers, (ii) re-optimising the route after each return to the depot, and (iii) re-optimising the route after each customer visit. The former is referred to in the literature as the *a priori optimisation* approach, while the latter two are referred to as *re-optimisation* approaches. This paper concerns with the second alternative where routes are reconsidered each time we return to the depot. Before presenting and discussing the details of the single scenario set within this context, we first provide a brief overview of the VRPSD. We refer the readers to Gendreau et al. (2016) for a broader overview. For clarity, we use the following descriptions and terminologies. We assume that a company delivers homogeneous goods at a set of customers in a transportation network, although the collection of goods is equivalent. Vehicles are limited by finite capacity and the demand of each customer is uncertain until visited. Hence, while *unvisited customers* have stochastic demand, *remaining customers* are unvisited or have some deterministic left-over demand. The *returning customer* is the one where the vehicle returns to the depot as a result of exhausting its capacity. We also use the term *failure* to refer to the exhaustion of a vehicle's capacity.

The a priori optimisation approach, which we refer to as the *pre-routing strategy*, pre-optimises the routes and adheres to them during delivery operations. It is formulated as a two-stage stochastic program where routes are fixed in the first stage, and a predetermined recourse policy is applied in the second stage when failures occur, guaranteeing the feasibility of the routes with replenishment trips. These replenishment trips can be static or dynamic in nature, which would affect how the expected cost in the second stage is calculated. Static replenishment trips are enforced by the *detour-to-depot policy* when a vehicle fails. We refer to the pre-routing strategy that uses the detour-to-depot policy for replenishment trips as the *plain* *pre-routing strategy.* Among existing strategies, some allow unlimited number of returns to the depot, others limited. Dynamic replenishment trips, on the other hand, are established by the *optimal restocking policy* (Yee & Golden 1980), focusing on a more advanced set of replenishment decisions to prevent or reduce the need to go to the same customer twice, especially if that customer is far away from the depot. The routes are fixed at the first stage, and the detour-to-depot policy is triggered in case of failure in the second stage. In addition, replenishment trips to the depot may be executed when the residual capacity is low. Note that while the models adopting the detour-to-depot and optimal restocking policies differ from each other in their use of replenishment trips (either static or dynamic in nature), the routing decisions remain static.

The re-optimisation approach, on the other hand, occurs either as generating a new route at the depot following a failure or dynamically creating the customer sequence at any location. Much of the literature in this area has concentrated on the latter, where the decision to visit the next customer (and if so, which) or to return to the depot for replenishment is given during the route execution and is formulated as a dynamic programming model. Although deciding where to go next provides a more powerful tool from an operational perspective, solving such models a large number of times is a challenging endeavour. Yang et al. (2000) report that solving the dynamic programming model for obtaining an optimal restocking policy becomes numerically intractable with more than 15 customers. As a result, the instances with more customers can only be solved heuristically through approximate dynamic programming (e.g., Novoa & Storer 2009). Such dynamic approaches, however, lack tactical aspects, such as an initial route derived through the pre-routing strategy, which captures stable plans that drivers may prefer.

Although benefiting from an initial route, the literature using pre-routing strategies primarily emphasises the implementation of more sophisticated return policies to the depot, despite also being capable of incorporating policies from a routing perspective. In this context, adjusting the customer visiting sequence each time the vehicle returns to the depot becomes a natural decision that can influence route planning. This *re-routing strategy* is clearly more effective than resuming a predetermined route since the predetermined route that foresee the customer locations where the vehicle fails is always feasible with respect to re-optimisation. However, re-optimisation models are formulated as multistage models with decision-dependent information structure, which are challenging to solve (Jonsbråten 1998). As a result, there has been relatively little emphasis on policies concerning the re-optimisation of the customer visits under the pre-routing strategy. In fact, this research gap, framed by Secomandi & Margot (2009), on optimising planned sequences under a re-optimisation recourse policy has remained as an open question until recently. In this regard, Florio et al. (2022) propose a simple recourse policy called the *switch policy*, which allows changes to the planned sequence by swapping the order of two consecutive customers during route execution. The authors compare the value of their policy to the optimal restocking one and conclude that the benefits are limited when comparing the optimal a priori solutions. These solutions are foreseeing in nature, as the planned routing sequences are generated while considering the recourse decisions. The authors also evaluate these recourse policies on routing sequences that are unforeseeable to the policies, meaning they are not optimised for any recourse decisions during planning. Instead, a set of routes is computed using a deterministic VRP algorithm and are analysed under these recourse policies. As noted by Florio et al. (2022), one might expect reasonably good VRPSD solutions with such an unforeseeing approach in practice. This is demonstrated in Florio et al. (2020) for the VRPSD with a single vehicle case.

While determining optimal a priori VRPSD solutions under a comprehensive re-optimisation recourse policy is an ideal way to move forward for the pre-routing strategy, its implementation remains highly challenging. Nevertheless, leveraging such a recourse policy, even with sequences not initially optimised for it (i.e., unforeseeing in nature), offers practical benefits and opens a door for further methodological developments. Our problem setting stems from this aspect, particularly in planning a new route for the remaining customers when the vehicle returns to the depot. In this regard, for a single vehicle, we evaluate the benefits of the re-routing strategy over the pre-routing one. Although unforeseeing in nature, this evaluation provides practical value by realising whether adjusting the customer sequence provides any benefits. This information can aid in deciding whether to keep an eye on the vehicle's visiting sequence during its operations. As will become evident later, one can identify customer locations where failure is likely valuable for considering re-optimisation at the depot. Our setup is also a natural subproblem while looking for a priori VRPSD solution that foresees re-routing, as well as the more complicated problem of an initial tactical decision of assigning customers to vehicles while foreseeing re-routing.

The replenishment trips in our problem setting occur when the vehicle fails, although other decision rules can also be employed. For instance, one can consider returning when the residual capacity of the vehicle is below a threshold, or when the distance between the current and next customer exceeds a threshold, or when the next customer is far away from the depot. Incorporating optimal restocking decisions, on the other hand, adds a layer of complexity. However, a single static representation of uncertainty can be utilised in this setting as well and we will return to this discussion.

In the remaining part of this section, we explore the information structure regarding the re-routing strategy. The subsequent sections of the paper are organised as follows: Section 2 introduces the basis on scenarios, Section 3 provides our algorithmic setup, Section 4 presents the experimental results, and Section 5 concludes the paper.

1.1 Information structure under the re-routing strategy

Re-routing models have a decision-dependent information structure in the sense that we learn, not as time goes by, but as we visit customers. Stages (in the multistage model) then enumerate returns to the depot, and the uncertainty in demand persist up to the time of exploration. Note that it is our information about the uncertain demand that changes between stages, not the demand itself.

In terms of model logic and information flow, when the vehicle returns to the depot, we know which customers have been visited, and how much was left behind at the returning customer, but *not* the demands at unvisited customers. This is our first important observation:

Observation 1 (Knowledge at the depot)**.** *When returning to the depot we know which customers have been visited, and how much was left behind at the returning customer, but not the demand at the unvisited customers.*

When a vehicle returns to the depot, this represents a new *state of information*. These information states have a discrete stage-structure since there is no decision-relevant information available between each stop at the depot (at least in the way the problem is stated). The level of information is determined by previously followed routes (i.e., decisions), and the specific realisation of demand that determines the returning customer of each trip. In a sense, the level of information we gain each time we leave the depot is stochastic since we do not know ahead-of-time which customer to return from.

Each time we leave the depot, we must consider *all* possible realisations of demand at the unvisited customers to reflect our lack of information about their specific demand. Intuitively, it seems we should be able to use the exact same representation of uncertainty (a scenario set) the next time around since nothing has changed for the unvisited customers. Which characteristics should the demand distribution exhibit for this to be valid? This leads us to the next observation:

Observation 2 (Dependent demand)**.** *If demands are dependent, the conditional demand of unvisited customers depends on the realisation of demand at already visited customers.*

Under dependent demand, knowing the realisation at some customers gives conditional information about the demand distribution of other customers. Clearly, it is then unreasonable to use the exact same representation of uncertainty. We can in principle generate new scenario sets on the fly using this dependence, but, in this paper, we are instead concerned about under which circumstances we do not have to do so. If we instead assume independence, we only learn about one customer at a time:

Observation 3 (Independent demand)**.** *If demands are independent, we learn nothing about unvisited customers based on the demand of already visited customers.*

This means the same scenario set can be used to represent the distribution at the unvisited customers. A minor adjustment of fixing the demand at the already visited customers is required to reflect that these are deterministic.

Observation 4 (Fixing known demand)**.** *Demands of visited customers must be fixed, either to zero (if demand is fulfilled) or to the left-over demand, to reflect that this is known information.*

To summarize, independent demands means that we learn one customer at a time; thus, we are exposed to the same distribution for all unvisited customers each time we return to the depot. Except for the deterministic demand at visited customers, which can be corrected for, we are exposed to an independent and identically distributed (IID) sequence of demands for all unvisited customers. These define a stochastic process. Conditional information states may then be summarized by which customers have been visited, and their remaining demand.

2 Scenarios

Scenarios are used to represent uncertainty in a parsimonious way. A *scenario set* is used to represent the distribution of a random variable, while a *scenario tree* is used to represent the distribution of a sequence of random variables (a stochastic process).

For the VRPSD problem, the uncertain demand at customers is in principle a static phenomenon since the demands themselves don't change in time. However, a re-routing strategy is exposed to a sequence of uncertain demands enumerated by each return to the depot. As previous discussed (in relation to Observation 1), the lack of knowledge about the demand of unvisited customers for each return to the depot requires treating uncertainty as a stochastic process (represented by a scenario tree). Since we treat the same uncertain phenomenon in each stage, it is intuitively reasonable that we use the same scenario set to represent the uncertain demand of all unvisited customers. Based on Observation 2 and Observation 3, this requires independent demands; otherwise, there might be in-sample learning about conditional demand distributions which violates our assumptions about the problem.

We introduce the concept of a *stagewise identical* scenario tree to describe a tree that is build using a single scenario set; in each node of the tree, the same scenario set is used to describe the conditional distribution in the consecutive stage. The representation of each consecutive stage is then conditionally identical throughout the scenario tree. In practice, such a scenario tree is constructed by appending the same scenario set to each node in a given stage of the tree (see Figure 1). For this to be valid representation of the underlying stochastic process, the underlying process must consist of a sequence of IID random variables. Note also that a stagewise identical scenario tree conserves the IID property exactly (see Section 2.1.3). Of course, other aspects of the underlying stochastic process are still subject to approximation when using a scenario tree.

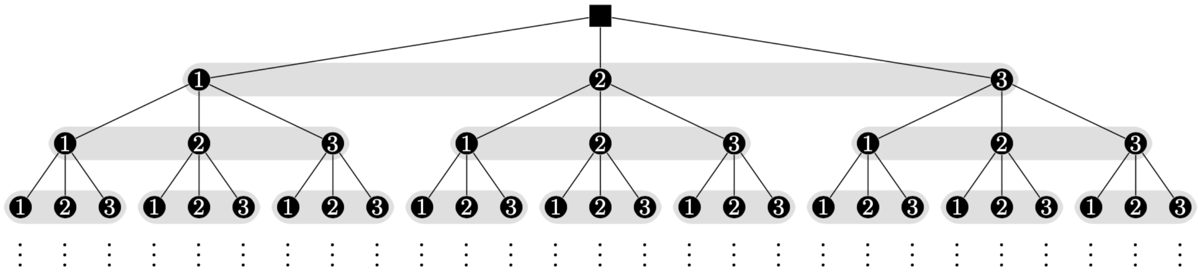

Figure 1: Illustration of a single scenario set that is repeatedly used to construct a scenario tree.

For the re-routing problem, the demand of visited customers must be fixed in all future stages. The following discussion concerns scenario trees where demands are yet unfixed and assumes such a modification is made later. Keep in mind that this modification is a result of decisions and not the uncertain phenomenon itself. While its is a fairly straight-forward modification to the scenario tree, it technically also violates the IID property. Hellemo et al. (2018) categorise this sort of stochastic program with decision-dependent uncertainty as ones where *stochastic parameters are added or removed.* This category can typically be reformulated as a traditional stochastic program, which is what the above mentioned modification accounts for.

In this section, we discuss some important aspects of dependence in scenario trees (Section 2.1), requirements for benchmarking of the re-routing strategy against the plain pre-routing strategy using scenarios (Section 2.2) and, lastly, we describe the procedure used for scenario generation (Section 2.3).

2.1 Dependence in stochastic processes and scenario trees

To discuss dependence structures for stochastic processes, we must distinguishing between *within-stage dependence* and *stagewise dependence.* Within-stage dependence refers to the dependence between different stochastic quantities within a given stage, conditional on information from past stages. Stagewise dependence refers to the dependence of a stochastic quantity in one stage compared to itself in a different stage (i.e., between stages). For example, we have stagewise dependence if demands in the future depend on realisations of demand from the past. Within-stage dependence is typically difficult to replicate exactly within a scenario set while stagewise dependence can often be dealt with quite effectively. Consider also that dependence between customers is a within-stage phenomenon while decision-dependent learning is a between-stage phenomenon.

Independence may be considered to be a special form of dependence. A stochastic quantity ξ is independent on some information state G (an event) if the conditional random variable $(\xi \mid G)$ is equivalently distributed to the original random variable ξ. Independence under distribution P may be stated as

$$(\xi \mid G) \overset{P}{\sim} \xi. \tag{1}$$

More specifically, given the distribution P, we have that

$$P\left(\xi \leq x \mid G\right) = P(\xi \leq x), \qquad \forall x \in \Xi, \tag{2}$$

where Ξ is the support of ξ.

Stagewise independence may then be stated as

$$(\xi(t) \mid \xi(t-1)) \sim \xi(t), \tag{3}$$

where $\xi(t-1)$ denotes the history of ξ up to and including stage $t-1$. Within-stage independence in stage t may be stated as

$$\left(\xi^i(t) \mid \xi^j(t)\right) \sim \xi^i(t), \qquad \forall i, j \in \mathcal{C} : i \neq j, \tag{4}$$

where $\xi^i(t)$ denotes the demand of customer i in stage t. Lastly, a stagewise identical process attains the property that

$$(\xi(t) \mid \xi(t-1)) \sim (\xi(s) \mid \xi(s-1)), \qquad \forall t, s. \tag{5}$$

A scenario tree can be stated as an alternative discrete distribution Q on the support of P and independence properties with respect to P do not necessarily hold for Q. We now consider ways of achieving good representations of independence in scenario trees which comes down to how we discretize and assign probabilities in the new distribution Q.

2.1.1 Within-stage independence

If we start out with discrete and finite marginal supports, there is one approach that always works to enforce within-stage independence:

Observation 5 (Complete enumeration)**.** *Assuming a discrete and finite support for the marginal demand distribution in each customer, independence can be fulfilled within a scenario set by complete enumeration of all combinations of the marginal outcomes.*

Essentially, this ensures each conditional information state is consistently represented. With many customers and large marginal supports, complete enumeration can lead to very large and unmanageable scenario sets. This gets worse by the resulting exponential growth in the size of the scenario tree. Hence, complete enumeration is primarily useful for benchmarking purposes on small instances.

In practice, the best we can do is to approximate within-stage independence as well as possible to be within some margin of error. This is the topic of Section 2.3.

2.1.2 Stagewise independence

Information states in our problem setting occur each time we return to the depot. Since we likely return only after having visited one or more customers, and not every realisation of a customer's demand causes a return, relevant information states are a smaller subset of the set of all information states. Not every conditional state is worth representing since the decision problem will likely not encounter all of them:

Observation 6 (Conditional enumeration)**.** *We can enumerate only the relevant conditional information states to represent conditional distributions, while other irrelevant conditional information states can be ignored.*

The critical distinction between complete and conditional enumeration is that the latter can be invoked along the way, while the former must be completed up-front and leads to redundancy. There are also advantageous in-sample properties stemming from this approach.

2.1.3 In-sample properties of stagewise identical trees

A scenario tree describes a discrete stochastic process in itself, which necessarily has different properties that the originally prescribed stochastic process it approximates, and we refer to these as *in-sample properties*. Specifically, any given scenario tree need not be in-sample IID even if the prescribed stochastic process is IID.

A particularly interesting characteristic about scenario trees constructed from a single scenario set is that they preserve the IID property *exactly*:

Observation 7 (In-sample IID)**.** *A scenario tree generated by inserting the same scenario set in each stage leads to an IID discrete stochastic process.*

This is a consequence of reusing the exact same scenario set to represent scenarios in each consecutive stage so that, by definition, the scenarios in each consecutive stage are independent of the previous information state and are identically distributed. Consider also that in-sample IID implies in-sample stagewise independence[1].

If the IID property is an important assumption for the problem at hand, it may be worthwhile to construct scenario trees that reflect this. For problems that have decision-dependent information structure, this is particularly interesting due to the following observation:

Observation 8 (In-sample distributional learning)**.** *An IID scenario tree eliminates in-sample learning of conditional distributions.*

This is a consequence of the fact that a scenario tree that is IID has no stagewise dependence, while even slight deviations from the IID property would lead to stagewise dependence that could be exploited through in-sample distributional learning. An example of a non-IID scenario tree (where each information state has a slightly different scenario set to represent the consecutive stage) is to draw new independent samples in each consecutive stage; the sampling noise means such representations deviates from being in-sample IID. Of course, the magnitude of distributional learning in such situations depends on the number of samples used in each stage, and tends to get smaller with larger samples. Since, generally, we strive to make as small scenario representations as possible to improve the computational tractability of solving decision models, using stagewise identical trees is a more effective strategy to mitigate in-sample distributional learning than, for example, using very large random samples.

2.2 Evaluating plain pre-routing strategy using scenarios

In earlier literature, objective evaluation of the plain pre-routing strategy used exact evaluation under restricted kinds of demand distributions Dror et al. (1989), while we wish to compare objective evaluations using scenarios. Using scenarios allows using arbitrary kinds of demand distributions but requires accepting there are approximation errors arising from scenario generation. For computational experiments, we wish to compare the re-routing and plain pre-routing strategies on equal grounds. This requires using scenario trees for multi-stage evaluation of the plain pre-routing strategy as well.

The plain pre-routing problem has a single stage followed by an evaluation of the predetermined route that can have multiple capacity failures. Since there are no decisions, this would be considered a *multi-period problem.* A *period* then denotes an incremental unit of time without decisions (here enumerated by returns to the depot), while a *stage* implies there must be decisions. Realisations of uncertainty within a sequence of periods can be represented by a single scenario and evaluated using single-stage evaluation. In principle, it would be possible to evaluate a plain pre-routing strategy using a single-stage evaluation where each scenario

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[1] The property of in-sample stagewise independence is also preserved in the way Stochastic Dual Dynamic Programming (SDDP) is normally set up (see Shapiro 2011)

represents the outcome in each period. The issue arises when we need to compare optimal objective values to those of a multistage problem.

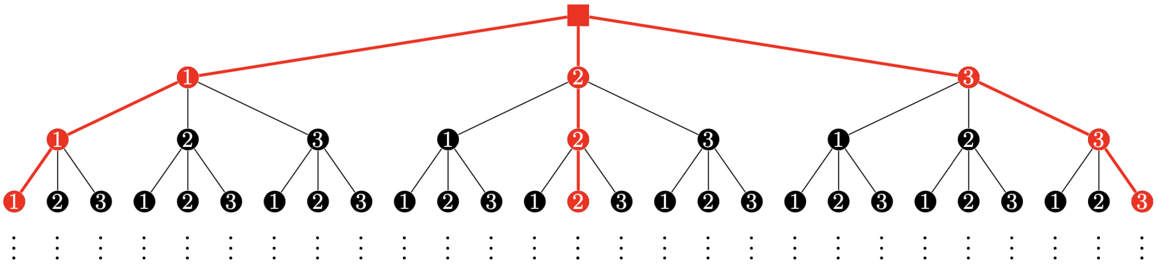

Figure 2: Comparison of multistage and single-stage evaluation using a single scenario set (in black and red, respectively). The single-stage evaluation keeps using the same scenario after each capacity failure, while the multistage evaluation reconsiders all scenarios after a failure. Overall, single-stage evaluation then uses fewer realisations.

Multistage evaluation will implicitly enumerate more realisations of uncertainty, causing a discrepancy between the two evaluation methods. This is illustrated in Figure 2. When the scenario tree branches, we enumerate outcomes conditional on the information state in the previous stage. Such realisations may not already be present in the original scenario set and causes the discrepancy between the two evaluation methods. Since the re-routing strategy requires multi-stage evaluation, the plain pre-routing strategy must use multi-stage evaluation in benchmarks as well.

2.3 Scenario generation

Scenario generation aims to reduce the within-stage dependence to approximate the assumption of independence well and to give an overall faithful representation of the prescribed distribution. Meanwhile, between-stage independence is fulfilled *exactly* by reusing the same scenario set in each branching of the scenario tree (see Section 2.1.3). The scenario set is generated by *property matching* (Høyland & Wallace 2001) (also referred to as moment matching) where we wish to enforce the first two moments and correlations in the scenario set such that they correspond to those of the prescribed demand distribution. Practically, this is achieved using the scenario reduction approach used by Narum et al. (2024).

We start with a large set of S sampled outcomes ξ_s where $s \in \{1, \dots, S\}$. These are generated using Latin Hypercube Sampling to resemble independence well initially (Homem-de-Mello & Bayraksan 2014). The scenario set is then chosen as a subset of these outcomes, assigned with probability weight $q \in [0,1]^S$ such that the prescribed properties are consistent with those of the prescribed distribution. This is solved as a linear program where the probability weights q

are decision variables, and the enforced properties are constraints. This is formulated as

$$\underset{q}{min} \quad \sum_{s=1}^{S} w_s q_s \tag{6a}$$

$$\text{s.t.} \quad \sum_{s=1}^{S} q_s \xi_s^i = \bar{\xi}^i, \quad \forall i \in \mathcal{C}, \tag{6b}$$

$$\sum_{s=1}^{S} q_s \left(\xi_s^i - \bar{\xi}^i)(\xi_s^j - \bar{\xi}^j\right) = \Sigma_{ij}, \quad \forall i, j \in \mathcal{C} : i \geq j, \tag{6c}$$

$$\sum_{s=1}^{S} q_s = 1, \tag{6d}$$

$$q \geq 0 \tag{6e}$$

where $\bar{\xi}$ are the expected demands and Σ their covariance matrix which reflects that demands are uncorrelated. The constraint (6d) ensures probabilities sum to one within the scenario set, and the weights w in the objective function (6a) should be positive to drive q towards zero. The scenario set is then given by the collection

$$\{(\xi_s, q_s) : q_s > 0, s \in \{1, \ldots, S\}\}, \tag{7}$$

of outcomes associated to non-zero probabilities in q. This results in a scenario set of maximally the same number of scenarios as there are constraints in (6), which is $|\mathcal{C}|^2 + |\mathcal{C}|/2 + 1$. To get different configurations of q that fulfil the given properties, we sample random values of the positive objective coefficients w. This is useful for the stability testing (Kaut & Wallace 2007) performed in Section 4.3.

Note that the prescribed values on the right-hand side of the constraints (6b) and (6c) are derived from the analytical distribution from which the S outcomes are sampled; technically, this may lead to infeasibility in (6) but that is unlikely if we assume S is very large. Other properties of the scenario set can be enforced in a similar fashion, like skew and kurtosis, and these may also be problem-based to achieve even more parsimonious scenario sets (Narum et al. 2024). For simplicity, we use only two moments and correlations in this paper.

3 Solution strategy

Finding solutions to re-routing models presents a great challenge since they imply that we should account for future re-routing decisions in each stage of the multistage problem. That is, multistage models incorporate a foresight of future decisions. To alleviate some of the difficulty of solving re-routing models with foresight, we present a heuristic procedure for finding solutions which relaxes the foresight of future re-routing decisions. Instead, we determine the route in each stage (conditional on current information) by solving a new plain pre-routing model each time the vehicle returns to the depot. This recursive setup is described in detail in Section 3.1.

As previously mentioned, plain pre-routing will always be out-performed by re-routing with foresight since a pre-optimised route is still feasible to a re-routing model; however, it is not necessarily optimal. Our approach represents a middle-ground that allows re-routing without the foresight of future routing decisions. It is not guaranteed that this will outperform pre-routing and, in some rare situations, may also lead to worse overall performance. To be certain, we may also directly compare the expected objective values of our approach to plain pre-routing.

Table 1: Overview of notation.

Sets	
$\mathcal{S} = \{1, \ldots, S\}$	Set of scenarios
$\mathcal{A} = \{1, \ldots, N\}$	Set of all customers
Parameters	
K	Vehicle capacity
N	Number of customers
S	Number of scenarios
p_s	Conditional probability of scenario s
ξ_s^i	Demand of customer i scenario s

3.1 Recursive setup

We introduce a recursive setup for determining the expected cost of visiting a given set of customers, where each recursion represents a stage in the multistage model. Accordingly, a recursive function first determines a route to follow, which is generated by solving the plain pre-routing model exactly using the L-shaped method of Laporte et al. (2002). It then evaluates the

```
Input: customer set $\mathcal{C}$ and scenario set $\mathcal{S}$
Output: var cost
Function recursion($\mathcal{C}$,$\mathcal{S}$):
    $\mathcal{R}$=vrpsd($\mathcal{C}$);        // generating the sequence of customers by solving the plain pre-routing model
    for $s \in \mathcal{S}$ do
        $d = 0$;                                 // initializing a variable that tracks the cumulative demand served
        for $i \in \mathcal{R}$ do
            $d = d + \xi_s^i$;                   // computing cumulative demand served
            if $d >= K$ then
                $\mathcal{S}' = \mathcal{S}$;    // reusing the same scenario set by generating a copy if a vehicle fails
                for $s' \in \mathcal{S}'$ do
                    $\xi_{s'}^i = d - K$;        // fixing the left-over demand for the returning customer
                end
                $\mathcal{C}'$=remaining_customers($\mathcal{R}, i$)
                $cost = cost + p_s \times$(distance_calculation($\mathcal{R}, i$)+recursion($\mathcal{C}', \mathcal{S}'$));    // calling the recursion
                $d = 0$;
            end
            break;
        end
        if $d > 0$ then
            $cost = cost + p_s \times$ route_cost($\mathcal{R}$);
        end
    end
    return cost                                  // obtaining the expected cost
End Function
```

Figure 3: Pseudo-code of recursion($\mathcal{C}, \mathcal{S}$)

cost in each scenario, and calls itself whenever the vehicle returns to the depot due to failure. As the customers are visited in subsequent stages, the number of remaining customers decreases gradually in each stage. The returning customer may have some (now known) left-over demand when the capacity of the vehicle is exhausted. This left-over demand is fixed within the scenario set for subsequent stages. The recursion continues until all demands are served.

Let $\mathcal{A}$ denote the set of all customers that eventually need to be visited by the vehicle, where we assume $\mathcal{A}$ to be given in advance. Now, we let $\mathcal{R}$ denote an *ordered* collection of customers which represents a route for the sequence of customers to visit. We let K denote the vehicle capacity, ξ_s^i the demand of customer i in scenario s while p_s denotes the conditional probability of scenario s. Table 1 provides an overview of the notations used.

Figure 3 presents the recursive function, recursion$(\mathcal{C}, \mathcal{S})$, which requires the customer set $\mathcal{C}$ and the scenario set $\mathcal{S}$ as its arguments. The setup is initialised by defining the customer set C as the set $\mathcal{A}$, constructing the scenario set $\mathcal{S}$ through the procedures described in Section 2.3, and setting the *cost* variable to zero. Furthermore, the setup relies on the following sub-functions for obtaining the expected cost of customer visits.

- vrpsd$(\mathcal{C})$: Solves a VRPSD with the given subset of customers $\mathcal{C}$ to generate a sequence of customers based on the plain pre-routing model.

  Input: customer subset $\mathcal{C} \subseteq \mathcal{A}$.
  Output: route $\mathcal{R}$

- remaining_customers$(\mathcal{R}, i)$: Returns the set of remaining customers in the route $\mathcal{R}$, including the returning customer i if it has a left-over demand.

- distance_calculation$(\mathcal{R}, i)$: Calculate the distance covered along route $\mathcal{R}$ until reaching the returning customer i, as well as the distance from the returning customer i to the depot.

  Input: route $\mathcal{R}$
  Output: Distance covered by route $\mathcal{R}$ up to the returning customer i, plus the distance travelled back to the depot.

- route_cost$(\mathcal{R})$: Returns the total distance of route $\mathcal{R}$.

4 Computational results

We design a series of experiments for testing the algorithmic setup with a single scenario set. These experiments enable us to compare the differences between the expected costs of the re-routing and plain pre-routing strategies as well. It is, however, important to note that our goal is not to conduct a comprehensive evaluation of the re-routing strategy, but rather to test our algorithmic setup using a single scenario set.

4.1 Instance generation

Our instances are generated using a real map of Bergen, Norway, which is a small city with complicated topography. The road network has numerous one-way streets which may cause complications and additional benefits of re-routing.

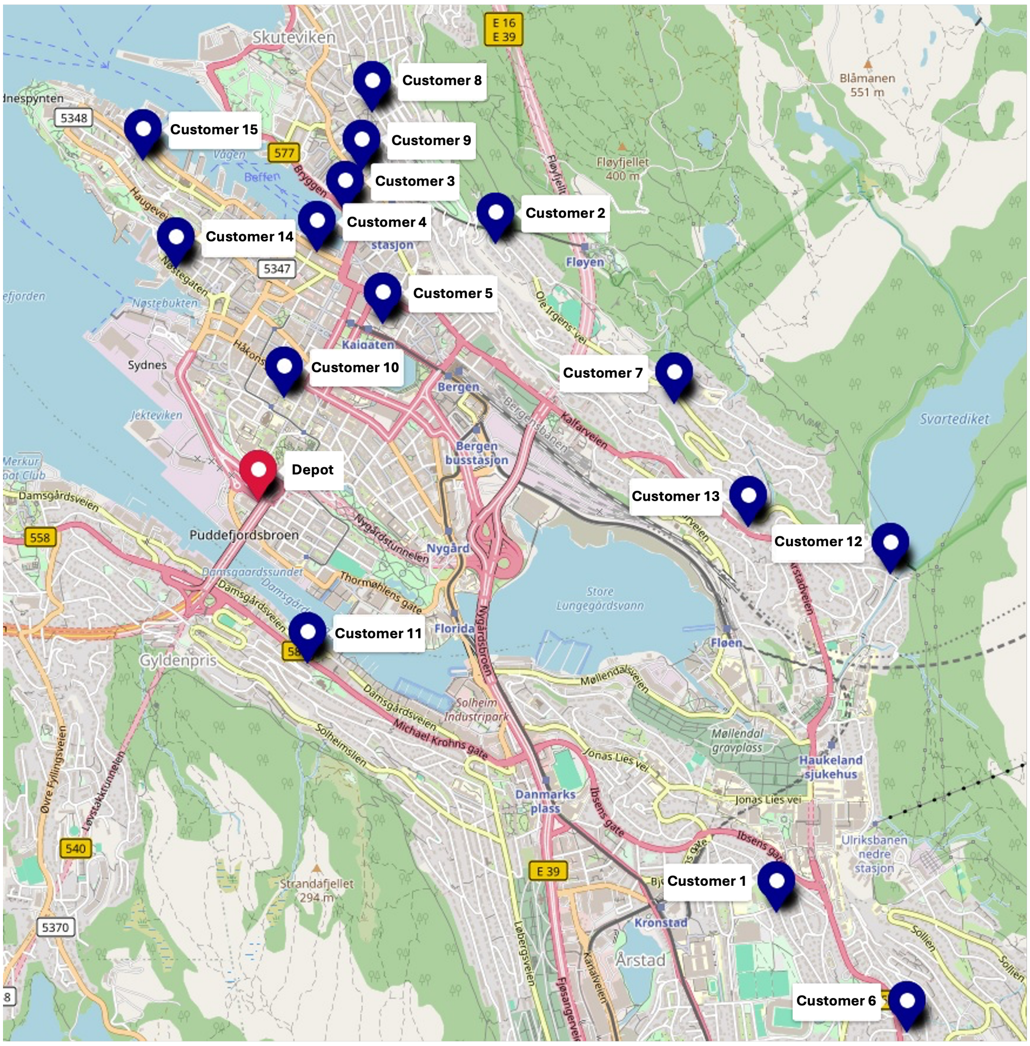

Figure 4: Bergen city map with depot and 15 customer locations

We generate instances of 5, 10, and 15 customers in accordance with the number of customers per vehicle in Florio et al. (2022). The instances are defined by selecting groups of customers. The locations of these 15 customers are displayed in Figure 4. These instances are found by selecting a subset of customers, such as Customer 1 to Customer 5, up to including all customers from 1 to 15.

Scenario generation has two major steps, sometimes these are handled at the same time in a scenario generation method, sometimes they are separated. The first is the discretisation of the marginals, the second constructing the dependence patters, possibly using a copula. We refer the readers to Chapter 4 of King & Wallace (2024) for an overview. In this article we focus only on the effects of lacking independence in the scenario set, as we now face not only the general approximation errors from discretisations (something we share with all approaches), but also an algorithmic effect from a lack of true independence. Hence, we shall focus on how serious the lack of independence might be.

We start by specifying the demand distributions to be identical among customers, using a Gamma distribution with shape parameter $\alpha = 10$ and scale parameter $\beta = 10$. We then create discrete distributions having five support points defined by the 10th, 30th, 50th, 70th and 90th percentiles of the Gamma distribution with equal probabilities of 1/5.

The vehicle capacity is set to a specific value for each instance such that we require one replenishment trip for the instance with 5 customers, and at most two replenishment trips for the other two instances to serve all customers. This restriction is only made for illustrative purposes. Our approach does not require this limitation.

4.2 Experimental setup

The models are implemented in Python (version 3.10) using the Gurobipy package. Mixed-integer programming formulations are solved using the version 12.6 Gurobi solver. Instances are solved on a 8-core machine having 16GB of RAM.

4.3 Validation

We wish to validate the effects of representing uncertainty using one single scenario set. This is achieved in several ways. We start by testing stability for the given number of scenarios.

4.3.1 In-sample test

An in-sample test was conducted using instances of 5, 10, and 15 customers. For each instance, twenty trials were performed, varying the weights w_s in the objective function (6a) randomly between 1 and 10. Given the number of rows in the linear program generating the scenario sets, the number of scenarios is 21 for the case of 5 customers, 66 for 10 customers and 136 for 15 customers. The point of the in-sample test is to check that the different scenario sets coming out of the linear program by varying w have approximately the same objective function values.

The results, including the L-shaped method applied to the plain pre-routing strategy and the recursive setup applied to both the plain pre-routing and re-routing strategies, are summarised in Table 2. We consider six instances with 5 customer case, one with 10 (Instance 6) and one with 15 (Instance 7).

We see from Table 2 that the stability is very similar for the three approaches. For the instances with 5 customers, the variation based on (max-min)/min is around 3-5% for all three, while for the 10 and 15 customer cases, the variation based on our approach is lower – around 1% rather than 2%. Note that this is *not* a test of the quality of the approaches, it only tests if the results are stable relative to the choice of scenario set. This way we know that we are not just producing noise.

Table 2: In-sample test on 5, 10 and 15 customer instances. The first six instances have 5 customers, the next 10 and the final 15 customers.

Instance	L-shaped method applied to the plain pre-routing strategy			Recursive setup applied to the plain pre-routing strategy			Recursive setup applied to the re-routing strategy		
	$\mu + 2\sigma$	**min**	**max**	$\mu + 2\sigma$	**min**	**max**	$\mu + 2\sigma$	**min**	**max**
0	21.73±0.57	21.26	22.31	21.73±0.57	21.26	22.31	21.73±0.57	21.26	22.31
1	21.25±0.44	20.77	21.64	21.26±0.44	20.77	21.65	20.96±0.34	20.59	21.25
2	24.94±0.45	24.41	25.18	24.94±0.45	24.41	25.18	23.59±0.48	23.01	23.81
3	23.92±0.59	23.39	24.49	23.93±0.59	23.40	24.52	23.93±0.59	23.40	24.52
4	17.75±0.28	17.45	18.11	17.75±0.28	17.45	18.11	17.75±0.28	17.45	18.11
5	25.08±0.34	24.73	25.48	25.09±0.35	24.75	25.51	25.03±0.34	24.71	25.47
6	26.73±0.41	26.41	27.08	26.81±0.14	26.65	26.90	25.34±0.13	25.20	25.43
7	31.30±0.24	31.02	31.52	31.28±0.12	31.12	31.38	30.00±0.12	29.85	30.10

4.3.2 Approximations of within-stage independence

We refer to Table 3 for this section. The six instances are the same as the six first instances in Table 2. First we check that the recursive setup presented in Section 3.1 produces the same results as the L-shaped method of Laporte et al. (2002) for the plain pre-routing strategy for all the instances using *complete enumeration*. The results highlight that the objective values obtained from both methods are identical for the plain pre-routing strategy.

As previously outlined, our chosen scenario generation method aims to reduce the within-stage dependence in the scenario sets (in addition to handling the marginals, of course) by enforcing zero correlations in the scenario sets. As independence among customer demands is one of our primary assumptions, it is important to understand and quantify the impact of not fully capturing independence.

While lacking perfect independence is common in all scenario generation methods, the results obtained from the L-shaped method and the recursive setup for the plain pre-routing strategy indicate a marginal variation in route lengths when moment-matching is used rather than complete enumeration. But the variation is not large, and well within the data and scenario errors. Note that the sign of the error is not important as lack of independence in the scenario sets can cause errors in both directions.

4.4 Case study

We next analyse how large the benefit of re-routing strategy is compared to plain pre-routing strategy. Accordingly, we utilise instances from the previous sub-section. The comparison using the first instance with 5 customers show that re-optimising the customer sequence once the vehicle returns back to the depot result in a savings of 6.9% (using complete enumeration for

Table 3: Comparison between complete enumeration and moment matching for the expected route length. All instances have 5 customers.

Instance	L-shaped method applied to the plain pre-routing strategy			Recursive setup applied to the plain pre-routing strategy			Recursive setup applied to the re-routing strategy		
	Complete enumeration (in km)	Moment matching (in km)	Change (%)	Complete enumeration (in km)	Moment matching (in km)	Change (%)	Complete enumeration (in km)	Moment matching (in km)	Change (%)
0	20.98	21.05	0.33	20.98	21.05	0.33	19.54	19.83	1.48
1	21.43	21.20	-1.08	21.43	21.10	-1.56	21.09	20.82	-1.30
2	22.61	22.51	-0.44	22.61	22.51	-0.44	21.04	21.05	0.05
3	21.61	21.69	0.37	21.61	21.69	0.37	21.60	21.69	0.41
4	17.77	17.85	0.45	17.77	17.85	0.45	17.77	17.85	0.45
5	25.11	24.54	-2.32	25.11	24.57	-2.20	25.02	24.53	-2.00

accuracy). Characterising the savings requires us to follow the routes followed by the vehicle. The sequence of the a prior route identified through the plain pre-routing strategy is given by "Depot - Customer 1 - Customer 2 - Customer 3 - Customer 4 - Customer 5 - Depot". We observe that capacity exhaustion at Customer 4 is the main driver of these savings, as the path from Customer 4 to Customer 5 requires a lengthy trip that is imposed by the traffic pattern of Bergen. This lengthy trip can be avoided by re-optimising the sequence. As illustrated in Figure 5, the left figure shows the route taken by a vehicle after its first failure for a given scenario following the plain pre-routing strategy, while the right figure shows the route under the re-routing strategy. While the path of "Depot - Customer 4 - Customer 5 - Depot" provides a driving distance of 6.9 km, switching the customer order reduces the distance to 5.2 km, a difference 24.6%. This suggests that, while following a tactical a priori route, specific customer locations, where the capacity of the vehicle is exhausted, may trigger the need to re-optimise the remaining customers. This characterisation points out that one can observe considerable savings and operational strategies of the re-routing strategy even through a small-sized example.

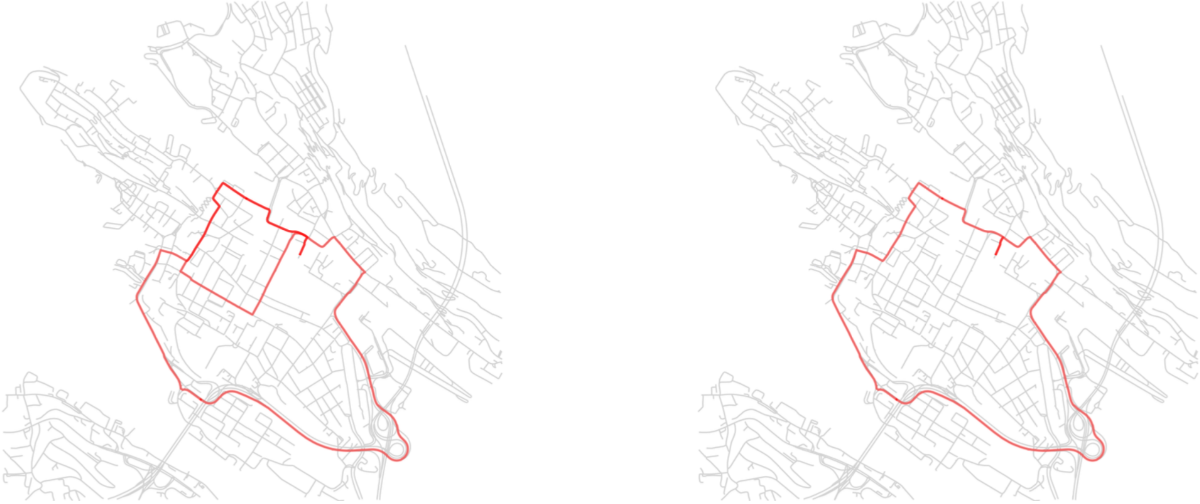

Figure 5: Routes generated after the first failure for a given scenario under the plain pre-routing strategy (left figure) and the re-routing strategy (right figure) for the instance with 5 customers

Note that the re-routing strategy, in this case, acts like the switch policy, as there are only two customers within the route. In practice, a driver may alter the route with experience when there are few customers, as like in this situation. However, this becomes more challenging with larger instances.

Solving larger problems with the recursive setup, however, poses numerical challenges, as it requires solving a plain pre-routing model at each branch to obtain the visiting sequence. Since developing special VRP algorithms for these large problems is outside the scope of this paper, we test our single scenario set approach by substituting the VRPSD with the TSP, thereby generating the visiting sequence much faster. Generating these sequences by solving a TSP, while evaluating the recourse decisions on the planned sequences that do not incorporate foresight, is an approach adopted in Florio et al. (2022) as well. We observe savings from the re-routing strategy of 5.5% and 4.1% for the 10 and 15 customer cases, respectively. Figure 6 and Figure 7 illustrate the route differences observed while evaluating the plain pre-routing and re-routing strategies using the TSP for the instances with 10 and 15 customers, respectively. The routes are modified with the re-routing strategy, resulting in benefits from changing the sequence of customer visits. Additionally, in a scenario where two failures occur for the instance with 10 customers, a customer initially served on the route created after the second failure in the plain pre-routing strategy is instead included in the route between the first and second failures in the re-routing strategy. This adjustment is made because this customer better fits the route compared to another customer, improving overall efficiency.

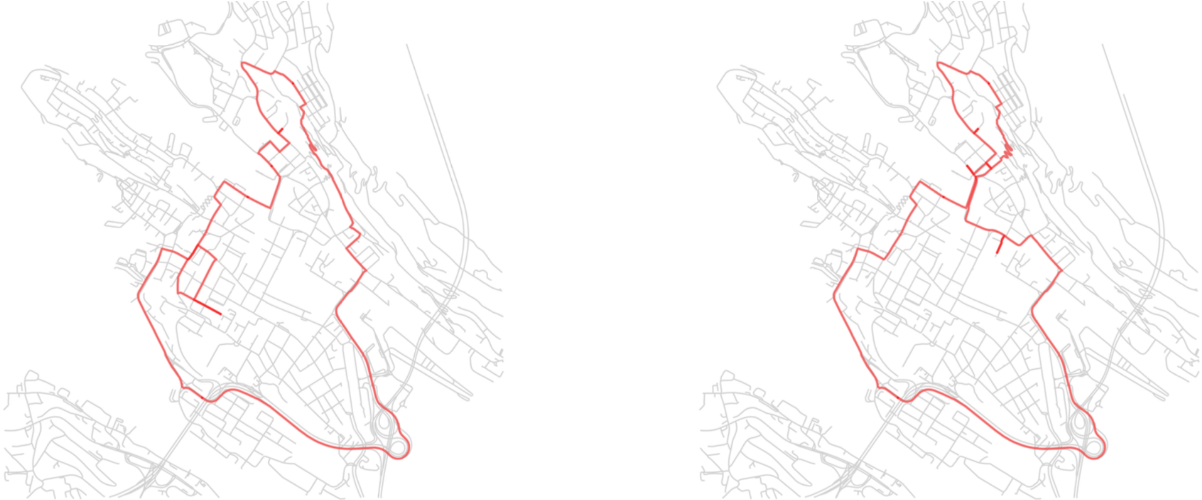

Figure 6: Routes generated after the first failure for a given scenario under the plain pre-routing strategy (left figure) and the re-routing strategy (right figure) for the instance with 10 customers

5 Concluding remarks

Motivated by extending the realism of stochastic vehicle routing problems to their multistage variants, we proposed using a single scenario set repeatedly to formulate multistage vehicle routing problems with uncertain demand and decision-dependent learning. In this regard, we discussed the conditions under which this approach would be valid, described how to construct such a scenario set, and tested it with a recursive algorithmic setup.

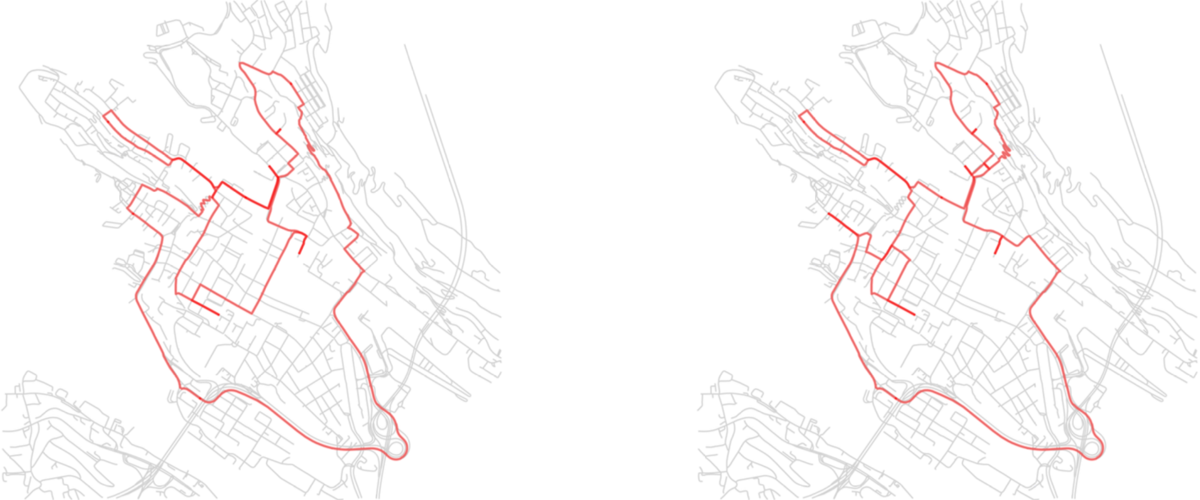

Figure 7: Routes generated after the first failure for a given scenario under the plain pre-routing strategy (left figure) and the re-routing strategy (right figure) for the instance with 15 customers

Before concluding, we reflect on limitations of our study and provide directions for further research. Normally, in an optimisation problem, when re-optimisation is used, the situation would improve (or remains the same) since the initial solution would be feasible in the re-optimisation case. Although this happens in our numerical tests, due to the rule of returning when capacity is exhausted, the effect of re-routing can actually be the opposite, particularly when the vehicle capacity is exhausted more than once. Note that this is re-routing without initially taking into account that re-routing would take place. The situation would always improve for models that account for future re-routing decisions.

Although we used property matching as our scenario generation method, we acknowledge that other construction methods may also meet the conditions we outlined. However, we emphasise the importance of using a method that at least produces zero correlations, even if it does not achieve full independence. Randomly sampling a limited number of scenarios is insufficient, as it focuses on the whole distribution but not on the correlation.

Regarding the solution procedure, it may be tempting to suggest the following. If several scenarios lead to a return at the same customer, the different amounts left behind amounts to a (conditional) probability distribution. And this is indeed the distribution of how much will be left at that customer, given that we end up returning from that customer. However, if we use this as a distribution of remaining demand at the customer when we calculate, we would contradict the information structure of the problem. When we are back at the depot, we *know* how much is left behind, it is not uncertain. In fact, using this as a distribution would lead to a *pessimistic* bound as we assume we know less than we really do. If we use this pessimistic bound, there are two important observations: The first is that instead of returning from some customer, scenario by scenario, we only need to return once from each customer where we can run full. This certainly reduces the computational burden. The second is that while the scenarios are still valid for the remaining customers, a way to combine the existing scenarios with the left-behind distribution at the returning customer needs to be identified, to end up with a valid (independent) scenario set.

The following idea might seem like a good way to create bounds: Use the smallest or largest amount left behind at a customer as a deterministic left-behind demand. The first will reduce the expected amount to collect, the second will increase it. However, even with less to collect, there can be more driving as the change can have unpredictable effects on where returns take place. This is caused by our tests that do not foresee future re-routing decisions. So in other contexts, in particular with re-routing that has foresight, this idea of min or max left behind, will produce bounds.

As a last point, the replenishment trips in our approach are executed whenever the vehicle fails, although more sophisticated replenishment trips could be employed, such as those established in optimal restocking policies. If this approach is adopted, the single static representation of uncertainty still remains valid; however, the corresponding VRPSD methodology has to consider the possibility of returning to the depot after visiting each customer. In this regard, one must account for all information states, unlike in our setting where only a relevant and smaller subset of information states is needed.

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