Consolidation of Urban Freight Transport – Models and Algorithms

Zur Erlangung des akademischen Grades Doctor rerum politicarum (Dr. rer. pol.)
Genehmigte Dissertation von Christian Friedrich aus Kassel
Tag der Einreichung: 31.01.2022, Tag der Prüfung: 03.05.2022

1. Gutachten: Prof. Dr. Ralf Elbert
2. Gutachten: Prof. Dr. Felix Weidinger
Darmstadt

TECHNISCHE UNIVERSITÄT DARMSTADT

Fachbereich Rechts- und Wirtschaftswissenschaften
Fachgebiet Unternehmensführung und Logistik

Consolidation of Urban Freight Transport – Models and Algorithms

Accepted doctoral thesis by Christian Friedrich

1. Review: Prof. Dr. Ralf Elbert
2. Review: Prof. Dr. Felix Weidinger

Date of submission: 31.01.2022
Date of thesis defense: 03.05.2022

Darmstadt

Acknowledgments

Die vorliegende Arbeit markiert das Ende eines langen Weges und entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Fachgebiet Unternehmensführung und Logistik der Technischen Universität Darmstadt. Während meiner Zeit am Fachgebiet hatte ich neben der Betreuung verschiedener Lehrveranstaltungen die Möglichkeit, an vielen abwechslungsreichen und spannenden Themen des städtischen Güterverkehrs, aber auch an Projekten aus anderen Gebieten – sei es die Simulation von Containerterminals oder die der Produktionsplanung von Haarpflegemitteln – zu arbeiten. Dabei konnte ich mich nicht nur fachlich, sondern auch menschlich weiterentwickeln.

An dieser Stelle möchte ich gerne einer Reihe von Personen danken, die mich in den vergangenen Jahren unterstützt und begleitet haben. Zuallererst möchte ich mich bei meinem Doktorvater Prof. Dr. Ralf Elbert, der mir die Möglichkeit gab, an seinem Fachgebiet zu promovieren, bedanken. Insbesondere möchte ich mich auch für die Unterstützung und das entgegengebrachte Vertrauen bedanken, welches mir große Freiheiten bei der Durchführung meiner Forschung ermöglichte. Darüber hinaus möchte ich mich auch bei Prof. Dr. Felix Weidinger dafür bedanken, dass er das Zweitgutachten für meine Dissertation übernimmt.

Mein Dank gilt außerdem auch meinen ehemaligen Kolleginnen und Kollegen am Fachgebiet, mit denen ich nicht nur einen regen fachlichen Austausch erlebte, sondern auch viele schöne Erinnerungen über die eigentliche Arbeit hinaus verbinde, wie etwa die gemeinsamen Fachgebietstreffen oder die Reisen zu Konferenzen und Kongressen. Ein großer Dank geht an meine ehemaligen Büronachbarinnen Anne Friedrich und Tessa Sarnow für ihre Hilfsbereitschaft und die sehr gute Arbeitsatmosphäre. Ein besonderer Dank geht auch an Daniel Reinhardt für den fachlichen Austausch zum Thema Simulation und die hilfreiche Unterstützung bei vielen Fragestellungen im universitären Lehr- und Forschungsbetrieb. Ebenso gilt mein Dank meinen Kolleginnen und Kollegen Katrin Coleman, Michael Gleser, Jan-Karl Knigge, Roland Lehner, Jan Philipp Müller, Johannes Rentschler, Felix Roeper, Jessica Schwarz, Dominik Thiel, Jan Tränkner und Julia Wenzel, mit denen es stets eine kollegiale Zusammenarbeit gab.

Besonderer Dank gilt natürlich auch meiner Familie für die Unterstützung, die ich durch sie erfahren habe. Insbesondere möchte ich mich bei meiner Mutter Heike für ihre unermüdliche Unterstützung bedanken. Ebenso gilt mein Dank meinem Vater Peter, meiner Schwester Anne, sowie ihrem Freund Martin. Abschließend möchte ich auch meiner Freundin Yogeswari meinen Dank dafür aussprechen, dass sie mich während der stressigen letzten Monate ertragen und liebevoll unterstützt hat.

Darmstadt, Januar 2022 Christian Friedrich

Abstract

Urban freight transport is an indispensable component of economic and social life in cities. Compared to other types of transport, however, it contributes disproportionately to the negative impacts of traffic. As a result, urban freight transport is closely linked to social, environmental, and economic challenges. Managing urban freight transport and addressing these issues poses challenges not only for local city administrations but also for companies, such as logistics service providers (LSPs). Numerous policy measures and company-driven initiatives exist in the area of urban freight transport to overcome these challenges. One central approach is the consolidation of urban freight transport. This dissertation focuses on urban consolidation centers (UCCs) which are a widely studied and applied measure in urban freight transport. The fundamental idea of UCCs is to consolidate freight transport across companies in logistics facilities close to an urban area in order to increase the efficiency of vehicles delivering goods within the urban area. Although the concept has been researched and tested for several decades and it was shown that it can reduce the negative externalities of freight transport in cities, in practice many UCCs struggle with a lack of business participation and financial difficulties. This dissertation is primarily focused on the costs and savings associated with the use of UCCs from the perspective of LSPs. The cost-effectiveness of UCC use, which is also referred to as cost attractiveness, can be seen as a crucial condition for LSPs to be interested in using UCC systems.

The overall objective of this dissertation is two-fold. First, it aims to develop models to provide decision support for evaluating the cost-effectiveness of using UCCs. Second, it aims to analyze the impacts of urban freight transport regulations and operational characteristics on the cost attractiveness of using UCCs from the perspective of LSPs. In this context, a distinction is made between UCCs that are jointly operated by a group of LSPs and UCCs that are operated by third parties who offer their urban transport service for a fee. The main body of this dissertation is based on three research papers. The first paper focuses on jointly-operated UCCs that are operated by a group of cooperating LSPs. It presents a simulation model to analyze the financial impacts on LSPs participating in such a scheme. In doing so, a particular focus is placed on urban freight transport regulations. A case study is used to analyze the operation of a jointly-operated UCC for scenarios involving three freight transport regulations. The second and third papers take on a different perspective on UCCs by focusing on third-party operated UCCs. In contrast to the first paper, the second and third papers present an evaluation approach in which the decision to use UCCs is integrated with the vehicle route planning of LSPs. In addition to addressing the basic version of this integrated routing problem, known as the vehicle routing problem with transshipment facilities (VRPTF), the second paper presents problem extensions that incorporate time windows, fleet size and mix decisions, and refined objective functions. To heuristically solve the basic problem and the new problem variants, an adaptive large neighborhood search (ALNS) heuristic with embedded local search heuristic and set partitioning problem (SPP) is presented. Furthermore, various factors influencing the cost attractiveness of UCCs, including time windows and usage fees,

are analyzed using a real-world case study. The third paper extends the work of the second paper and incorporates daily and entrance-based city toll schemes and enables multi-trip routing. A mixed-integer linear programming (MILP) formulation of the resulting problem is proposed, as well as an ALNS solution heuristic. Moreover, a real-world case study with three European cities is used to analyze the impact of the two city toll systems in different operational contexts.

Zusammenfassung

Städtischer Güterverkehr ist ein wichtiger Bestandteil von Städten. Doch im Vergleich zu anderen Verkehrsträgern trägt der städtische Güterverkehr unverhältnismäßig stark zu den negativen Auswirkungen des Verkehrs bei. Infolgedessen ist der städtische Güterverkehr eng mit sozialen, ökologischen und wirtschaftlichen Herausforderungen verbunden. Das Management des städtischen Güterverkehrs stellt nicht nur lokale Stadtverwaltungen, sondern auch Unternehmen wie beispielsweise Logistikdienstleister vor Herausforderungen. Zahlreiche politische Maßnahmen und unternehmensgetriebene Initiativen zielen auf die Bewältigung dieser Herausforderungen im städtischen Güterverkehr ab. Ein zentraler Ansatz ist die unternehmensübergreifende Konsolidierung von städtischen Gütertransporten. Diese Dissertation konzentriert sich auf städtische Konsolidierungszentren (Urban Consolidation Centers (UCC)), die eine weithin untersuchte und angewandte Maßnahme im städtischen Güterverkehr darstellen. Der Grundgedanke von UCCs besteht darin, den Güterverkehr unternehmensübergreifend in Logistikeinrichtungen in der Nähe eines Stadtgebiets zu konsolidieren, um so die Effizienz der in das Stadtgebiet einfahrenden Lieferfahrzeuge zu erhöhen. Obwohl das Konzept seit mehreren Jahrzehnten erforscht und erprobt wird und gezeigt wurde, dass es die negativen externen Effekte des Güterverkehrs in Städten verringern kann, kämpfen in der Praxis viele UCCs mit mangelnder Beteiligung von Unternehmen und finanziellen Schwierigkeiten. Diese Dissertation konzentriert sich in erster Linie auf die Kosten und möglichen Einsparungen, die mit der Nutzung von UCCs aus der Perspektive von Logistikdienstleistern verbunden sind. Die Kosteneffizienz der Nutzung von UCCs, die auch als Kostenattraktivität bezeichnet wird, kann als eine maßgebliche Voraussetzung für das Interesse von Logistikdienstleistern an der Nutzung von UCC-Konzepten gesehen werden.

Die vorliegende Dissertation verfolgt zwei übergeordnete Ziele. Erstens sollen Modelle entwickelt werden, die als Entscheidungsunterstützung für die Bewertung der Kosteneffizienz von UCCs dienen. Zweitens sollen die Auswirkungen von städtischen Güterverkehrsvorschriften und operativen Aspekten auf die Kosteneffizienz der Nutzung von UCCs analysiert werden. In diesem Zusammenhang wird dabei zwischen UCCs unterschieden, die gemeinsam von einer Gruppe von Logistikdienstleistern kooperativ betrieben werden, und UCCs, die von Dritten betrieben werden, die den Transport von Gütern in Städte gegen eine Gebühr anbieten. Der Hauptteil dieser Dissertation stützt sich auf drei Forschungsbeiträge. Der erste Beitrag konzentriert sich auf kooperativ-betriebene UCCs, die von einer Gruppe von kooperierenden Logistikdienstleistern betrieben werden. Hierfür wird ein Simulationsmodell zur Analyse der finanziellen Auswirkungen auf einzelne Logistikdienstleister vorgestellt. Ein besonderer Schwerpunkt liegt dabei auf städtischen Güterverkehrsvorschriften. Anhand einer Fallstudie wird ein kooperativ-betriebenes UCC für verschiedene Szenarien mit unterschiedlichen Güterverkehrsvorschriften analysiert. Der zweite und dritte Beitrag verfolgen eine andere Sichtweise auf UCCs, indem sie sich auf von Dritten betriebene UCCs konzentrieren. Im Gegensatz zum ersten Beitrag wird im zweiten und dritten Beitrag ein Bewertungsansatz vorgestellt, bei dem die Entscheidung über die Nutzung von UCCs in

die Tourenplanung von Logistikdienstleistern integriert wird. Neben der grundlegenden Version dieses integrierten Tourenplanungsproblems, das als Vehicle Routing Problem With Transshipment Facilities (VRPTF) bekannt ist, werden im zweiten Beitrag Problemerweiterungen vorgestellt, die Zeitfenster, Entscheidungen über Flottengröße und deren Zusammensetzung sowie neue Zielfunktionen beinhalten. Um das Grundproblem und die neuen Problemvarianten heuristisch zu lösen, wird ein Adaptive Large Neighbourhood Search (ALNS) mit eingebetteter lokaler Suche und einem Mengenzerlegungsproblem zur Rekombination der Touren vorgestellt. Außerdem werden verschiedene Faktoren, wie beispielsweise Zeitfenster und UCC-Nutzungsgebühren, welche die Kostenattraktivität von UCCs beeinflussen, anhand einer Fallstudie analysiert. Der dritte Beitrag erweitert den Ansatz des zweiten Beitrags um eine tagesbasierte und einfahrtsbasierte City-Maut und ermöglicht es mehrere Touren pro Fahrzeug und Tag zu planen. Für das resultierende Problem wird ein gemischt-ganzzahliges lineares Optimierungsproblem formuliert und eine ALNS Meta-Heuristik präsentiert. Zudem werden anhand einer Fallstudie mit drei europäischen Städten die Auswirkungen der beiden Stadtmauten in verschiedenen operativen Situationen analysiert.

Contents

List of Figures

List of Tables

List of Algorithms

List of Abbreviations

2E-VRP	Two-echelon vehicle routing problem
2E-VRP-CO	Two-echelon vehicle routing problem with covering options
ALNS	Adaptive large neighborhood search
CEP	Courier, express, and parcel
CVRP	Capacitated vehicle routing problem
CVRPPAD	Capacitated vehicle routing problem with pick-up and alternative delivery
FPDP	Flexible parcel delivery problem
FSASP	Fixed sequence arc selection problem
FSM	Fleet size and mix vehicle routing problem
FSMTW	Fleet size and mix vehicle routing problem with time windows
FSMTWTF	Fleet size and mix vehicle routing problem with time windows and transshipment facilities
HoReCa	Hotels, restaurants, and cafés
LEZ	Low emission zone
LNS	Large neighborhood search
LRP	Location-routing problem
LRPTW	Location-routing problem with time windows
LSP	Logistics service provider
MD-2E-VRPDO	Multi-depot two-echelon vehicle routing problem with delivery options
MILP	Mixed-integer linear programming
MTMP-FSMTWTF	Multi-trip multi-path fleet size and mix vehicle routing problem with time windows and transshipment facilities
MTVRP	Multi-trip vehicle routing problem
MTVRPTW	Multi-trip vehicle routing problem with time windows
OSM	OpenStreetMap
PM	Particulate matter
PRP	Pollution-routing problem
RP	Research proposition
RQ	Research question
RRA	Record-to-record acceptance
RVND	Randomized variable neighborhood descent
SDL	Shared delivery location
SPP	Set partitioning problem

SPPRC	Shortest path problem with resource constraints
TA	Threshold acceptance
UCC	Urban consolidation center
ULEZ	Ultra-low emission zone
VRP	Vehicle routing problem
VRPDO	Vehicle routing problem with delivery options
VRPHLB	Vehicle routing problem with heterogeneous locker boxes
VRPHRDL	Vehicle routing problem with home and roaming delivery locations
VRPPSDL	Vehicle routing problem with private and shared delivery locations
VRPRDL	Vehicle routing problem with roaming delivery locations
VRPTF	Vehicle routing problem with transshipment facilities
VRPTW	Vehicle routing problem with time windows
VRPTWTF	Vehicle routing problem with time windows and transshipment facilities

1 Introduction

Today, more than half of the world's population lives in cities, and further growth of this share is expected (World Bank, 2021). As urbanization accelerates around the world, the transport of goods within, to, and from cities increases as well. Associated with this are negative social, environmental, and economic challenges. This dissertation focuses on the consolidation of urban freight transport, as a measure to address these challenges. In doing so, this dissertation provides models and algorithms for decision support.

This chapter begins with Section 1.1, which provides an introduction to the research area of urban freight transport, its associated challenges, and the concept of urban freight consolidation. Subsequently, Section 1.2 presents the research setup of this dissertation. First, the research scope is described, then the overall research objective, the research questions (RQs), and the research design and structure of the dissertation are explained. Finally, Section 1.3 concludes with a theoretical classification explaining which research disciplines the research of this dissertation pertains to.

1.1 Research Motivation

Our world today is characterized by a high degree of urbanization. In 2020, 56.2 % of the world's population lived in cities (World Bank, 2021). In the future, the global share of the urban population is expected to grow even further to 68.4 % by 2050 (United Nations, 2019). Meanwhile, the proportion of the urban population in the European Union is already higher today, at around 75 % in 2020 (World Bank, 2021). The high proportion of the urban population is also associated with a concentration of economic activity and demand for consumer goods in urban areas. It is estimated that about 80 % of the global gross domestic product is generated in cities (Grubler et al., 2012). Along with the economic activity and demand for goods in urban areas also comes a demand for urban freight transport. In Great Britain, for example, approximately 56 % of all goods transported by heavy trucks domestically started and ended in urban regions in 2018 (Department for Transport, 2019). In contrast, only 2 % of goods transported had their origin and destination in rural areas (Department for Transport, 2019).

There are a number of definitions of urban freight transport in the literature. A basic definition, given by Ogden (1992, p. 15), states that urban freight transport denotes *"[...] the movement of things (as distinct from people), to, from, within and through urban areas."* Thereby, urban freight transport not only fulfills the function of supplying goods to the inhabitants of a city but is also a necessary factor for the economic activities in cities (Crainic et al., 2009). Although urban freight transport is fundamental to the functioning of cities and urban regions (Ogden, 1992; Allen et al., 2000; Crainic et al., 2009), there are also negative externalities associated with urban freight transport that can have a large impact on city residents. These economic, environmental, and societal negative external effects include, for example, congestion, increased traffic accidents, noise emissions, and pollutant emissions (OECD, 2003; Anderson et al., 2005). Given the typically larger and heavier vehicles used in freight transport, the impact of urban freight transport is often shown to be disproportionate to that of passenger transport (Anderson et al., 2005). For example, Coulombel et al. (2018) show that although urban freight transport accounts for only a small share of vehicle kilometers in Paris (8 %), it emits up to 30 % of the pollutant emissions. Heavy-duty vehicles, in particular, emit two to five times more emissions than light-duty vehicles, depending on the type of pollutant. According to the calculations of Coulombel et al. (2018), emissions from urban freight transport cause billions of euros in environmental social costs each year in the Paris region alone. The calculations of the German Federal Environment Agency, shown in Figure 1.1, present a similar result. Although light and heavy-duty vehicles, which are usually used in freight transport, account for only 13.2 % of the kilometers driven on urban roads in Germany, they are responsible for approximately 24.7 % of CO_2 emissions, 34.8 % of NO_x emissions, and 36 % of the particulate matter (PM) emissions (Douglas et al., 2020).

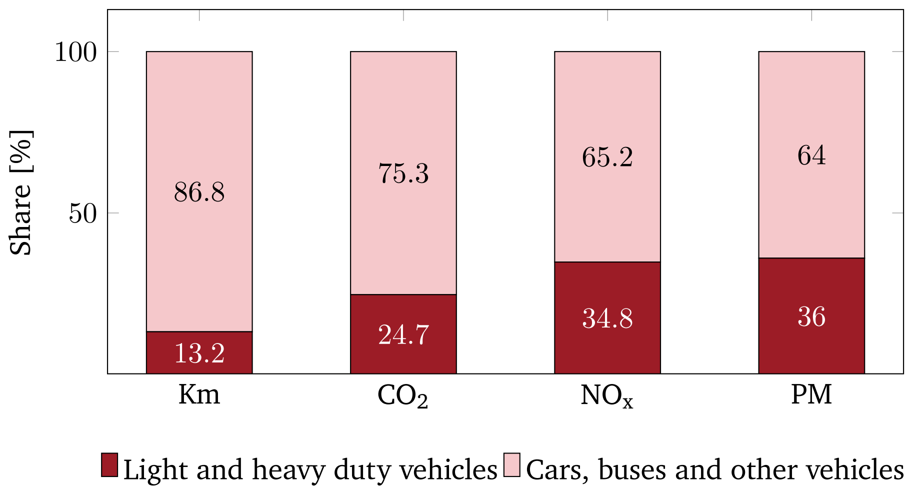


Figure 1.1: Share of light- and heavy-duty vehicles in kilometers driven, air pollutant emissions, and CO_2 emissions on urban roads in Germany 2018. Adapted from Douglas et al. (2020).

In addition to its environmental and societal impacts, urbanization and urban freight transport also pose challenges from a business perspective. Especially logistics service providers (LSPs)[1] that operate in urban areas face challenges arising from the complex urban environment. Rose et al. (2016), distinguish between physical and societal urban environmental pressures for LSPs. Physical pressures affect the efficiency of urban freight transport and encompass challenges related to constrained space, finite resources, and saturated infrastructure. Examples include limited logistics and parking spaces (Rose et al., 2016; de Carvalho et al., 2019; Aljohani and Thompson, 2020a), qualified labor shortages (Rose et al., 2016), and congestion (Anderson et al., 2005; Aljohani and Thompson, 2020a). Often, these infrastructure and spatial challenges are exacerbated by the presence of historic city centers, which are common in European cities, for instance. Societal

[1] Throughout this dissertation, the term LSPs is used to encompass all actors performing transport operations, as their challenges are comparable. In addition to LSPs per se, this consequently also includes carriers and suppliers who perform their own transport operations.

pressures, in contrast, result from the interaction with other urban stakeholders, such as residents and local administrations.

Due to its manifold challenges, urban freight transport is of interest to both private companies (e.g., LSPs and retailers) as well as public administrations. On both sides, a wide range of approaches and measures exist to overcome these challenges. Local administrations address the negative impacts of urban freight transport with a number of policy measures, ranging from infrastructure measures to regulatory measures, such as vehicle access restrictions and time windows (Muñuzuri et al., 2005). On the other hand, there are also a number of company-driven measures. These company-driven measures include technological and operational improvements regarding the vehicles and planning processes, as well as cooperation-based approaches (Anderson et al., 2005; Quak, 2008).

One approach that is pursued from both a public and a business perspective to make urban freight transport more efficient and thus more sustainable is the concept of urban consolidation centers (UCCs). UCCs refer to transshipment facilities for the bundling of urban freight transport (Browne et al., 2005). There are various types of UCCs, including UCCs operated separately or jointly by a group of actors. The overall goal of UCCs is to increase the efficiency of urban freight transport by aggregating less-than-truckload shipments across companies. As such, UCCs act as a decoupling point between urban and non-urban freight transport operations. By transshipping their goods at a UCC for a fee, LSP can avoid entering congested urban areas and increase their efficiency. UCCs, in turn, can sort and consolidate shipments from different LSPs and then transship them to smaller and more environmentally friendly vehicles to deliver them to the urban receivers (Browne et al., 2005; Allen et al., 2012). The receivers of the goods (e.g., retail shops), in turn, can also benefit from the UCC. For example, through value-added services offered by the UCC (Browne et al., 2005; van Rooijen and Quak, 2010). Thus, in theory, UCCs offer the opportunity to address environmental and social challenges of urban freight transport on the one hand, and the operational challenges of companies on the other.

The idea of consolidating urban freight transport from different LSPs in a transshipment facility and its application in practice can be traced back as far as the 1940s (Holguín-Veras et al., 2020). During the last three decades, a large number of UCC projects and pilot studies have been launched worldwide. Allen et al. (2012) identified 114 UCC projects and pilot studies in 17 countries. However, despite some initial success, many of the UCC projects have either not progressed beyond a feasibility or pilot study, or have failed over time (Allen et al., 2012). A frequently given reason for this failure is the lack of financial viability of the projects (Allen et al., 2012; Kin et al., 2016). Often, this lack of financial viability is attributed to the failure to secure sufficient commitment from LSPs and receivers to use the scheme (van Rooijen and Quak, 2010; Browne et al., 2005; van Duin et al., 2010). Similarly, Björklund and Johansson (2018) argue that logistics management-oriented aspects, such as collaboration between actors and cost-benefit analyses, are often not sufficiently considered. Albeit these issues, UCCs remain a highly relevant topic for urban freight transport as they can be found in various European cities. Furthermore, when surveyed in 2020, 100 out of 178 cities in Germany responded that they believe the potential of UCCs to be high or rather high for freight transport in their city (Douglas et al., 2020).

Urban freight transport in general and UCCs in specific are well-established research areas in the field of transport research and business administration. Indeed, UCCs are among the most studied measures in urban freight transport research (Lagorio et al., 2016; Dolati Neghabadi et al., 2019). Within this field, the research on UCCs is considered to be fragmented and transdisciplinary (Björklund and Johansson, 2018). Research on UCCs, therefore, spans several topics, including the operations of UCCs (see e.g., Lebeau et al., 2015; van Heeswijk et al., 2019b), stakeholder management (e.g., Nordtømme et al., 2015), and environmental and economic evaluations (e.g., Mepparambath et al., 2021; Janjevic and Ndiaye, 2017b). As Lagorio et al. (2016) conclude, the interest in urban freight transport research has shifted in recent years from the mere description of urban freight transport to the identification of key performance indicators and methods for ex-ante evaluation. Likewise, research regarding the evaluation of UCCs has increased over the years. However, even though the UCC concept was introduced several decades ago, quantitative model-based research to evaluate the cost benefits of UCCs remains still scarce. Moreover, the decision-making and planning problems of actors involved in UCCs are rarely addressed in the literature.

1.2 Research Setup

This section describes the setup of the research presented in this dissertation. In doing so, the scope of the research, the overall objective as well as the formulated RQs, and the structure of the dissertation are addressed.

1.2.1 Research Scope

In the following, the scope of the research presented in this dissertation is delineated. The first aspect that defines the scope of the research is the considered sector and type of goods transported. Urban freight transport is composed of different heterogeneous sectors which are characterized by the goods transported and their specific requirements, as well as the employed logistics and transport systems (see e.g., Danielis et al., 2010; Sánchez-Díaz, 2017). One way to divide the urban freight transport market is to distinguish it into the retail, courier, express, and parcel (CEP) sector, hotels, restaurants, and cafés (HoReCa), construction, and waste sectors (MDS Transmodal Limited, 2012). Many studies show that there are significant differences regarding the requirements and design of logistics and transport operations in individual sectors (see e.g., Cherrett et al., 2012). For instance, the types of goods transported and subsequently, the vehicles and equipment used can vary considerably between the sectors. The HoReCa sector, for example, often involves the transport of specialized or perishable goods which require special vehicle and handling characteristics, such as temperature-controlled vehicles (Danielis et al., 2010; Verlinden et al., 2020). Waste transport, in turn, is characterized by different types of waste, which often cannot be transported together, and specialized processes and transport systems (Asefi et al., 2019). Furthermore, even within a separate sector, such as the HoReCa sector, the requirements, and employed logistics and transport systems can vary largely (Danielis et al., 2010; Verlinden et al., 2020).

Although there are also efforts in other sectors (e.g., construction and HoReCa sectors), the consolidation of urban freight transport and the use of UCCs is usually considered for freight transport in the retail sector of non-perishable goods (Browne et al., 2005; Allen et al., 2012; Panero et al., 2011). This prevalent focus on retailing of non-perishable goods can be attributed to a number of factors. First, sectors, such as the construction and HoReCa sectors, often involve goods that require specialized handling and transport equipment (e.g., bulk goods, hazardous goods, or perishable goods) (Lundesjö, 2019; Danielis et al., 2010; Morganti and Gonzalez-Feliu, 2015). For UCCs, however, it can be difficult to handle a wide range of goods and to accommodate the specific handling and storage requirements, such as required for perishable goods (Browne et al., 2005). Consequently, focusing on a sector without special requirements regarding the temperature control of the goods simplifies the operations of a UCC. In addition, LSPs may be reluctant to transship their temperature-sensitive goods to UCCs. For example, Stathopoulos et al. (2012) report that LSPs expressed concerns regarding UCCs to ensure the quality of fresh and frozen products. Paddeu et al. (2018) also conclude that the transport of perishable goods could be a barrier to the operation of UCCs. Moreover, a survey of municipalities in Germany by the Federal Ministry for the Environment also shows that food distribution was only ranked fourth out of five in terms of urban freight transport challenges perceived by municipalities, as it is often considered to be already highly optimized (Douglas et al., 2020). However, some specialized UCCs were attempted, such as the food hub in Parma and the construction logistics UCC in Hammarby, Sweden (Morganti and Gonzalez-Feliu, 2015; Allen et al., 2007). Second, retailers, especially independent retailers using decentralized logistics systems, are often supplied through multiple less-than-truckload deliveries from different LSPs and wholesalers (Cherrett et al., 2012; Blanco and Fransoo, 2013; Aljohani and Thompson, 2020b). Therefore, consolidation benefits could be achieved by bundling deliveries (Cherrett et al., 2012). Moreover, deliveries to retailers are often performed by small and medium LSPs which only have relatively few deliveries per city (Olsson and Woxenius, 2014).

Due to the reasons explained above, the focus of the research in this dissertation is on deliveries to retailers of non-perishable goods. Thereby, the research is limited to the delivery of palletized goods and similar-sized shipments, such as roll containers, the delivery of which is generally handled by LSPs rather than courier and express service providers. Although some of the points also apply to the CEP sector, it is not considered in this dissertation, because the CEP sector is dominated by a few large service providers, and efficient network structures already exist due to the very large delivery volumes (Ducret, 2014). Due to this, CEP service providers usually already operate their own inner-city distribution centers.

The second aspect that defines the scope of the research is the type of UCC studied. Over the years, various types and business models for UCCs have been developed and implemented in practice. A detailed overview of the different types of UCCs is given in Subsection 2.2.3 in Chapter 2. In addition to area-based UCCs that supply a city or urban area, there are also specialized UCCs that supply only a specific location, such as an airport or a construction site. Furthermore, UCCs can also be distinguished by the type of actors, such as LSPs or receivers, which are the customers of the UCC. Similarly, a distinction can be made between UCCs being operated jointly by a group of actors (e.g., LSP-led) and UCCs that are operated by third-parties (i.e., users and operators or owners of the UCC are different). The research in this dissertation is focused on UCCs in the traditional sense that serve an entire city or a sub-area of a city. The rationale for this selection is that this type of UCC is the most common in practice and also presents the greatest challenges in terms of operation and financing (Allen et al., 2012). Furthermore, similar to many UCCs in practice, only LSPs are considered as the decision-makers regarding the use of UCCs. This can be attributed to the difficulty of quantifying the cost benefits of UCCs for receivers, as there is, for example, only little knowledge and data on the cost benefits of mandating the use of UCCs and outsourcing value-added services to UCCs (van Heeswijk et al., 2020). Lastly, both jointly-operated

UCCs and third-party UCCs are considered.

Two other aspects that define the scope of research for this dissertation are the elements of the supply chain and the geographic boundaries considered when studying urban freight transport and UCCs. The research in this dissertation is primarily concerned with the concept of UCCs from the perspective of LSPs. As in most studies on urban freight transport, only a section of the supply chain is considered, namely only the section from the warehouse or depot of the LSPs to the receiver of the goods. Upstream processes, such as the collection of goods from shippers, which may be located in distant regions or even overseas, and the associated line-haul transport are not under consideration in this dissertation. However, as mentioned earlier, the term LSPs used in this dissertation also includes suppliers that provide their own transport services. Unlike other studies, this dissertation expands the geographic scope, by considering the freight transport processes of LSPs in an entire region including multiple towns and suburbs. As van Heeswijk et al. (2016) note, many studies on UCCs and urban freight transport suffer from the weakness that they only consider processes within the boundaries of the city under study. Therefore, when analyzing the operations of LSPs, only the subset of customer requests from receivers within the city or UCC service area under study is considered. Customer requests hereby refer to transport requests for the delivery of a shipment from a central depot to a receiver. Several authors in the literature, however, indicate that LSPs often operate in a wider geographic area and may deliver to receivers in multiple towns and cities in one tour, if possible (see e.g., Olsson and Woxenius, 2014; Verlinde et al., 2012; Eren Akyol and de Koster, 2018). For this reason, the geographic scope is expanded in this research to include the freight transport operations within an entire region.

Finally, the research in this dissertation is primarily centered on urban freight transport in Europe. Although UCC schemes exist around the world, they have been implemented and studied mainly in Europe (Allen et al., 2012). While the developed models and algorithms could also be applied in other settings, the focus on Europe is particularly evident in the exclusive consideration of European cities and regions in the real-world studies presented in this dissertation.

In summary, the scope of research in this dissertation is limited to UCCs serving retailers of non-perishable goods within a city or urban area. In particular, UCCs are considered from the perspective of LSPs. Hence, freight transport is considered from the depot of the LSPs and it is assumed that LSPs can decide whether they want to use the service of UCCs for their urban deliveries or not. In this context, the entire freight transport operations within a region, including transport to suburbs and towns adjacent to urban areas, are taken into account for LSPs.

1.2.2 Research Objectives and Questions

The implementation of UCCs in practice is, as indicated in Section 1.1, often characterized by a lack of financial viability and participation of LSPs. In addition, there is only limited quantitative model-based research on the cost benefits of UCCs in the literature. Especially the influence of urban freight transport regulations and operational characteristics received only little attention. Motivated by this gap, the overall objective of the research in this dissertation is twofold: First, the dissertation aims to develop models and solution algorithms to support the evaluation of the cost-effectiveness of using UCCs from the perspective of LSPs. Second, it aims to provide quantitative insights into the impact of urban freight transport regulations and operational characteristics on the cost attractiveness of UCCs for LSPs. Cost attractiveness in this context can be defined as the cost savings that LSPs can achieve by using a UCC while maintaining their required quality of service. Therefore, for a UCC to be cost-attractive for a LSP, the cost of using the UCC must not exceed the savings that can be achieved by using the UCC, such as time and distance savings or toll costs (Marcucci and Danielis, 2008; Janjevic and Ndiaye, 2017b).

In order to determine the cost attractiveness of UCCs and support the decision-making of LSPs, a distinction is made between jointly-operated and third-party UCCs. For third-party UCCs, a particular focus is placed on integrating the decision to use third-party UCCs into the vehicle routing of LSPs. In this integrated planning problem, LSPs not only decide the size and composition of their fleet, the assignment of customer requests to vehicles, and the order of their visits, but they can also decide whether and which customer requests should be transshipped to which UCC. By modeling the proposed integrated planning problem and providing an efficient solution algorithm, LSPs should be able to make more refined economic decisions about the use of UCCs. By analyzing the various influencing factors, local administrations and UCC operators, in turn, can gain a better understanding of how supporting policies and operational characteristics affect the cost attractiveness of using UCCs for LSPs with different operational characteristics. To address the aforementioned research objectives, four RQs are formulated.

The first research gap addressed in this dissertation relates to approaches for evaluating the cost attractiveness of UCCs that serve an urban area from the perspective of LSPs. Many studies on UCCs are characterized by a narrow focus and several simplifications. One simplification is the limited consideration of urban freight transport regulations. Although urban freight transport regulations are a popular policy measure applied by local administrations, their presence is often neglected or given only limited consideration in UCC studies. Related to this is the typically narrow geographic scope, where only freight transport within a UCC's service area is considered and the remaining transport operations and customer requests of LSPs are disregarded. This is problematic, in that LSPs could serve customers in multiple cities and suburbs, and that UCCs even often serve only part of an urban area (e.g., the Gnewt Cargo UCC in London served only the historic center the City of London (Browne et al., 2011)). Consequently, delivery vehicles from LSPs might deliver to multiple parts of an urban area or different cities in a day, and only some customer requests of a vehicle trip might be feasible to be transshipped to a UCC. Thus, by not considering the overall transport operations of LSPs in a region, overarching effects resulting from urban freight transport regulations are missing in the evaluation of UCCs. A further research gap pertains to the modeling of transport costs and decisions to UCC. Transport costs are often based on cost approximations instead of results from vehicle routing procedures when evaluating UCCs. Likewise, when analyzing the cost attractiveness of UCCs for LSPs simplifications regarding the transshipment decisions are made and it is rarely differentiated between different types of UCCs. These research gaps give rise to the first RQ, which is divided into two subquestions:

RQ 1: *How can the cost attractiveness of UCCs be evaluated for LSPs, taking into account urban freight transport regulations?*

- **RQ 1.1:** *How can the cost attractiveness of jointly-operated UCCs be strategically evaluated for all participating LSPs, taking into account urban freight transport regulations?*
- **RQ 1.2:** *How can the cost attractiveness of third-party UCCs be evaluated operationally from the perspective of an individual LSP, taking into account urban freight transport regulations?*

By emphasizing the importance of considering urban freight transport regulations when evaluating UCCs, RQ 1 aims to address the shortcomings resulting from simplifications found in the literature on UCCs. In doing so, a distinction is made between UCCs that are jointly operated by a group of LSPs and UCCs that are operated by third parties and offer their service to LSPs for a fee. RQ 1.1 addresses the evaluation of the cost attractiveness of jointly-operated UCCs. To evaluate the cost attractiveness of jointly-operated UCCs for LSPs, both the transport processes of the LSPs and the handling and transport processes of the jointly-operated UCC must be taken into account. In addition, a strategic planning horizon can be assumed for the LSPs, since the initiation of a UCC is associated with significant setup costs. To evaluate the cost attractiveness of this type of UCC, a simulation model considering urban freight transport regulations is proposed. With this model, different regulatory scenarios can be analyzed to evaluate the cost attractiveness for each participating LSP. A unique feature of this model is that the costs of using a UCC depend on the total operating cost incurred by the jointly-operated UCC during the planning period. RQ 1.2 focuses on the evaluation of the cost attractiveness of third-party UCCs. In the case of third-party UCCs, unlike for jointly-operated UCCs, LSPs do not have to make a long-term commitment to using a UCC and can decide individually for each customer request whether a UCC should be used, given a known transshipment fee per customer request. To evaluate this type of UCC from the perspective of individual LSPs, sensitivity analyses are proposed based on the obtained solutions from integrated vehicle routing problems (VRPs) that consider transshipment decisions and urban freight transport regulations.

The second research gap relates to the decision-making of LSPs regarding the use of UCCs. In past research, it is assumed that LSPs either tranship all or none of their urban deliveries to a single UCC (see e.g., Teo et al., 2015; Firdausiyah et al., 2019). Thereby, the decision for or against the use of a UCC is made by comparing the (estimated) routing costs of both options. This simplifying blanket approach can thus be solved with standard vehicle routing algorithms but has the disadvantage that the results are limited to the two possible courses of action only. Insights from practice, however, suggest that this all-or-none blanket approach does not reflect the real-world needs and behavior of LSPs. For example, a survey conducted by Stathopoulos et al. (2012) indicates that LSPs interested in using a UCC show only interest to transship some and not all of their possible customer requests. Further support for this is provided by Köhler (2004), who reports that LSPs that participated in a cooperative urban consolidation scheme in Kassel tended to use the scheme predominantly for unattractive customer requests. Some reasons for the unattractiveness of customer requests may be for example characteristics of their delivery location (e.g., unloading infrastructure, vehicle access restrictions) or mandated customer requirements (e.g., time windows). Moreover, the cost benefits of using a UCC for customer requests might vary on the volume of customer requests, as the fee that LSPs must pay to transship customer requests to a UCC is usually based on the quantity or volume to be delivered (Janjevic and Ndiaye, 2017a). Finally, the decision to transship individual customer requests could also be influenced by the overall workload of the LSPs. If delivery volumes fluctuate seasonally, UCCs could be used to cope with spikes in demand by transshipping a portion of urban customer requests to reduce driver workload. Another aspect is that in previous research, usually only a single UCC is studied and thus only one transshipment option exists for the customer requests. If, however, multiple UCCs are serving the same city or parts of it, the transshipment decisions become more complex to be handled with a blanket approach. Thus, in summary, a blanket decision to use UCCs for all or no customer requests without considering their specifics could lead to inefficiencies and higher costs for LSPs. An alternative, approach to addressing the decision to use third-party transshipment facilities, such as UCCs, can be found in the integration of the transshipment decisions into the vehicle route planning of LSPs. This integrated routing problem, referred to as the vehicle routing problem with transshipment facilities (VRPTF) (Baldacci et al., 2017), allows to decide for each customer request individually whether to use a UCC. Through this decision on an individual customer request basis, it is possible for LSPs to transship only a portion of their customer requests to a UCC or to split their customer requests across different UCCs. So far, however, this problem has only been addressed by assuming simplifications (e.g., no urban freight transport regulations, homogeneous fleets, only distance-based costs) and using exact solution approaches with high computation times. Consequently, these gaps give rise to RQ 2, which is divided into three subquestions:

RQ 2: *How can the integrated routing problem of LSPs, which features the decision of whether and which customer requests to transship to which third-party UCC, be solved heuristically?*

> **RQ 2.1:** *How can the integrated routing problem be solved heuristically considering time windows and heterogeneous fleets?*
>
> **RQ 2.2:** *How can the integrated routing problem be modeled and solved heuristically considering city toll schemes and multi-trips?*
>
> **RQ 2.3:** *How do the proposed heuristic solution algorithms perform for the problem variants of this integrated routing problem?*

RQ 2 addresses the integration of the decision to use third-party UCCs into the vehicle route planning of LSPs and aims to provide decision support for LSPs. Assuming that LSPs can decide for each customer request individually whether to use a UCC, RQ 2 investigates how this decision can be integrated into vehicle routing. In this context, the integrated approach pays particular attention to urban freight transport regulations that could affect the cost attractiveness of UCCs. Since the resulting integrated problem is very complex – especially for real-world variants and attributes – RQ 2 focuses on the development of efficient heuristic algorithms for solving the resulting planning problem. Subquestion RQ 2.1 focuses on how to solve the VRPTF heuristically. In this context, extensions to consider time window constraints and heterogeneous fleets are proposed. Moreover, new objective functions featuring duration-based and fixed vehicle costs are presented. Subquestion RQ 2.2 extends the problem further, by integrating two city toll schemes and the possibility to use vehicles for multiple trips per day. Moreover, a mathematical formulation for the problem is presented. Lastly, subquestion RQ 2.3 addresses the question of how the heuristic solution methods perform for the different problem variants of the VRPTF. In the course of this, the solution quality of the algorithms and their runtimes are compared with exact approaches and other heuristics on benchmark instances for the VRPTF and its variants as well as instances of related problems.

With the two different approaches to model the decision to use UCCs, the question arises as to how the results differ between the two approaches. This involves, first, examining how routing plans and usage of third-party UCCs differ. Second, it includes the analysis of the cost differences between using the integrated routing approach and using the blanket approach. In summary, this led to RQ 3, which is divided into two subquestions:

RQ 3: *How does the integration of UCC transshipment decisions into vehicle routing affect the transport plans of LSPs compared to a blanket decision approach?*

RQ 3.1: *How does the cost attractiveness of UCCs change for LSPs, compared to a blanket decision approach?*

RQ 3.2: *How do the overall transport costs of LSPs differ between the integrated routing approach and the blanket decision approach?*

RQ 3 aims to compare the solutions provided by the integrated routing approach with those obtained by a blanket decision approach. While the integrated routing approach includes the decision regarding the use of UCCs into the vehicle routing, the blanket decision approach sets all customer requests to be either transshipped to a UCC or to be served directly and selects the option with the lower routing costs. Subquestion RQ 3.1 seeks to demonstrate how the cost attractiveness of UCCs, and hence their usage, differs between the two approaches. RQ 3.2, by contrast, intends to provide insight into the cost savings that LSPs can possibly achieve through the use of the more complex integrated approach, compared to the simplifying blanket approach. To answer both questions, solutions resulting from the integrated approach are compared for various factor level combinations with those obtained by a blanket approach using a real-world case study.

The fourth and final research gap addressed in this dissertation arises from the common presence of regulations, the heterogeneity of operational characteristics, and the interaction between these two aspects in the context of UCCs. As the review of Lebeau et al. (2017) illustrates, many UCCs in practice are or have been indirectly supported by urban freight transport regulations. In fact, UCCs could be even initiated in response to urban freight transport regulations. In addition to time window restrictions, which are among the most common regulations used by local administrations (Quak and de Koster, 2007), urban freight transport regulations commonly encompass city toll schemes and vehicle-based access restrictions (e.g., based on the vehicle weight or size) (see e.g., Sadler Consultants Europe GmbH, 2021). Although regulations are frequently mentioned in the context of UCCs in the literature, there is little research on quantifying the impact of regulations on the cost attractiveness of UCCs. If at all, regulations are only analyzed within the service area of the UCC under study. However, as Quak and de Koster (2007) and Eren Akyol and de Koster (2018) show for time windows, the effects of regulations oftentimes cannot be analyzed in isolation from the remaining freight transport operations outside of the regulation area. Because, for example, if customers in more than one city or area are supplied in a single trip, regulations in one area may affect also the deliveries to other areas and therefore impair the overall transport efficiency. Similar to the studies on time windows, Hiermann et al. (2019) illustrate how four different city toll schemes affect the fleet and operations of LSPs when delivering to customers inside and outside of city toll areas. Consequently, to gain insight into the cost attractiveness of UCCs, the impact of urban freight transport regulations must be examined in the overall context of the geographic region in which LSPs operate. Moreover, the impacts of urban freight transport regulations have only been studied assuming that LSPs make blanket decisions regarding the use of UCCs.

Together with urban freight transport regulations, the operational characteristics of urban freight transport play an important role. As described earlier in Subsection 1.2.1, urban freight transport is characterized by its heterogeneity even within a single sector, such as the retail sector. Accordingly, some operational characteristics, such as the delivery volume per stop, and vehicle characteristics, have previously been studied in the context of UCCs (see e.g., Janjevic and Ndiaye, 2017b; Estrada and Roca-Riu, 2017). However, these studies either did not consider urban freight transport regulations at all or considered them only to a limited extent (e.g., in terms of geographic scope or factor levels). To obtain a more generalized understanding of the impact of urban freight transport regulations on the cost attractiveness of UCCs, it is necessary to account for different operational characteristics. Operational characteristics that influence the cost attractiveness of UCCs include, for example, the fee charged for the use of UCCs, the number and type of customer requests per LSP, and the type of vehicle fleet employed. Therefore, to extend the knowledge of how urban freight transport regulations and operational characteristics of urban freight transport affect the cost attractiveness of UCCs for LSPs, RQ 4 is presented:

RQ 4: *How do urban freight transport regulations and operational characteristics affect the cost attractiveness of UCCs for LSPs?*

- **RQ 4.1:** *Which impact do urban freight transport regulations (time windows, city tolls, vehicle-based restrictions) have on the cost attractiveness of jointly-operated UCCs for LSPs?*
- **RQ 4.2:** *How do time windows, UCC usage fees, customer request sizes, and the employed fleet affect the cost attractiveness of third-party UCCs for LSPs?*
- **RQ 4.3:** *How do per-day and per-entrance city tolls affect the cost attractiveness of third-party UCCs for LSPs*?

To address the aforementioned research gaps and to shed light on the combined effects of urban freight transport regulations and operational characteristics on the cost attractiveness of UCC usage, RQ 4 is divided into three subquestions. RQ 4.1 focuses on jointly-operated UCCs and analyzes how urban freight transport regulations (time windows, city toll, vehicle-based restrictions) affect the cost attractiveness of jointly-operated UCCs for the participating LSPs using a simulation study. In contrast, RQ 4.2 and RQ 4.3 address the impact of urban freight transport regulations and operational characteristics on the cost attractiveness of third-party UCCs. RQ 4.2 aims to investigate how time windows, UCC usage fees, customer request sizes, and the employed fleet affect the cost attractiveness of UCCs for LSPs. RQ 4.3 aims to analyze the impact of per-day and per-entrance city tolls on the cost attractiveness of third-party UCCs for LSPs under various operational settings (e.g., UCC usage fees). Both subquestions are answered using heuristic solution algorithms and sensitivity analyses featuring real-world data.

1.2.3 Outline

The research in this dissertation is divided into six chapters, three of which are based on independent research articles. Figure 1.2 outlines the overall structure of this dissertation. Chapter 1 contains the introduction, which motivates the research topic, delineates the scope of research, and details the research objective, RQs, and structure of the dissertation. In addition, a brief classification of the research presented in this dissertation is provided. Chapter 2 provides the theoretical background to the research in this dissertation. It begins with a comprehensive overview of urban freight transport and urban freight transport policy in general, followed by a detailed overview of the concept of UCCs. In this process, the motivation for establishing UCCs and the operational challenges of UCCs that have been identified both in practice and literature are briefly addressed. Moreover, a classification of UCCs and a classification of planning problems in the context of UCCs are provided, and the literature on quantitative models for evaluating UCC concepts is reviewed. Following the overview of the concept of UCCs, the chapter presents an overview of VRPs in the

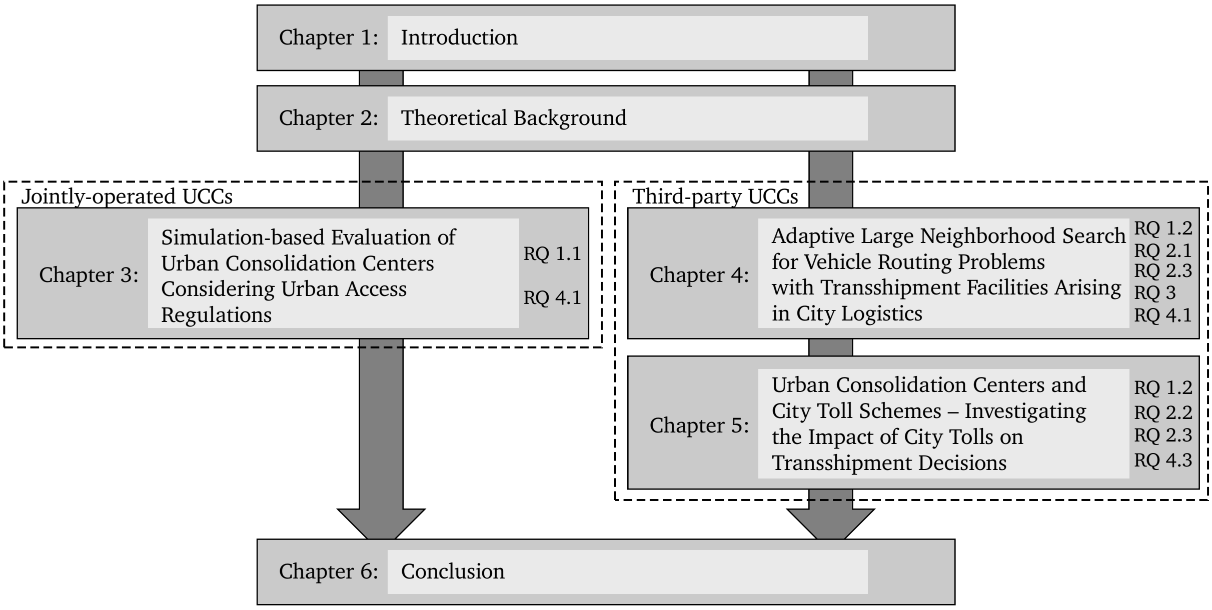


Figure 1.2: Overview of the research design and dissertation structure.

context of urban freight transport. Lastly, the chapter concludes with a brief description of the derivation of the overall research design.

The following three chapters are dedicated to answering the RQs described above and are each based on a research paper. Chapter 3 presents the first paper, which focuses on jointly-operated UCCs and is titled *Simulation-based Evaluation of Urban Consolidation Centers Considering Urban Access Regulations*. The paper is characterized by a holistic view that encompasses both the operations of LSPs and the UCC they jointly operate and provides a framework for scenario-based evaluation of this type of UCCs. In this way, both the cost impact for participating LSPs and the impact on the number of vehicles used and kilometers driven can be studied for different operational characteristics and regulatory conditions. Using a case study, for each participating LSP, the costs of delivering without the use of a UCC are compared to the costs arising from using a jointly-operated UCC. In this context, three urban freight transport regulation scenarios featuring time window constraints, per-day city tolls, and vehicle-based access restrictions are considered. Chapter 3 thus answers RQ 1.1 and RQ 4.1.

Chapter 4 is based on the paper titled *Adaptive Large Neighborhood Search for Vehicle Routing Problems with Transshipment Facilities Arising in City Logistics*. It focuses on third-party UCCs, where the decision to use UCCs is integrated into the vehicle routing of LSPs. Thus, contrary to Chapter 3 the decision to use a UCC can be made individually for each customer request. Due to this focus, the scope is limited to the operations of LSPs. Deliveries emanating from the UCCs to the urban receivers are not considered. Chapter 4 answers RQ 1.2 by presenting a UCC evaluation approach based on heuristic solutions of an integrated VRP. Subsequently, question RQ 2.1 is answered by presenting an adaptive large neighborhood search (ALNS) heuristic to solve the newly proposed problem variants. RQ 2.3, in turn, is answered by providing comparisons of the ALNS with other approaches for closely related problems. Furthermore, a comparison between the solutions of the integrated approach and the blanket approach, where either all or no customer requests are transshipped, is presented using a real-world case study to answer RQ 3. Finally, Chapter 4 also aids in answering RQ 4.2 by providing insights from the aforementioned real-world case study.

Chapter 5 represents the third research paper titled *Urban Consolidation Centers and City Toll Schemes – Investigating the Impact of City Tolls on Transshipment Decisions* and extends the work of Chapter 4. In light of RQ 2.2, Chapter 5 focuses on extending the heuristic solution method of Chapter 4 to consider two types of city toll schemes and multiple trips per vehicle and day. To answer RQ 4.3, Chapter 5 investigate the impact of per-day and per-entrance city tolls for four toll levels on the usage of UCCs using three real-world case studies. To consider operational characteristics, the shares of customers in cities, UCC usage fees, and the quantities per customer request are varied as well.

Finally, Chapter 6 concludes the dissertation. It reflects on the achievement of the research objective and the answering of the RQs, summarizes the derived managerial insights, discusses the limitations of the research, and lastly provides recommendations for future research.

1.3 Scientific Theoretical Classification

In the following, the research in this dissertation will be discussed from a philosophy of science perspective. Philosophy of science can be described as a meta-discipline that studies not only the definition of science and its objectives but also its classification, principles of knowledge, and methods (Fülbier, 2004). The research presented in this dissertation pertains to multiple research areas. The main research areas covered are business administration and operations research. In the following, the classification of this research is discussed related to these two areas.

As with economics, a consensus is that business administration, which is also denoted as business management, is characterized by its economic perspective on the handling of scarce goods (Fülbier, 2004). However, contrary to economics, the focus of business administration is on companies as individual units within the overall economy and their associated activities (Helfrich, 2016). Generally, business administration is seen as an area of social science (Whitley, 1984; Domschke and Scholl, 2008; Heinen, 1985). Social sciences, according to Heinen (1985), deal with human behavior in the most general sense. Helfrich (2016), by contrast, uses the term cultural sciences instead of social sciences and describes its subject area as everything that is made or significantly influenced by people. Social sciences together with natural sciences form the real sciences, whose object of research are phenomena of the real world (Domschke and Scholl, 2008; Helfrich, 2016). Opposed to them are the formal sciences (e.g., computer science and mathematics), which deal with structures that are independent and detached from reality (Helfrich, 2016). Often, however, the interdisciplinary nature of business administration is emphasized (see e.g., Heinen, 1985; Tsang, 2017), and as Domschke and Scholl (2008) note, business administration is closely linked to formal sciences, such as applied mathematics, statistics, and computer science. The research in this dissertation relates to the social sciences, as it focuses on urban freight transport, which can be considered a sociotechnical system due to the interplay of technical and infrastructural systems and interdependent actors (Quak et al., 2016). Specifically, since the research in this dissertation focuses on the transport of goods by LSP companies and their decisions, the research can be assigned to the subfield of logistics within business administration.

In addition to the classification into formal and real sciences, a distinction can also be made between basic and applied sciences (Helfrich, 2016). According to Helfrich (2016), basic sciences are more concerned with the study of theoretical relationships and explanations, whereas applied sciences are primarily focused on practical needs. Business administration is nowadays predominantly seen as a practical applied science (see e.g., Heinen, 1985; Fülbier, 2004; Helfrich, 2016). Fülbier (2004) justify this classification of business administration as a practical applied science with the argument that business administration is not only concerned with the determination of theoretical causal relationships but also intends to provide assistance for economic activities at the enterprise level from a microeconomic perspective. The research in this dissertation can be considered to be applied, practical-oriented research for multiple reasons. First, through RQ 4, the research provides insights into how various factors affect the operation of LSPs in the context of UCCs and under what circumstances UCCs can provide cost savings and attract users. Second, it provides a conceptual simulation model for evaluating cooperative UCCs that could be used for an ex-ante assessment of the cost effectiveness of setting up a UCC. Third, decision support methods are provided for deciding whether to tranship customer requests to third-party UCCs by proposing a heuristic solution algorithm that considers several real-world characteristics of urban freight transport.

According to Burr (2012), business administration, as it is understood in Germany, is characterized by methodological and content-related pluralism and is divided into different, often competing schools of thought. Among these schools of thought are, for example, the system-oriented approach (Ulrich, 1970; Ulrich, 1981) and the decision-oriented approach (Heinen, 1971; Heinen, 1985). The research in this dissertation is primarily characterized by a decision-oriented perspective on business administration. Decision-oriented business administration places decisions and the process of decision-making into the focus of business administration (Heinen, 1985). Heinen's decision-oriented approach is particularly characterized by its consideration of the human decision-making process and interpersonal aspects in management processes (Heinen, 1971; Heinen, 1985). As such, particular emphasis is placed on the importance of using research findings from related social sciences. Domschke and Scholl (2008), in contrast, emphasize a decision-oriented view of business administration in which business administration is primarily seen as a practical-normative science that provides decision support to decision-makers. In this context, Domschke and Scholl (2008) distinguish business administration based on its research objectives into the three directions *descriptive business administration*, *practical-normative business administration*, and *ethical-normative business administration*. According to them, *descriptive business administration* aims at describing companies and their actions but does not provide recommendations and instructions for action. *Practical-normative business administration*, also called decision-oriented business administration, aims at the description and explanation as well as at the design of business operations through managerial decisions. The *ethical-normative business administration*, in turn, expands the *practical-normative business administration* to include the consideration of desirable factual goals, such as social goals for employees, in addition to the goal of pure profit maximization.

Although the concept of UCCs addressed in this dissertation is largely influenced by desirable social goals (e.g., mitigating the negative impacts of freight transport), the research in this dissertation pertains predominantly to the practical-normative approach described by Domschke and Scholl (2008). By providing quantitative models, this dissertation aims to provide decision support in logistics and urban freight transport management in form of simulation and planning models. In this regard, the focus is primarily on the cost-effectiveness of operations in the context of UCCs. Analogous to the decision support view of Domschke and Scholl (2008), the development of recommendations and instructions for rational economic actions is the focus of this work, while behavioral aspects of decision making are not considered. In addition to this practical-normative orientation, there is, however, also a descriptive component to this dissertation, as the effects of regulations and operational characteristics are analyzed and described.

In addition to business administration, the research in this dissertation falls under the research area of operations research. According to Bertrand and Fransoo (2002), operations research can be seen as a sub-discipline of applied mathematics and computer science. Domschke and Scholl (2008), in contrast, view operations research as a sub-discipline of business administration. Following the Institute for Operations Research and the Management Sciences, operations research can be defined as *"[...] a discipline that deals with the application of advanced analytical methods to help make better decisions"* (Institute for Operations Research and the Management Sciences, 2021). Operations research and decision-oriented business administration, as described by Domschke and Scholl (2008), are therefore closely related as both aim at decision support. However, decision support relies predominantly, but not exclusively, on operations research (Roy, 1993).

Quantitative modeling of decision problems is a core element of operations research (Domschke et al., 2015). Bertrand and Fransoo (2002, p. 242) define quantitative models to be *"[...] based on a set of variables that vary over a specific domain, while quantitative causal relationships have been defined between these variables"*. In their analysis of quantitative model-based research, they distinguish between empirical and axiomatic research. Empirical model-based research relies primarily on empirical findings and measurements. A major concern is to ensure that models appropriately represent observations and actions from reality. Axiomatic research, on the other hand, seeks to obtain solutions within the defined model and to ensure that these solutions provide insights into the problem defined in the model. In this regard, Bertrand and Fransoo (2002) classify axiomatic research into axiomatic quantitative research and axiomatic quantitative research using simulation. Unlike the former, axiomatic quantitative research using simulation is characterized by the use of computer simulation instead of mathematical analysis. Axiomatic quantitative research using simulation is therefore used for models that are too complex for formal mathematical analysis. According to Bertrand and Fransoo (2002), axiomatic research is typically normative, and operations research, in particular, falls predominantly into this category. Bertrand and Fransoo (2002) characterize normative research as being primarily interested in developing policies, strategies, and measures aimed at finding optimal solutions to newly defined problems, improving results in the literature, or comparing strategies for solving a particular problem.

The research in this dissertation includes both axiomatic quantitative research and axiomatic quantitative research using simulation. The research presented in Chapter 3 uses the methodology of computer simulation and therefore falls under axiomatic quantitative research using simulation. Meanwhile, the research in Chapters 4 and 5 uses formal mathematical analysis and heuristic solution methods and therefore can be considered as axiomatic quantitative research.

2 Theoretical Background

This chapter provides an overview of the research field of urban freight transport and city logistics, the concept of urban consolidation centers (UCCs), and research on the vehicle routing problem (VRP).

2.1 Urban Freight Transport and City Logistics

In this section, an overview of urban freight transport and city logistics is given. Starting with the definition of both terms and their objectives, a brief outline of the origins of the research area is given. Subsequently, in Subsection 2.1.2 the main stakeholders of urban freight transport, as well as their objectives and challenges, are described. Lastly, in Subsection 2.1.3 the subject area of urban freight transport policy is reviewed, highlighting its complexity and areas of action.

2.1.1 Definition and Overview

Over the past decades, a number of definitions of urban freight transport have been proposed. The definitions of urban freight transport found in the literature vary in their granularity and the type of transport encompassed. As mentioned in the introduction, Ogden (1992, p. 15) defines urban freight transport as *"[...] the movement of things (as distinct from people), to, from, within and through urban areas."* Later, the OECD proposes a more focused definition that defines urban freight transport as *"[...] the delivery of consumer goods (not only by retail but also by other sectors such as manufacturing) in city and suburban areas, including the reverse flow of used goods in terms of clean waste."* (OECD, 2003, p. 7). Allen et al. (2000), on the other hand, propose a broader definition that explicitly includes all freight types, all vehicle types, all freight vehicle movements, and all other essential commercial vehicle trips, such as service trips. Ambrosini and Routhier (2004) similarly suggest that the definition of urban freight transport should be expanded to include vehicle movements related to household purchasing trips, urban road maintenance and building, and waste collection. Dablanc (2008) in contrast, explicitly excludes households and limits urban freight transport to transport performed by professionals. As described in Chapter 1.2.1, the focus of the research in this dissertation is specifically on the transport of goods for the retail sector which is carried out by logistics service providers (LSPs). Thus, urban freight transport in this chapter is primarily related to the operations of LSPs.

Similar to the variety of definitions, there are several terms used in the literature and in practice to describe freight transport in cities. These terms, which are usually used interchangeably, include for example urban goods movement, urban freight distribution, and urban freight transport (Macharis and Kin, 2017). Throughout this dissertation, the term urban freight transport is predominantly used.

Closely related to urban freight transport is the term city logistics, also called urban logistics, which refers to logistics and transport activities in the context of urban freight transport (Dolati Neghabadi et al., 2019). City logistics specifically addresses issues and challenges associated with urban freight transport, such as congestion, on-street parking, and stakeholder interaction (Muñuzuri et al., 2005). Taniguchi (2001) defines that the objective of city logistics is the global optimization of logistics systems within an urban area. Dolati Neghabadi et al. (2019, p. 1) state that the objective is to *"[...] elevate a city's prosperity while alleviating its emerging negative consequences [...]"*. Savelsbergh and van Woensel (2016, p. 579) similarly summarize that *"[...] city logistics is about finding efficient and effective ways to transport goods in urban areas while taking into account the negative effects on congestion, safety, and environment."* In line with this, Taniguchi (2001) emphasize that city logistics is characterized by a trade-off between the costs and benefits for both the public and private sectors as their interests are in conflict. The conflicting goals of local administrations and LSPs can be taken as an example of this. While local administrations seek to reduce the negative impacts of urban freight transport, LSPs try to ensure that their transport operations run efficiently and aim to keep their costs low.

The origins of urban freight transport and city logistics research can be traced back to the early 1970s. Ogden (1992) provides an overview of the early research on urban freight transport and city logistics in the 1970s and 1980s. After a decline in interest during the 1980s, interest in and research on urban freight transport and city logistics surged beginning in the 1990s (Quak, 2008; Köhler, 2004). Especially in Europe and Japan a number of city logistics projects were initiated during the 1990s (see e.g., Egger and Ruesch, 2002; Köhler, 2004; Allen et al., 2012). Today, urban freight transport and city logistics encompass an immense multi-disciplinary field of research, which is composed of various research streams addressing managerial, social, and engineering aspects (Dolati Neghabadi et al., 2019; Lagorio et al., 2016). Lagorio et al. (2016), for example, divide the research on city logistics into fourteen main research topics. According to their systematic literature review, among the most studied topics are VRPs, stakeholder involvement, solution concept analysis, and consolidation concepts.

2.1.2 Stakeholders of Urban Freight Transport

A distinctive feature of urban freight transport and city logistics, which stems from the desired trade-off between costs and benefits for the private and public sectors, is the strong focus on different stakeholders. Similar to the diversity of the research field, urban freight transport is characterized by numerous heterogeneous stakeholders with divergent goals (Quak, 2008; Taniguchi, 2001; Stathopoulos et al., 2012).

In the literature, different approaches to classify the stakeholders in urban freight transport exist. Likewise, various terms to denote the individual stakeholders can be found. The stakeholders usually considered in urban freight transport include receivers, LSPs, and shippers (also called forwarders) (Ogden, 1992; Stathopoulos et al., 2012). Receivers describe the recipients of shipments of goods and include, for example, retailers, hotels, restaurants, and other businesses. LSPs or carriers, in turn, denote companies that perform the transport of goods. Shippers are the consignors of the goods. They may also act as freight carriers themselves if they decide to conduct own-account transport. Many authors, however, such as Muñuzuri et al. (2005) and Stathopoulos et al. (2012) argue that its also important to include policy-makers, such as public administrations, since they influence urban freight transport through regulations and policies. Local administrations are particularly in focus, as urban freight and city logistics are generally addressed at the local level (OECD, 2003). Nevertheless, Visser et al. (1999), as well as Ballantyne et al. (2013) point out that regional and national administrations can also impact urban freight transport through regional as well as national policies and regulations in different fields. Depending on the object and objective of the study, additional stakeholders are considered in the literature. For example, Tamagawa et al. (2010) consider a private profit-oriented toll road operator. Ballantyne et al. (2013) include vehicle manufacturers as well as trade associations and commercial organizations in their analysis of stakeholders. Moreover, van Heeswijk et al. (2016) consider the operators of UCCs as a separate type of stakeholder.

Given the heterogeneity of stakeholders, there are different approaches to group stakeholders based on their characteristics. Dolati Neghabadi et al. (2019) categorize stakeholders into public and private stakeholders. Therein, the public stakeholder category refers to local administrations, also commonly called local authorities, local governments, or policymakers (Dolati Neghabadi et al., 2019). Muñuzuri et al. (2005) divide the stakeholders of urban freight transport into carriers/logistics operators, receivers, and local administrations. Russo and Comi (2011) build upon the stakeholders identified by Ruesch and Glückler (2001) and group stakeholders into public administrations (local and national), end consumers, such as residents and visitors, and logistics and transport operators. Gonzalez-Feliu et al. (2018) propose a functional approach to categorize stakeholders in urban freight transport, in which stakeholders are classified into space users and space organizers. In this classification, space organizers describe local administrations and other organizations involved in the planning and organization of urban spaces and the transport of goods. Space users, on the other hand, include the generators of urban freight transport, the transport service providers, and the intermediaries between these two groups. Finally, Ballantyne et al. (2013) suggest categorizing stakeholders based on their possibility for action. They describe actors as the subset of stakeholders who not only have an interest in urban freight transport but also have the means to influence urban freight transport. For example, the authors categorize LSPs and local administrations as actors, whereas residents are only regarded as stakeholders. However, it could be argued that residents could exert influence indirectly through elections and referendums, but also directly through legal actions.

Based on the different categorizations in the literature, the categorization, presented in Table 2.1 is proposed. In this categorization, a distinction is made between public and private stakeholders. Public stakeholders include the different levels of public administrations, such as local and regional administrations. The category of private stakeholders is divided into commercial and non-commercial stakeholders. The commercial stakeholders include shippers (e.g., wholesalers and producers), LSPs (e.g., carriers), and receivers (e.g., retailers, manufacturers). Here, LSP is chosen as an umbrella term for all actors that perform transport operations, as explained in Chapter 1.1. Non-commercial stakeholders, in turn, include residents and visitors (e.g., shoppers) to an urban area. A special case are UCC operators, which can be private businesses as well as public entities or public-private partnerships, as detailed later in Subsection 2.2.3.

The three groups of urban freight stakeholders are characterized by different goals and challenges. Whereas non-commercial stakeholders are primarily interested in livable cities, jobs, and the provision of goods, commercial stakeholders focus mainly on economic interests. For example, according to a survey conducted by Lebeau et al. (2018), shippers place the most importance on transport costs. Similarly, LSPs appear to value profitability the most. The residents surveyed, on

Table 2.1: Categorization of stakeholders of urban freight transport.

Public	Private	
	Commercial	Non-commercial
• Local administrations • Regional administrations • National administrations	• Shippers • Logistics service provider • Receivers	• Residents • Visitors
• UCC operators		

the other hand, place particular importance on emissions and safety in the context of urban freight transport. Russo and Comi (2011) denote this goal of local residents as the minimum disruption from freight traffic. On the one hand, local administrations, therefore, pursue environmental and traffic goals, but on the other hand also consider economic aspects (Russo and Comi, 2011).

In addition to the heterogeneity of their goals, stakeholders also face different challenges. Special focus is given to LSPs, whose challenges resulting from the density and complexity of urban areas are highlighted by various authors. Among the identified challenges for LSPs are the lack of logistics and parking space, congested infrastructure, and compliance with urban regulations (see e.g., Stathopoulos et al., 2012; Nuzzolo et al., 2016; Rose et al., 2016). Rose et al. (2016) divide the issues that affect LSPs into physical and societal pressures. Physical pressure describes challenges associated with space, resources, and infrastructure and includes, for example, the lack of logistics spaces and congested infrastructure. Societal pressure describes challenges that arise from the interactions between businesses, local administrations, and the community. In contrast, the operational challenges of shippers and receivers related to urban freight transport are only rarely addressed in the literature. Johansson and Björklund (2017) report from interviews with retail stores that many face a lack of storage space, especially during peak seasons. In addition, the authors report that some retail stores perceive in-store logistics activities as time-consuming and a hindrance to customer service. De Carvalho et al. (2019) report that in agreement with LSPs retail receivers also emphasize the importance of parking space for logistics activities. Due to the heterogeneity of the stakeholders, several authors highlight that it is important to consider the perspective of different stakeholders and to integrate them into the planning and implementation of urban freight transport policies and measures (Dolati Neghabadi et al., 2019; Anand et al., 2012; Stathopoulos et al., 2012; Lindholm, 2013).

2.1.3 Urban Freight Transport Policy

Although urban freight transport policy is a frequently used term, it is rarely defined in concrete terms. Analogous to the definition of transport policy provided by Slack et al. (2020, p. 322), urban freight transport policy could be defined as being concerned with the development of *"a set of constructs and propositions that are established to achieve specific objectives relating to social, economic, and environmental conditions, and the functioning and performance of the transport system."* However, in line with the general definition of public policy, given by Dye (2017, p. 1) which states that *"public policy is whatever governments choose to do or not to do"*, Visser et al. (1999) emphasize that even the absence of policy in relation to a particular area, such as urban freight transport, can still be considered as a policy. As indicated in the definition, urban freight transport policy, similarly to city logistics, addresses the social, economic, and environmental impacts of urban freight transport. Quak (2008, p. 4) analogously denotes the objectives of urban freight transport policies as *"environmental sustainable development, social sustainable development, and economic sustainable development"*. Visser et al. (1999) use a more detailed breakdown of goals for urban freight transport policies and follow the urban freight transport objectives proposed by Ogden (1992). These goals include the following target areas: efficiency, economic, road safety, environment, infrastructure, urban structure.

Following growing public attention to sustainability, the interest of public administrations in urban freight transport policy has increased in recent years (Savelsbergh and van Woensel, 2016; Browne et al., 2012; Cherrett et al., 2012). Managing urban freight transport and its impacts, however, is by no means a new issue for public administrations. Already in the first century B.C., Gaius Iulius Caesar was concerned with the negative effects of urban freight transport and issued with the Lex Iulia Municipalis the following regulation on the transport of goods in the city of Rome (Johnson et al., 2003, pp. 94–95):

> *"(14) After January 1 next no one shall drive a wagon along the streets of Rome or along those streets in the suburbs where there is continuous housing after sunrise or before the tenth hour of the day, except whatever will be proper for the transport and the importation of material for building temples of the immortal gods, or for public works, or for removing from the city rubbish from those buildings for whose demolition public contracts have been let. For these purposes permission shall be granted by this law to specified persons to drive wagons for the reasons stated."*

Despite this long history and its implications, urban freight transport policy planning, unlike passenger transport planning, has traditionally often been neglected by local administrations in Europe (Cherrett et al., 2012; Ballantyne et al., 2013; Lindholm, 2013; Letnik et al., 2018). Correspondingly, many authors in the literature attest that local administrations have only very limited knowledge and experience about urban freight transport (Lindholm, 2012; Ballantyne et al., 2013; Lindholm and Blinge, 2014; Kiba-Janiak, 2017). Multiple authors, moreover emphasize that urban freight transport policies are characterized by complex environments (Janjevic et al., 2019; Lindholm, 2012; Stathopoulos et al., 2012). Janjevic et al. (2019) argue that the complexity of urban freight transport policy stems from the highly interrelated stakeholders of urban freight transport and their divergent objectives. Similarly, Quak (2008) notes that the environmental, social, and economic goals of urban freight transport policies are often in conflict. An example of this can be illustrated by the intended improvement of social sustainability through city time window restrictions. City time window restrictions, enacted by local administrations, limit the entry of delivery vehicles into the city center or pedestrian zones to certain times of the day. Their aim is to reduce the nuisance caused by freight traffic, as perceived by residents and visitors, and thus to make the city more attractive and accessible for these stakeholders (Quak and de Koster, 2007). While local administrations are mostly satisfied with the success of time window restrictions in terms of social sustainability effects, time window restrictions can also lead to negative environmental effects such as higher emissions and higher transport costs (Quak and de Koster, 2007; Quak and de Koster, 2009).

Another factor Janjevic et al. (2019, p. 335) identify as a contributing cause of complexity is the *"diversity of implementation settings"*. What is meant by this is that cities and urban areas can differ with respect to various characteristics and thus the setting of the implementation of urban freight transport policies varies locally. The relevant characteristics of urban areas include, for example, geographic and demographic attributes, as well as the legislation and culture (Balm et al., 2014). In addition, the operations and requirements of businesses, such as retailers, shippers, and LSPs might vary from city to city. For example, Nuzzolo et al. (2016) compare attributes of urban freight transport in the European cities of Rome, Barcelona, and Santander through industry surveys and interviews. They find differences in terms of freight demand, such as the type and average delivery quantities, as well as in terms of freight transport operations (e.g., the share of own-account transport and vehicle types used). Another example of this can be seen in the major differences in the structure and processes of retailing and related logistics systems between emerging and developed countries, as highlighted by several authors (Blanco and Fransoo, 2013; Kin et al., 2017).

Analogous to the heterogeneity of urban areas and the freight transport within them, there are also considerable differences in the urban freight transport policies. Visser et al. (1999) underline that urban freight transport is affected more than other types of transport by local, regional and national policies from different areas. As mentioned earlier, urban freight transport is mostly considered at the local level by local administrations. One problem with this, however, as Nuzzolo et al. (2016) note, is that the policies and measures used by local administrations are often not uniformly implemented. Kiba-Janiak (2017) furthermore suggests that cities in Europe differ in how they incorporate urban freight transport policies and measures into their strategic city planning and that different levels of maturity can be distinguished.

In the literature, different approaches exist to categorize and describe the field of urban freight transport policy. Dolati Neghabadi et al. (2019) divide urban freight transport policy into the areas of governance, planning, and measures. A particular focus is on measures, which they describe as actions aimed at implementing a plan or decision. Regarding measures in urban freight transport, they distinguish between public regulations and private innovative solutions. In addition to this granular distinction, a number of approaches to categorizing urban freight transport policy measures can be found in the literature (see e.g., Ogden, 1992; Visser et al., 1999; Muñuzuri et al., 2005; Russo and Comi, 2011; Stathopoulos et al., 2012; Lindholm, 2012; Kiba-Janiak, 2017). Although these approaches are similar in some aspects, they differ not only in the number and naming of categories but also in the naming and assignment of measures within those categories. Nevertheless, several common categories can be summarized:

- **Infrastructure**. At its core, this category refers to measures related to the construction and adaptation of the transport network and logistics facilities in urban freight transport. Stathopoulos et al. (2012), Russo and Comi (2011), as well as Muñuzuri et al. (2005) mention in this context, for example, intermodal terminals and facilities to consolidate freight transport. Lindholm (2012) and Kiba-Janiak (2017) also address the public infrastructure for alternative modes (e.g., trams, underground, waterways).

- **Land use**. This category includes measures that control the allocation of space to logistics areas and sectors with high transport demand (e.g., retail and manufacturing). In addition, Muñuzuri et al. (2005) and Russo and Comi (2011) mention measures concerning loading and unloading zones in urban areas.

- **Regulation**. This category mainly includes access restrictions for urban freight transport.

Muñuzuri et al. (2005) distinguish between spatial and temporal restrictions. Widely used measures include time window restrictions, vehicle access restrictions, and city toll schemes. Related to this, Muñuzuri et al. (2005) particularly highlight enforcement activities as a separate category.

- **Management**. The Management category is less narrowly defined than the previous categories. A central aspect, however, is the cooperation between LSPs (Visser et al., 1999; Muñuzuri et al., 2005; Stathopoulos et al., 2012; Kiba-Janiak, 2017). Moreover, Muñuzuri et al. (2005) include traffic management measures, such as the harmonization of regulations.
- **Technology**. This category includes measures to promote the use of innovative technologies in urban freight transport. In this context, Kiba-Janiak (2017) lists, for example, the adoption of electric delivery vehicles and the use of cargo bikes. Russo and Comi (2011) extend the perspective to include measures that increase efficiency (e.g., handling equipment) or improve road safety in urban freight transport. Stathopoulos et al. (2012) highlight the introduction of information systems that allow, for example, to optimize routing to the current congestion situation.

Based on the categorizing schemes from the literature, Table 2.2 additionally summarizes the measures commonly mentioned within the categories. It should be noted, however, that depending on the categorization, some measures are assigned to different categories in the literature. For example, the measure loading and unloading zones is assigned in the literature to both infrastructure (Russo and Comi, 2011) and land use (e.g., Muñuzuri et al., 2005; Kiba-Janiak, 2017).

2.2 Urban Consolidation Centers

In this section, a detailed overview of the concept of UCCs and related research is provided. Subsection 2.2.1 briefly outlines the origins of UCCs, their definition, and how they can be classified within the categorization of urban freight transport policy measures. Subsection 2.2.2 describes the basic concept of UCCs and the motivation behind the concept of UCCs. Next, Subsection 2.2.3 presents different approaches to categorizing UCCs. Subsection 2.2.4 provides a brief overview of the operational challenges of UCCs identified in the literature based on real-world implementations of UCCs. Subsection 2.2.5 provides an overview of strategic, tactical, and operational planning issues in the context of UCCs, and Subsection 2.2.6 reviews the quantitative evaluation of UCCs.

2.2.1 Definition and Overview

According to Crainic et al. (2009), the consolidation of goods across actors is one of the fundamental concepts of city logistics. The first research on UCCs as a city logistics measure began as early as the 1970s (e.g., McDermott, 1975), and Holguín-Veras et al. (2020) report that there already existed a UCC in the United States for a few years during the 1940s and 1950s. Similar to urban freight transport and city logistics in general, different definitions and terms exist for the UCC concept. For example, terms used in this regard include urban distribution centers or urban freight platforms (Björklund and Johansson, 2018). Despite the variety of names used, according to Verlinde

Table 2.2: Categorization of urban freight transport policy areas and measures.

Category	Measures
Infrastructure	• Network extensions • Intermodal terminals (rail, water, road) • Urban consolidation centers • Use of public transport infrastructure (e.g., tram network)
Land use	• Loading and unloading zones • Parking space planning • Relocation of freight intensive businesses
Regulation	• Vehicle access restrictions based on weight, volume or load factor • Low emission zones • Road pricing and city toll schemes • Truck transit bans • Off-hour deliveries • Access time windows
Management	• Carrier cooperation • Harmonization of regulations • Freight zone and carrier classifications
Technology	• Low-emission and alternative fuel vehicles • Vehicle safety improvements • Cargo bikes • Loading and unloading equipment • Information technology (e.g., online reservation of loading zones, intelligent transport systems)

(2015), almost all definitions begin by defining UCCs as a physical location for the consolidation of goods for an urban area or place. Based on Browne et al. (2005) and Allen et al. (2012), the following simple definition for UCCs is used in this dissertation: UCCs describe transshipment facilities in the proximity of an urban area to bundle urban freight transport flows. With reference to the classification of urban freight transport policies presented in Subsection 2.1.3, UCCs are generally considered to be an infrastructure measure (Muñuzuri et al., 2005; Russo and Comi, 2011; Stathopoulos et al., 2012; Kiba-Janiak, 2017). However, one could also argue that UCCs can be understood as a management measure since UCCs are also considered as a cooperative measure between multiple actors and do not necessarily require new infrastructure. Furthermore, connections can be drawn to the category of technology and regulation. For example, the use of environmentally-friendly vehicles is often a central element of UCCs (Allen et al., 2012). Moreover, cases from practice, show that the operation of UCC requires the interchange of information between actors and thus often involves the adoption of platforms to interchange information (Quak et al., 2020). Lastly, the implementation of UCCs is sometimes accompanied by supporting regulations to promote their use (Allen et al., 2012; Lebeau et al., 2017). An extreme example of this is found in the Italian city of Vicenza, where the use of the local UCCs was made mandatory (Ville et al., 2013). Contrary to the classification from Subsection 2.1.3, Lindholm (2012) considers consolidation to be its own category of urban freight transport policy measure and distinguishes different consolidation approaches.

2.2.2 Motivation and Basic Concept

UCC initiatives are often primarily motivated by environmental goals (Browne et al., 2005). As such, the implementation of UCCs is commonly initiated and supported by local administrations (Allen et al., 2012; Lebeau et al., 2017). In theory, on the one hand, the consolidation of freight transport can reduce the number of delivery vehicles within an urban area by increasing the utilization of delivery vehicles. On the other hand, by consolidating deliveries from different LSPs, more efficient tours can be planned than those of LSPs individually (Verlinde, 2015).

The idea of the UCC concept is to enable cross-company consolidation of freight flows onto smaller or more environmentally friendly vehicles with a higher load factor. Instead of delivering freight to its destination in the urban area, inbound delivery vehicles can tranship their deliveries at a UCC located outside of the urban area. There at the UCC, goods from multiple LSPs are temporarily stored and bundled for delivery. Subsequently, the deliveries are distributed to the receivers by the UCC operator or a contracted LSP. As a result, inbound vehicles, which may have low loading factors, do not have to drive into the urban area. Occasionally, UCCs also refer to transshipment facilities used to consolidate freight flows to a single site, such as an airport or shopping mall (Allen et al., 2012).

Figure 2.1 shows a comparison between conventional deliveries to an urban area and deliveries using a UCC. On the left side, each of the three depicted LSPs performs the deliveries on its own. On the right side, each of the three LSPs tranships its goods destined for the urban area at the UCC. The UCC, in turn, consolidates the goods and performs the urban deliveries.

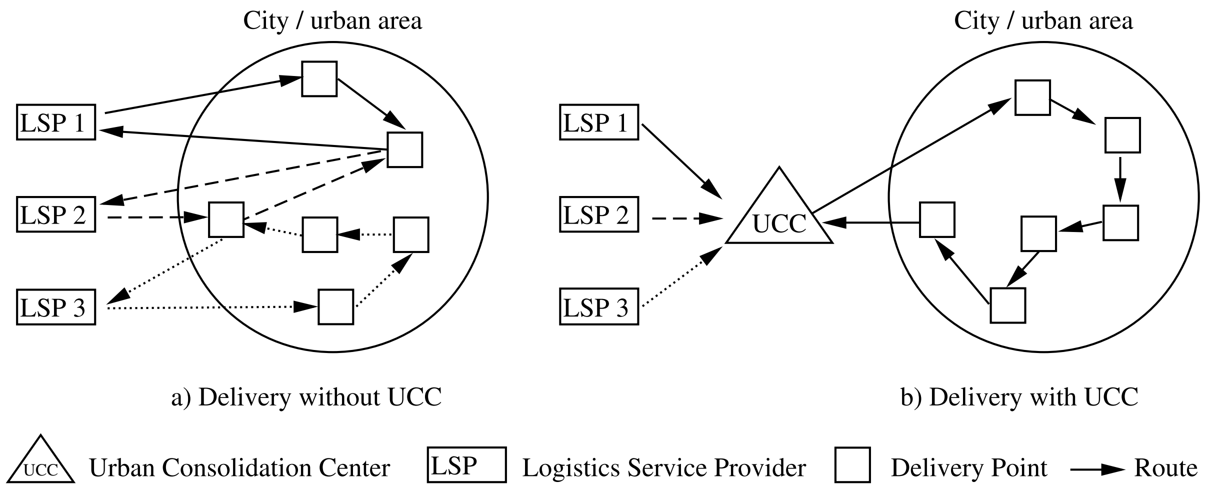


Figure 2.1: Comparison between conventional deliveries and deliveries using a UCC. Adapted from Elbert and Friedrich (2018b).

Although UCCs are primarily motivated by environmental goals, Allen et al. (2012) and Verlinde (2015) point out that studies on UCCs often only mention potential and expected environmental impacts without quantifying them. However, to provide an overview of the environmental effects of UCCs and their evaluation, Verlinde (2015) examines 93 UCC impact analyses from studies and reports. The comparison of the reported environmental and transport impacts, such as vehicle kilometers traveled, emissions, and the number of trips shows that the vast majority of UCC impact analyses (87 %) report improvements in terms of vehicle kilometers and emissions. The analysis, however, also shows that there are widely varying approaches to quantifying UCC impacts (e.g., ex-ante versus ex-post assessments) and that different factors, such as the type of UCC should be considered.

In addition to environmental impacts, the literature also addresses potential operational and cost benefits from UCCs. For example, some authors argue that the use of UCCs allows LSPs to use larger, more efficient vehicles that are often not allowed or able to enter a city center (e.g., due to restrictions or narrow streets) (Quak, 2008; Quak et al., 2020). Browne et al. (2005) mention for example that LSPs could perform more deliveries in routes that use a UCC. Similarly, Janjevic and Ndiaye (2017b) point out the potential benefits and reduced opportunity cost resulting from the time savings of using a UCC. However, several studies also show that the cost benefits of using a UCC for LSPs are highly dependent on usage fees and operational characteristics (e.g., number of cargo units per stop) (Janjevic and Ndiaye, 2017b; van Heeswijk et al., 2020).

Receivers of deliveries, such as retailers, can also benefit from UCCs. Browne et al. (2005) list numerous potential benefits for receivers, such as increased delivery reliability and reduced storage space requirements. Moreover, receivers can combine their deliveries from different LSPs by using a UCC to increase the efficiency of incoming goods processes. In addition, if necessary, retailers could individually determine the time of delivery through the UCC (van Rooijen and Quak, 2010; Paddeu, 2017). Johansson and Björklund (2017) conclude from an interview study with retailers in Sweden that cost savings could be achieved by outsourcing the logistics activities of retailers related to goods receipt to a UCC. Lastly, in practice, some UCCs also offer a range of value-added services aimed at receivers in order to attract them as customers (Browne et al., 2005; Allen et al., 2012; Paddeu, 2017; Quak et al., 2020).

2.2.3 Classification of Urban Consolidation Center Schemes

Different approaches to categorizing UCCs have been proposed in the literature. Figure 2.2 provides an overview of the categorization criteria proposed in the literature and their characteristics. One way to distinguish UCCs is by the type of area the UCC serves. Allen et al. (2012) identify three types of service area and operations for UCCs:

- UCCs serving all or part of an urban area
- UCCs serving large sites with a single landlord
- Construction project UCCs.

The first UCC type aims to serve a city or urban sub-area, such as a historic district or a shopping street and corresponds to the UCC concept depicted in Figure 2.1. The focus here is often on supplying retail businesses (Browne et al., 2005; Allen et al., 2012; Panero et al., 2011). Examples of UCCs that are limited to one shopping district are the Bristol Bath UCC or the Motomachi UCC in Yokohama (Paddeu, 2017; Taniguchi, 2014). The UCC in Monaco, on the other hand, covers almost the entire urban area except for the industrial area in which it is located (ADEME, 2004).

The second type of UCCs serves individual buildings or building complexes with a single landlord, such as shopping malls or airports. Here, a distinction can be made between UCCs where the use is made mandatory by the landlord and UCCs where use is only suggested (Panero et al., 2011).

The former can be found, for example, at London Heathrow Airport, where a UCC whose use was initially voluntary later became mandatory for all deliveries to retailers (Allen et al., 2007).

The third UCC type refers to construction project UCCs and is characterized by serving either a single or multiple construction projects. In addition, the lifetime of construction project UCCs are often linked to the duration of the construction projects it serves. One example is the construction consolidation center in Hammarby, Sweden. This UCC was operated in the course of a major construction site lasting several years and was intended to help coordinate deliveries for the construction site (Allen et al., 2007). Other similar construction project UCCs are described, for example, in Lundesjö (2019).

In addition to their service area, UCCs can also be distinguished in terms of the involvement of public administrations and the way they are operated. Panero et al. (2011) find that the involvement of local administrations can vary greatly depending on the UCC. On the one hand, there are UCCs in which local administrations are not or only slightly involved. On the other hand, there are UCCs where local administrations are involved through various direct and indirect measures, such as subsidies and regulations. The Motomachi UCC in Yokohama, Japan, for example, only received an initial grant from the city of Yokohama (Taniguchi, 2014). However, in addition to the financial support, parking spaces for delivery vehicles were created in the service area of the UCC (Taniguchi, 2014). The UCC in Bristol and Bath, on the other hand, is reimbursed 45 % of its operating costs as a subsidy, after initially receiving a 100 % subsidy (van Duin et al., 2016). Other UCCs, by contrast, such as the Meadowhall UCC, in Sheffield, UK, and the London Heathrow Retail Consolidation Centre, have not received any public funding (Allen et al., 2014). Björklund and Johansson (2018) summarize the types of UCC financing as public, private, and mixed public-private. A detailed overview of the further public support measures for UCCs and their usage can be found in Lebeau et al. (2017).

Depending on the involvement of public administrations, the ownership and operation of UCCs also differ. Panero et al. (2011) differentiate between four types of UCC ownership and operation:

- **Single private ownership**. This type of UCC is owned by a single company, which performs the operation of the UCC itself or subcontracts the operation to a LSP. Typical examples are UCCs which serve large sites with a single landlord (e.g., the London Heathrow Retail Consolidation Centre) (Panero et al., 2011). Another example is the Dutch UCC Binnenstadservice, which is run as a private company and outsources its distribution activities to local LSPs (Quak et al., 2020).

- **Private joint ventures**. The second type of UCCs is characterized by collaboration among private stakeholders. Estrada and Roca-Riu (2017) distinguish between receiver-led and LSP-led initiatives. An example of an LSP-led UCC is, for instance, the Tenjin UCC in Japan, which was established in 1978 through the cooperation of multiple LSPs (Nemoto, 1997).

- **Public-private partnerships**. The third type of UCCs is characterized by the participation of at least one public partner. According to Panero et al. (2011), this type is often found in Italy and a distinction can be made between starting a new joint company and entering into an agreement with an existing company. An example of the latter is the UCC in Padua, Italy, where the city council and other public institutions established an agreement with a local company. In Vicenza, Italy, in contrast, the municipality and its partners established a new joint venture (Città di Vicenza, 2007).

- **Publicly owned**. This type of UCC is owned solely by a public administration. The operation of the UCC, however, is usually awarded to a LSP through a public tender. Examples include the UCC in La Rochelle, France, and the UCC in Monaco (ADEME, 2004).

Another characteristic to distinguish UCCs is the customer group that is addressed by the UCC and thus decides to use and pay for the service. Verlinde (2015) distinguishes between UCCs that are targeted at either LSPs, shippers, or receivers. UCC initiatives have traditionally focused on LSPs to enable them to route more efficiently and avoid entering congested urban areas with restrictions (Browne et al., 2005; van Rooijen and Quak, 2010). Conversely, some other UCCs focus on the shippers of goods as customers (see e.g., Leonardi et al., 2012). Yet other UCCs focus on receivers as the main customer group. For example, the Binnenstadservice UCCs in the Netherlands aim to attract retailers to use its services (van Rooijen and Quak, 2010). Thereby, in addition to the mere transport of goods, additional value-added services are offered by the UCCs (van Rooijen and Quak, 2010; Quak et al., 2020). Receivers that decide to use the service of the UCCs instruct their LSP to deliver their goods to the UCC instead of delivering them directly. Lastly, van Heeswijk et al. (2019a) and van Heeswijk et al. (2020) combine both the LSP-oriented and receiver-oriented business models into a hybrid model and investigate a UCC where either the LSPs or the receivers can decide to use the UCC.

The focus of this dissertation is on UCCs that serve an urban area or a portion of it. It is assumed that the UCCs do not receive any special support from the public administrations. However, urban freight transport regulations, from which UCCs are not exempt, are included. In terms of the customer group, the UCCs considered in this dissertation focus on LSPs. In this context, both jointly-operated UCCs (private joint ventures) and third-party UCCs (e.g., single private, public-owned, public-private) are considered.

2.2.4 Operational Challenges of Urban Consolidation Centers

Although it was shown numerous times that UCCs can reduce the negative effects of urban freight transport (Verlinde, 2015), most UCC projects have failed over the years (Allen et al., 2012; Browne et al., 2005). Allen et al. (2012), for example, estimate that of 114 UCC systems that have been the subject of feasibility studies and trials or went into operation, less than half are still in operation. As Allen et al. (2012) conclude from the analysis of real-world implementations, the lack of financial viability is one of the main reasons for the failure of UCCs. Likewise, Nordtømme et al. (2015) also identify financial issues as a major barrier to implementing a UCC. According to Allen et al. (2012), especially UCCs serving an urban area, or part of it, are affected by financial problems. The reason for this is attributed to the voluntary participation in this type of UCC and the lack of a single private actor that receives the benefits of the UCC and is responsible for funding the UCC. It is therefore not surprising that these UCCs often lack participation and therefore depend on subsidies from administrations, in the beginning or throughout their lifetime, to cover initial investment and ongoing operating costs (Allen et al., 2012; Lebeau et al., 2017).

To finance their operations, single-owner third-party UCCs charge their users a fee for their services. Analogous to the UCC customer groups, private financing is primarily conducted through LSPs and receivers (Björklund and Johansson, 2018). As Janjevic and Ndiaye (2017a) analyze, the pricing of deliveries usually depends on the number and type of goods transshipped to the UCC. Thus, in the analyzed UCCs from practice, a distinction is made between a fee per package

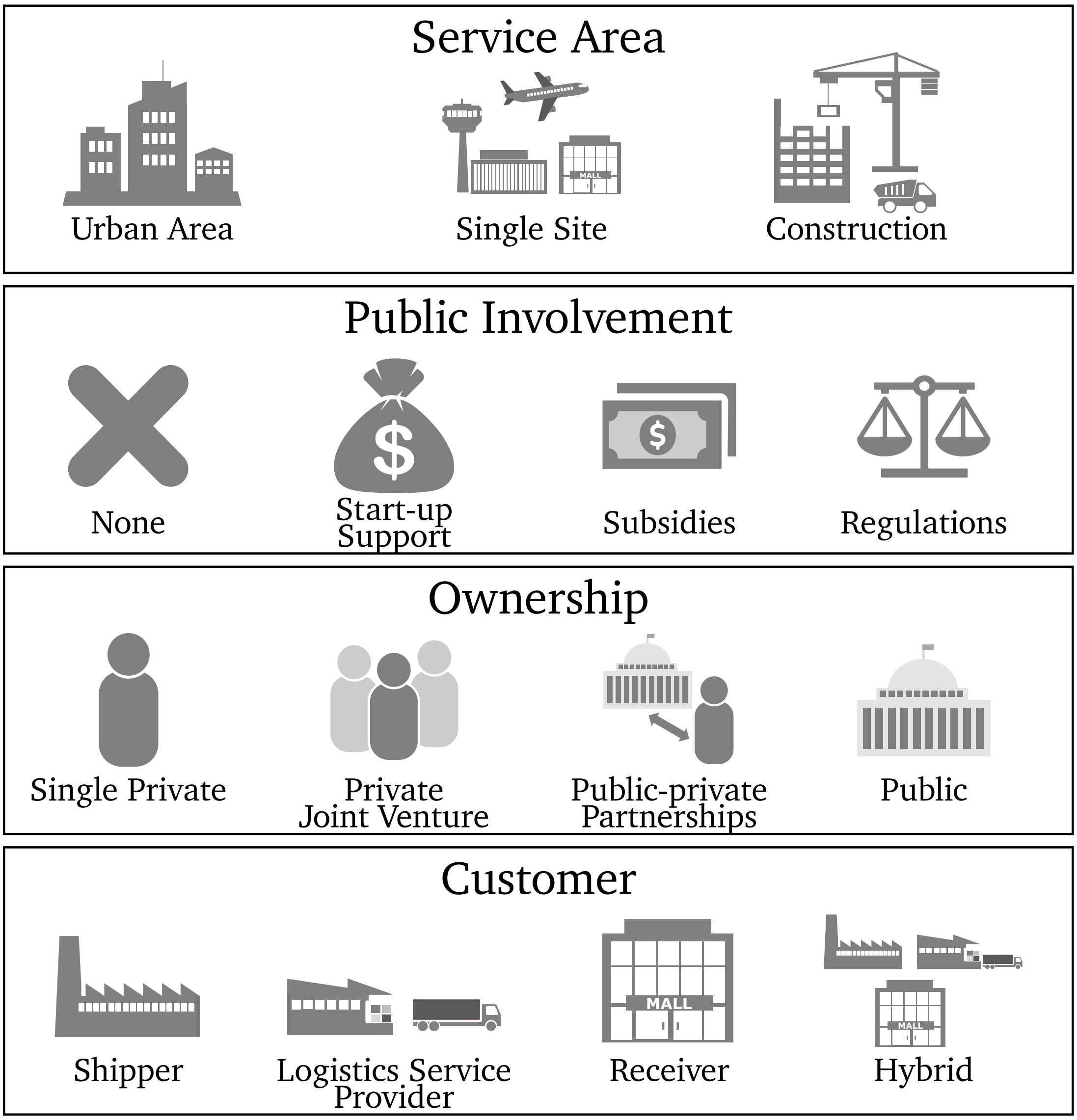


Figure 2.2: Overview of ways to classify UCCs.

transshipped and a fee per pallet transshipped. However, also alternative approaches, where LSPs pay a fee per weight, delivery stop or receivers may pay a monthly flat rate for receiving goods through a UCC, exist (Janjevic and Ndiaye, 2017a; van Heeswijk et al., 2019a; van Heeswijk et al., 2020). In the case of jointly operated UCCs, the costs of setting up and operating the UCC must be allocated among the participating partners (Cleophas et al., 2019). This raises the question of how costs and gains can be shared fairly so that all partners reap benefits from the cooperation. In this respect, game-theoretic approaches are frequently discussed to allocate the costs and benefits of UCCs (see e.g., Hezarkhani et al., 2019; Ciardiello et al., 2021).

Closely related to usage fees and the financial viability of UCCs are the economic benefits of UCC usage from the perspective of the UCC users. A key element in this context, as mentioned in Subsection 1.2.2, is the notion of cost attractiveness. Cost attractiveness means that for a customer the costs of using a UCC must not exceed the benefits it provides (Marcucci and Danielis, 2008; Janjevic and Ndiaye, 2017b). As Marcucci and Danielis (2008) point out, the costs and benefits of UCCs depend in large part on a number of factors. They mention, for example, goods-related, LSP-related, and UCC-related factors as well as regulations and geographical characteristics to impact the costs and benefits of UCCs.

In addition to financial challenges and barriers, several other barriers are identified in the literature. Janjevic and Ndiaye (2017b) for example, mention psychological barriers while Nordtømme et al. (2015) refer to social and cultural barriers. Together, both papers draw attention to the resistance of stakeholders to change because they have already invested in and adapted to the existing infrastructure. There are several examples in the literature that illustrate reasons for stakeholder resistance. Nordtømme et al. (2015), for example, describe based on their experience from a case study in Norway that LSPs were reluctant to share their operational data with other stakeholders. Similarly, van Duin et al. (2016) mention that LSPs perceive UCCs as competitors. Stathopoulos et al. (2012) report that LSPs fear losing control and the legal responsibility for the goods transported. Additionally, van Duin et al. (2018) highlight for LSPs the fear of losing visibility and marketing impact in addition to the fear of losing control. Likewise, some LSPs are reported to raise the importance of maintaining face-to-face contact with their customers as a major argument against using a UCC (Egger and Ruesch, 2002).

Besides the psychological barriers, some practical barriers in the implementation of UCCs are also given in the literature. For example, Holguín-Veras et al. (2020) state that it is often difficult to find suitable areas for UCCs due to the shortage of space in urban areas. Björklund et al. (2017) and Quak et al. (2020) identify the importance of information technology systems and information sharing between stakeholders. However, due to the different information technology systems of companies involved in a UCC, challenges can arise for the operation of UCCs (Olsson and Woxenius, 2014; Björklund et al., 2017). In addition, potential legal problems regarding the practical implementation of goods and the transshipment of goods are also mentioned in some cases (Egger and Ruesch, 2002; Nordtømme et al., 2015; Quak et al., 2020).

Concerning operational challenges of UCCs, the focus of this dissertation is mainly on the cost attractiveness of UCCs from the perspective of their users, as many UCCs suffered from low participation and resulting financial problems.

2.2.5 Planning Problems in the Context of Urban Consolidation Centers

As Crainic et al. (2009) and van Heeswijk et al. (2020) point out, operations research approaches are not yet widely used in research on urban freight transport in general and UCCs in particular. Analogous to freight transport in general, the actors in the context of UCCs face strategic, tactical, and operational planning problems. However, the planning horizons of decisions often vary depending on the model assumptions and type of UCC studied. In this overview, only planning problems that are specific to the operation and context of UCCs are presented. Table 2.3, adapted and extended from van Heeswijk et al. (2020), provides an overview of planning problems in the context of UCCs which will be explained hereafter.

Table 2.3: Overview of planning problems in the context of UCCs. The planning horizons are indicated by [S]: strategic, [T]: tactical, and [O]: operational.

Actor	Decision
UCC operator	• UCC location [S] • Fleet size and mix [T] • Pricing of deliveries and value-added services [T], [O] • Bid selection [O] • Delivery dispatching problem [O] • Vehicle routing [O]
Logistics service provider	• Fleet size and mix [T] • UCC usage [S], [T], [O] • Vehicle routing [O]
Receiver	• UCC usage and value-added service selection [T], [O]
Local administration	• Regulations [S] • UCC subsidies [S], [T]

UCC operator

For the UCC operator, the planning problem for determining the UCC location is found at the strategic level. Taniguchi et al. (1999) formulate a mathematical model for determining the optimal location and number of berths of public UCCs that offer their services to LSPs. To solve the problem in a reasonable time, Taniguchi et al. (1999) propose a genetic algorithm. Sopha et al. (2016) also address the problem of determining the locations of UCCs. They propose a two-step approach, in which a ranked list of potential sites is generated first, and then a multi-criteria optimization model that considers both costs and emissions is solved.

At the tactical level, fleet planning can be identified as a planning problem for UCC operators. Although this is a frequently addressed problem in transport planning (Hoff et al., 2010; Koç et al., 2016c), and there are some reports of real-world UCCs operating heterogeneous fleets (e.g., ADEME, 2004; Björklund et al., 2017), most studies and models assume a homogeneous vehicle fleet (see e.g., van Duin et al., 2012; Wangapisit et al., 2014; Teo et al., 2015; van Heeswijk et al., 2019a). Only a few studies consider that UCC operators have more than one vehicle type to choose from (see e.g., Lebeau et al., 2015; Elbert and Friedrich, 2018a). In particular, Lebeau et al. (2015) explore the extent to which UCCs can deploy electric vehicles by formulating a fleet size and mix vehicle routing problem (FSM) with electric vehicles.

A second tactical planning problem for UCC operators is the pricing problem of the UCC transport service. UCC operators have to balance potential profits and cover their costs on the one hand and attract customers to use their service on the other. Since this pricing problem is strongly related to the decision-making of UCC customers, the problem is mostly considered in the form of reinforcement learning algorithms (see e.g., Teo et al., 2015; Firdausiyah et al., 2019). A different approach is suggested by Anand et al. (2021) in which UCCs determine their fees based on the moving average of costs over the past few months and current subsidies from local administrations. In contrast to van Heeswijk et al. (2019a), van Heeswijk et al. (2020), and Anand et al. (2021) who assume that UCC operators can change their fees at tactical decision epochs (e.g., every twenty-five working days or two months), other approaches, such as Firdausiyah et al. (2019) assume that the UCC operators may modify their fee daily. Thus, the problem could also be considered an operational problem.

At the operational level, van Heeswijk et al. (2019b) focus on the dispatching problem of UCC operators. In this problem, UCC operators, who have limited information about the arrival of transshipments at the UCC, try to periodically consolidate customer requests to ensure efficient delivery trips. In doing so, however, the capacity and time window constraints of the requests must be taken into account at the same time. To address this, van Heeswijk et al. (2019b) formulate the problem as a delivery dispatching problem with time windows and define a corresponding Markov decision model. To solve the problem efficiently, they present an approximate dynamic programming algorithm.

Another operational planning problem for UCCs that is closely related to pricing is the auction-based selection of UCC orders. Handoko et al. (2014) present a profit-maximizing auction mechanism in which UCC operators can select the bids of the LSPs they want to serve. Expanding on this, Handoko et al. (2016) present a bicriteria auction mechanism in which UCC operators pursue both financial and environmental objectives.

Finally, UCC operators also need to plan the delivery routes from the UCC to the receivers in the city. This, however, is usually realized through standard vehicle routing algorithms without UCC-specific modifications (see e.g., van Duin et al., 2012; Firdausiyah et al., 2019; van Heeswijk et al., 2020).

Logistics Service Provider

A key planning problem for LSPs in the context of UCCs concerns the decision to use a UCC. Table 2.4 summarizes the different characteristics of the decision-making approaches found in the literature. The decision to use a UCC and transship the customer requests is usually considered to be a tactical or operational decision. Van Heeswijk et al. (2020), for example, assume that UCC operators decide after every 25 workdays whether to use a UCC for the next period. Teo et al. (2015) and Firdausiyah et al. (2019), on the other hand, model the decision to use a UCC daily, following the daily UCC pricing modifications. Moreover, the decision of whether to use a UCC can also be seen as a strategic decision, if LSPs operate a UCC cooperatively and require long-term investments to do so. This strategic approach is followed in Chapter 3 of this dissertation.

Regardless of the selected decision horizon, almost all approaches have in common that they assume that if a UCC is used by a LSP, all of its customer requests within the UCC service area will be transshipped to the UCC. Accordingly, LSPs are assumed to face an all-or-none blanket decision regarding the use of the UCC. This blanket decision to use the UCC is based on a comparison of the expected costs of direct delivery and the costs of delivery using the UCC. To estimate the costs, either routing cost approximations or standard vehicle routing algorithms are used (see e.g., van Duin et al., 2012; van Heeswijk et al., 2020). However, similar to the pricing decision of UCC operators, reinforcement learning approaches are used in few studies to account for uncertainty factors, such as stochastic parking times (see e.g., Teo et al., 2015; Firdausiyah et al., 2019). A different approach to model decisions on an operational level is taken in Baldacci et al. (2017) and Chapters 4 and 5 of this dissertation. In this integrated approach, the decision of whether and which UCC should be used for which customer requests is integrated into the vehicle route planning. This allows deciding for each customer request individually whether it should be transshipped to a UCC. Thus, LSPs could decide to transship customer requests with unfavorable time windows, while other orders are delivered directly.

Table 2.4: Characteristics of UCC usage decision approaches for LSPs.

Decision characteristic	Options
Planning horizon	• Strategic • Tactical • Operational
Data basis	• Deterministic • Stochastic
Approach	• “Blanket decision” • Integrated VRP

Besides the UCC usage decision, other problems, such as standard location planning, fleet planning, and VRPs might also be mentioned. However, these are usually not studied in the context of UCCs.

Receiver

The planning processes of receivers are usually only considered in relation to the decision to use UCCs and the offered value-added services of the UCCs (van Heeswijk et al., 2020). Other potential planning issues, such as personnel scheduling for goods receiving, have not yet been taken into account. Van Heeswijk et al. (2019a) and van Heeswijk et al. (2020) consider the tactical decision of receivers to use a UCC. In contrast, Anand et al. (2021) assume that receivers decide whether to use a UCC each time they place an order.

Local administration

As previously indicated, UCCs are often supported by local administrations through policy measures. Usually, these policy measures are regarded to be strategic and not subject to any concrete optimization problem or learning process when modeling UCCs (see e.g., van Duin et al., 2012; van Heeswijk et al., 2020). Instead, policy measures are considered in the form of scenarios. Van Heeswijk et al. (2020), for example, investigate the impact of time windows and toll restrictions on a scenario basis. This approach is also followed in this dissertation. A contrasting approach is provided by Anand et al. (2021). In their model, the decision regarding the level of subsidy for a UCC is based on the local administration's achievement of its truck kilometer target.

2.2.6 Quantitative Evaluation of Urban Consolidation Centers

In the literature, UCCs are analyzed with different objectives and approaches. Figure 2.3 gives an overview of the main objectives and evaluation approaches. In general, two main categories of objectives can be distinguished. The first category of objectives encompasses the analysis of UCCs in terms of externalities, such as local and global emissions or traffic impacts. In this context, the main aim is to analyze to what extent the use of UCCs affects the vehicle kilometers driven and the associated global and local emissions (e.g., CO_2, particulate matter (PM), NO_x) (see e.g., Wangapisit et al., 2014; Teo et al., 2015; van Heeswijk et al., 2019a; van Heeswijk et al., 2020). In some of these models, the change in the number and type of vehicles used is also evaluated (see e.g., Wangapisit et al., 2014; Teo et al., 2015). The second category of objectives involves the analysis of the economic aspects of UCCs. One area of interest in this category is the analysis of the cost attractiveness of UCCs for their users. As Janjevic and Ndiaye (2017b) note, assuming rational users, it can be inferred that service quality and cost in particular influence the decision to use UCCs. Janjevic and Ndiaye (2017b) even go so far as to say that the cost attractiveness may be seen as a required condition for the use of UCCs. The cost attractiveness of a UCC is expressed in terms of the cost savings that can be achieved by using it (Estrada and Roca-Riu, 2017; Marcucci and Danielis, 2008). For LSP, for example, the costs of using the UCC must be weighed against the potential savings in transport costs (Estrada and Roca-Riu, 2017). Examples for quantitative evaluations focusing on the cost attractiveness of UCCs include, for example, Estrada and Roca-Riu (2017), Janjevic and Ndiaye (2017b), and Roca-Riu et al. (2016). Another area of interest is the analysis of the financial viability of UCCs. Approaches that focus on the overall financial viability of UCCs include, for example, van Duin et al. (2012), Janjevic and Ndiaye (2017a), van Heeswijk et al. (2020), and Anand et al. (2021). In these approaches, both the costs and revenues of UCCs are examined in order to determine whether and under which conditions UCCs can achieve financial viability.

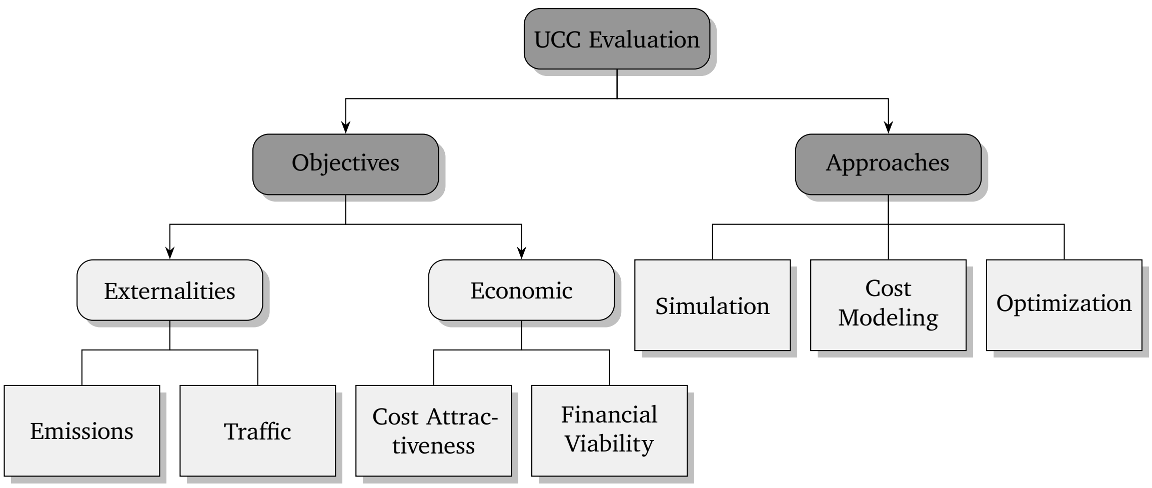


Figure 2.3: Overview of UCC evaluation objectives and approaches.

In the literature, there are several quantitative approaches to the evaluation of UCC concepts. Similar to urban freight transport in general, especially simulation modeling is a frequently used method (Björklund and Johansson, 2018; Jlassi et al., 2018). Several authors argue that simulation, especially agent-based simulation, is an appropriate method to evaluate complex urban freight transport systems (Anand et al., 2016; Jlassi et al., 2018). This can be attributed to the ability of agent-based simulations to represent the relationships and interactions between actors in the context of UCCs. An example of an agent-based simulation can be found in van Heeswijk et al. (2020). Therein, besides a local administration and a UCC operator, shippers, LSPs, and receivers are modeled. Between these actors, interactions, as well as monetary flows and information flows, are considered. Using this simulation model, the use of a UCC by receivers and LSPs, as well as the environmental impacts, are examined for numerous scenarios.

Often, agent-based simulation models are combined with reinforcement learning methods to represent the decision-making of the actors. For example, Teo et al. (2015) use Q-learning as a reinforcement learning algorithm to model the pricing decisions of a UCC operator and the decisions of LSPs on whether to use the UCC. Firdausiyah et al. (2019) also consider these two decisions and compare the performance of Q-learning and adaptive dynamic programming-based reinforcement learning. Furthermore, optimization problems of the actors and corresponding solution methods are also often integrated with simulations. A prominent example is the inclusion of vehicle routing algorithms to plan the routes of LSPs and UCC operators. For example, van Duin et al. (2012) (genetic algorithm), Wangapisit et al. (2014) (insertion heuristics), and Anand et al. (2021) (tabu search) use heuristic algorithms to solve the VRP of the LSPs and UCC operators. However, if at all, these algorithms include only time windows and are only mentioned on a side note. The decisions regarding the use of UCCs or the fleet composition, as well as other characteristics of urban freight transport, are not considered. In addition to routing problems, the dispatching problems of UCC operators and shippers are also considered in one simulation study (van Heeswijk et al., 2020).

Besides dynamic simulation models, various static cost-modeling approaches in which transport costs are approximated can be found in the literature. A common approach is the use of continuous approximation techniques to determine an estimate of the routing costs of LSPs. These approximations consider for example the vehicle capacity, spatial receiver density, and detour factors (see e.g., Roca-Riu et al., 2016; Estrada and Roca-Riu, 2017). Using a continuous approximation of transport distances and costs, Roca-Riu and Estrada (2012), Roca-Riu et al. (2016), and Estrada and Roca-Riu (2017) investigate the cost attractiveness of UCCs for LSPs. Analogously, Janjevic and Ndiaye (2017a) analyze the overall financial viability of UCCs. Janjevic and Ndiaye (2017b) also approximate transport costs in their study to analyze the cost attractiveness of UCCs using a continuous approximation approach. Based on empirical relationships between different tour attributes identified in surveys, they estimate, for example, the average distances between delivery locations. Although these approaches are frequently used in evaluating UCCs, as shown, they often do not take into account common characteristics of urban freight transport (e.g., heterogeneous fleets and regulations). An exception can be found in Estrada and Roca-Riu (2017), who consider an overall time window constraint that is, however, modeled as a limited planning horizon in their study.

Both dynamic and static approaches are used to examine various influencing factors in the course of evaluating UCCs. Concerning the impacts of operational characteristics on the cost attractiveness of UCCs the influences of receiver density (Janjevic and Ndiaye, 2017b; Estrada and

Roca-Riu, 2017), the number of delivery stops per tour (Janjevic and Ndiaye, 2017b), delivery volume per stop (Janjevic and Ndiaye, 2017b), and LSP market share distributions (Roca-Riu et al., 2016; Estrada and Roca-Riu, 2017) are studied using approximation-based approaches, for example. Using simulations several operational characteristics are studied in the literature. These include, among others, the UCC usage fees and handling costs (van Duin et al., 2012; Wangapisit et al., 2014; van Heeswijk et al., 2019a; van Heeswijk et al., 2020), UCC value-added service profit margins (van Heeswijk et al., 2019a; van Heeswijk et al., 2020), and delivery quantities (van Heeswijk et al., 2020). Furthermore, van Heeswijk et al. (2020) analyze different receiver distributions, city sizes, and distances to the UCC. Regarding the impact of policies, on the one side subsides to LSPs or UCC are studied (van Duin et al., 2012; Wangapisit et al., 2014; van Heeswijk et al., 2019a; van Heeswijk et al., 2020). On the other sides, time windows (Estrada and Roca-Riu, 2017; van Heeswijk et al., 2019a; van Heeswijk et al., 2020) and area-based access fees (city tolls) (van Duin et al., 2012; van Heeswijk et al., 2019a; van Heeswijk et al., 2020) are analyzed.

In this dissertation, two quantitative evaluation approaches are taken. In Chapter 3, a jointly-operated UCC is investigated using an agent-based simulation for a period spanning multiple days. With this, different regulatory scenarios, featuring time windows, vehicle type restrictions, and area-based access fees (city tolls) can be simulated. Contrary to the aforementioned approaches, heterogeneous fleets are considered and an entire urban region including urban and non-urban receivers can be analyzed. Chapters 4 and 5 take a static optimization-based approach, in which it is assumed that the decision to use UCCs is an operational planning decision. Unlike previous analysis approaches that rely on approximation methods, vehicle routing heuristics are used to calculate routing costs. In this process, urban freight transport regulations, fleet size and mix decisions, as well as the decision to use UCCs, are taken into account. Chapter 4 addresses the impact of UCCs usage fees, heterogeneous fleets, varying customer request sizes, and receiver counts, as well as time windows. Chapter 5 also looks at different UCCs usage fees and customer request sizes. In addition, the impact of a per-day and a per-entrance city toll with different toll levels, as well as the share of urban receivers, are examined.

2.3 Vehicle Routing in Urban Freight Transport

Vehicle routing is a central task for LSPs in urban freight transport. In this section, an overview of VRPs in the context of urban freight transport is given. VRPs describe a class of combinatorial optimization problems with a research history of more than 60 years since their introduction by Dantzig and Ramser (1959). The most commonly studied and archetypal variant of the VRP is the capacitated vehicle routing problem (CVRP) (Drexl, 2012; Irnich et al., 2014). Following the definition provided by Drexl (2012), the CVRP can be described as follows. Given a set of customer requests and a fleet of identical vehicles with limited loading capacity stationed at a single depot, the CVRP aims to determine a set of vehicle routes to perform all deliveries associated with the customer requests. This includes determining the assignment of customer requests to vehicles and their visit sequence. In the process, each customer request must be served exactly once and the loading capacity of the vehicles on each route must be adhered to. Its overall goal is the optimization of an objective function.

As Vidal et al. (2020) point out, over the last few years there has been a large increase in the number of problem variants of the VRP. Especially urban freight transport has some distinctive characteristics that led to the development of new problem extensions of the VRP (Cattaruzza et al., 2017). Cattaruzza et al. (2017), for example, identify four main challenges in the optimization of vehicle routes for urban freight transport. These four identified challenges are time-dependent travel times, multi-echelon (level) distribution, dynamic information, and routes with multiple trips. In summary, these challenges comprise aspects related to the structure of the distribution network and operations, as well as to the characteristics of urban areas. Urban freight transport regulations are however not taken into account.

At a more general level, several approaches to structure and classify VRPs regarding their characteristics exist (see e.g., Drexl, 2012; Irnich et al., 2014; Braekers et al., 2016; Lahyani et al., 2015). Although not specifically focusing on urban freight transport, Vidal et al. (2020) propose a simple, yet helpful structure for systematizing VRP extensions, which is used to guide the overview of VRP problem extensions in the context of urban freight transport in this chapter. Vidal et al. (2020) divide the ways to extend the VRP into three broad categories. The first category relates to the extension regarding the objectives, side metrics, or combinations of objectives. The second category concerns the integration of vehicle routing optimization with other business decisions. Lastly, the third category refers to the development of more precise and fine-grained models. Numerous VRP problem extensions in the literature have a more or less pronounced relevance to urban freight transport. However, due to the general abundance of problem variants, it is difficult to provide a comprehensive overview of VRP extensions, as Vidal et al. (2020) also note in general. In the following, therefore, only a selection of problem variants relevant to urban freight transport and this dissertation will be presented, as illustrated in Figure 2.4. Therein, the extension areas with particular relevance to this dissertation are highlighted in dark grey.

2.3.1 Problem Objectives

A key aspect of VRPs is the modeled objective. A distinction can be made between VRPs with a single objective or multiple objectives (Lahyani et al., 2015). Most commonly, objectives related to profitability, such as costs, are considered (Vidal et al., 2020). Typically, the costs of vehicle routing are depicted in a simplified way, so that only the distance traveled or travel time are considered. These objectives, however, only inaccurately represent the reality of (urban) freight transport. In the context of time windows, for example, the total route duration, which includes possible waiting times, is a more realistic objective than the traveled time or distance (Savelsbergh, 1992; François et al., 2019). In recent years, several variants of the VRP feature more complex and realistic cost functions. These include fixed costs per route for using a vehicle, as well as variable costs that are proportional to the traveled distance, duration, or fuel consumed (Drexl, 2012; Vidal et al., 2020). Ehmke et al. (2018), for example, propose a VRP with a rich objective function, in which the fuel consumption of vehicles is based on the current load and variable speed in urban areas.

In addition to profitability, which refers not only to cost, Vidal et al. (2020) also list service quality, equity, consistency, simplicity, reliability, and externalities as other objective metric categories. Due to the inherent trade-offs in urban freight transport, externalities such as pollutant emissions are of particular importance in addition to profitability. Examples of this, but focused primarily on CO_2 emissions and not limited to urban freight transport, are the green VRP (Moghdani et al., 2021) and the pollution-routing problem (PRP) (Bektaş and Laporte, 2011). Within these problems, a number of factors that influence fuel consumption and thus emissions can be taken into account. These factors include, for example, vehicle, traffic, and operational factors (Demir et al., 2014). A

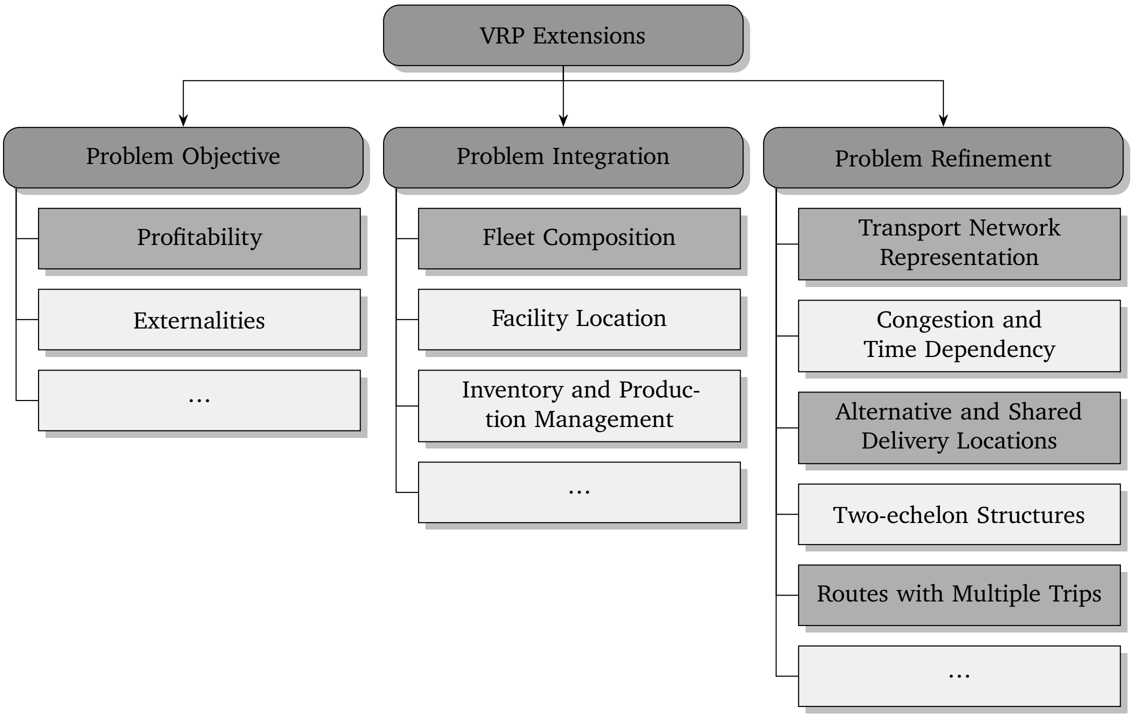


Figure 2.4: Overview of discussed vehicle routing problem extensions related to urban freight transport. Areas considered in the research of this dissertation are highlighted in dark grey.

notable example with respect to urban freight transport is provided by Raeesi and Zografos (2019). In their paper, a variant of the PRP called Steiner PRP which considers an urban road network with time-dependent travel times is presented. In this problem, fixed vehicle costs, the amount of fuel consumed, and the duration of routes are taken into account.

2.3.2 Problem Integration

Real-world systems, such as urban freight transport systems and supply chains, are characterized by their high complexity and interdependent planning issues. Failure to consider the intertwined planning problems holistically can lead to suboptimal business decisions (Schmid et al., 2013). Consequently, VRPs are frequently extended to include other business decisions (Schmid et al., 2013; Lahyani et al., 2015; Vidal et al., 2020). Especially in the context of supply chain management various integrated problems that consider production, warehousing and inventory decisions have been proposed (Schmid et al., 2013). In general, several VRP extension categories can be distinguished. Vidal et al. (2020) divide the extensions of the VRP into multiple areas, including routing and fleet composition, routing and facility location, and other integrated problems.

Fleet Composition

A widely studied integrated problem in the context of the VRP is the tactical decision on the size and composition of the fleet. In freight transport in general and urban freight transport in particular, heterogeneous vehicle fleets are often used (Hoff et al., 2010). For example, a survey conducted among LSPs that perform urban deliveries shows that LSPs employ between two to three different sized vehicle types (Cherrett et al., 2012). The types of vehicles used by LSPs are influenced by urban freight transport regulations, such as weight restrictions, freight characteristics, and other operational characteristics (Allen et al., 2008). A distinctive feature of heterogeneous VRPs are the considered vehicle characteristics. Each vehicle or vehicle type can be defined by a number of different characteristics. These characteristics include, for example, costs, load capacity, driving speed, as well as customer-request, location- or arc-specific restrictions (Drexl, 2012; Vidal et al., 2020).

In general, two problem classes can be distinguished: the FSM and the heterogeneous fixed fleet VRP (Koç et al., 2016c). The FSM was introduced by Golden et al. (1984) and assumes an unlimited fleet of heterogeneous vehicles. The heterogeneous fixed fleet VRP, introduced by Taillard (1999), assumes a predetermined limited fleet of heterogeneous vehicles in contrast. Building on these two basic problems, a plethora of problem variants can be found in the literature. An important variant is for example the fleet size and mix vehicle routing problem with time windows (FSMTW), introduced by Liu and Shen (1999), which incorporates time window constraints.

Among the numerous problem variants, several problem variants related to urban freight transport can be identified. One stream of FSM problem variants focuses on emissions. For example, some problem variants combine the FSM with the PRP to find the best fleet for urban freight transport from an emissions and cost perspective (Koç et al., 2014; Koç et al., 2016b; Raeesi and Zografos, 2019). For example, using a case study in an urban context, Koç et al. (2016b) show that using heterogeneous fleets can reduce costs, but slightly increase emissions compared to using only small vehicles. Also motivated by the goal of reducing emissions from freight transport, some studies focus on FSM problems with conventional and electric vehicles (Lebeau et al., 2015;

Hiermann et al., 2016; Hiermann et al., 2019; Rezgui et al., 2019). Another FSM problem variant related to urban freight transport focuses on the fleet mix in the presence of urban freight transport regulations. Besides time windows, which are commonly considered within FSMs since their introduction by Liu and Shen (1999), Hiermann et al. (2019) study a FSM with city toll schemes and vehicle type access restrictions. In their article, they analyze the effects of four city toll schemes, taking into account both electric and conventional vehicles. Moreover, they examine the effects of a ban that prohibits conventional vehicles from entering city centers. A broad overview of further heterogeneous VRPs as well as approaches to model and solve these problems can be found in Koç et al. (2016c).

Facility Location and Other Integrated Problems

In addition to integrated problems related to fleet size and fleet mix, several other integrated problems are found in the literature. A further category of integrated problems revolves around the location of facilities. A prominent problem class in this category is the location-routing problem (LRP), which aims to simultaneously determine the location of depots serving customer requests and the routes departing from these depots. Especially LRPs for multi-echelon distribution systems that consider the locations of satellite facilities have a strong connection to urban freight transport (Nguyen et al., 2012). Koç et al. (2016b) for example analyze a LRP with heterogeneous fleets in the context of city logistics. Therein, fuel consumption and resulting CO_2 emissions are considered. With their problem and the results of a case study, they show that it is favorable from a pollution perspective to locate depots outside of city centers. Nataraj et al. (2019) consider a LRP in which they determine the location of jointly-operated UCCs. In this context, however, no upstream processes, such as transport from the LSPs to the UCCs, are considered. Nguyen et al. (2012) investigate a two-echelon LRP in which the location of the satellite facilities is to be decided, while the location of the depot is already known in advance. Contardo et al. (2012), by contrast, study a two-echelon LRP in which facility locations are subject to decision-making at both the depot and satellite levels.

Other integrated problems in the context of VRPs include inventory-routing problems (Bell et al., 1983) and production routing problems (Chandra and Fisher, 1994). However, these integrated problems are rarely motivated by aspects of urban freight transport. An exception is provided by Nolz (2021), who proposes an integrated construction logistics optimization problem featuring a location-routing problem in the context of a construction UCC. In addition, some other works address two-echelon inventory routing and production routing problems that, like the two-echelon vehicle routing problem (2E-VRP), are commonly described to be used in large cities (Qiu et al., 2021; Rohmer et al., 2019).

2.3.3 Problem Refinements

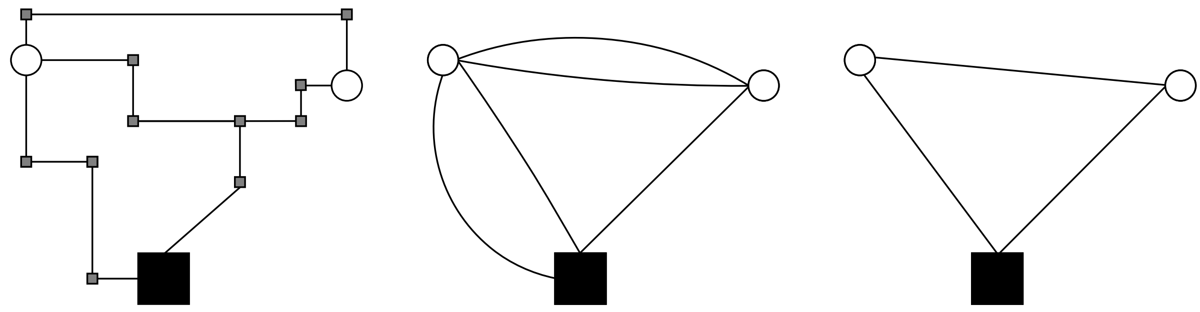
The third category of VRP problem extensions is about problem refinements that aim to incorporate real-world attributes of freight transport in the vehicle routing process. With regard to urban freight transport, problem refinements mainly focus on the specifics of urban transport networks including urban freight transport regulations, congestion, and multi-echelon structures as well as the multiple uses of vehicles per day. Overviews of further problem refinements which are not necessarily specific to urban freight transport, such as driver-related or vehicle-related aspects, as well as customer request aspects, can be found in Vidal et al. (2020), Drexl (2012), and Lahyani et al. (2015).

Transport Network Representation

An emerging area for problem refinements is the transport network. Transport networks in reality are usually characterized by a variety of attributes. These attributes include, for example, distances, expected travel times, emissions, and tolls (Ben Ticha et al., 2018; Vidal et al., 2020). Most works on VRPs assume customer-based graphs, where a vertex is introduced for each point to visit (e.g., depot, customers, transshipment facilities), and a single arc represents the best path between each of these points (Ben Ticha et al., 2017). In reality, however, the paths between any two points are usually characterized by trade-offs and the best path for a given situation might depend on other decisions (Ben Ticha et al., 2018; Reinhardt et al., 2016). For example, the path with the least distance between two points does not necessarily correspond to the path with the least travel time when road characteristics, such as speed limits and congestion, are taken into account (Ben Ticha et al., 2019b). Furthermore, access to some areas, such as city centers, might be restricted by area-based tolls or access time windows (Ben Ticha et al., 2018). Therefore, it is not trivial to determine a single best path between any two points, and instead, a set of efficient paths with different trade-offs should be considered (Ben Ticha et al., 2019b; Vidal et al., 2020). However, in the commonly used customer-based graphs, only one path exists between each vertex, so any information about alternative paths is lost (Ben Ticha et al., 2019a). As a result, the use of customer-based graphs can lead to suboptimal solutions compared to approaches that consider multiple efficient paths with different trade-offs (Garaix et al., 2010).

To address this problem, the field of VRPs with more detailed road-network information has emerged in recent years (Ben Ticha et al., 2018). Ben Ticha et al. (2018) distinguish between two alternative modeling approaches. In the first approach, a so-called road-network graph is used which mimics an original road network. Apart from customers and depot vertices, this type of graph consists of road segments, which constitute the arcs, and road junctions, which represent vertices connecting these arcs. Only a few works follow a road-network graph approach. Letchford et al. (2014) were the first to propose a road-network approach and present pricing routines for the vehicle routing problem with time windows (VRPTW) on a road-network graph. Ben Ticha et al. (2019b) continue into this research direction and propose a branch-and-price algorithm for a VRPTW on a road-network graph with travel time and cost attributes.

In the second, more common approach, a multigraph in which multiple efficient paths can exist between any two vertices, is used. As a consequence, not only the visit sequences but also the arcs connecting the visits must be optimized (Garaix et al., 2010). Garaix et al. (2010) denote this problem of selecting the arcs between consecutive visits as the fixed sequence arc selection problem (FSASP). By comparing the problem with a multidimensional multiple-choice knapsack problem, the authors show that the FSASP is NP-hard. Figure 2.5 illustrates a comparison between the road-network graph, multigraph, and customer-based graph network representations using a simple example. Figure 2.5 a) shows a road-network graph with road segments and road junctions. In Figure 2.5 b) the road-network graph has been transformed into a multigraph with multiple arcs representing non-dominated paths between any two vertices. Figure 2.5 c) depicts a customer-based graph in which only one arc exists between any two vertices (e.g., the time-minimal arc).



a) Road-network graph b) Multigraph c) Customer-based graph

Figure 2.5: Comparison of the road-network graph (a), multigraph (b), and customer-based graph (c) representations. Customers are represented by circles and the depots by large black squares. Road junctions are symbolized by small grey squares.

A number of different VRP problems have been studied using multigraphs. Garaix et al. (2010) were among the first to use a multigraph in the context of a VRP with multiple arc attributes. They study a VRP for on-demand transport. Behnke et al. (2021) study an emission-oriented vehicle routing problem using a multigraph. In their studied problem, each arc considers the individual traffic speed and acceleration of the underlying road segments which leads to vehicle-dependent sets of emission-efficient arcs between every two vertices. Further examples of VRPs using multigraphs include Lai et al. (2016) (heterogeneous VRP), Ben Ticha et al. (2019a) (VRPTW), Huang et al. (2017) (time-dependent VRP), and Soriano et al. (2020) (VRP with arrival time diversification).

One application area with particular relevance to this dissertation and urban freight transport is city toll regulations. Numerous cities around the world have implemented different city tolls schemes that apply not only to individual streets but also to urban areas (Wen and Eglese, 2016). In practice, a distinction can be made between day-based and entry-based tolls, and tolls that are proportionate to the distance driven or duration spent in the toll area (Hiermann et al., 2019; Zhang et al., 2019). In addition, city tolls can be further divided into time-dependent variable tolls and constant tolls (Wen and Eglese, 2016). Especially per-day city tolls, which are only payable the first time a vehicle enters a toll area on a given day, are interesting from a vehicle routing perspective. This is because the decision on whether a vehicle passes through a toll area or avoids it might depend on the number of times the vehicle crosses the area.

In recent years several papers addressed city toll schemes in connection with VRP. Wen and Eglese (2015) study a time-dependent multi-trip vehicle routing problem with time windows (MTVRPTW) with an area-based toll per day. In their heuristic algorithm, they compare two timetables: one where the toll must be paid for every entry, and one where the toll is ignored. Based on the cost comparison between the two timetables, a decision is made for each vehicle route whether or not to enter the toll area. Zhang et al. (2019) extend the heuristics from Wen and Eglese (2015) by implementing entry-based, duration-based, and distance-based city toll schemes. Contrary to Wen and Eglese (2015), however, they disregard vehicle capacities, arguing that the maximum route duration in urban areas is a more limiting factor. Using their algorithm and artificial instances, they compare the different city toll schemes and analyze the effects of time windows and different city and toll area sizes on costs and fuel consumption. Reinhardt et al. (2016) consider a VRPTW that is related to city toll schemes. In the problem, fixed costs for accessing a set of arcs are considered. This could be, for example, area-based tolls or other types of fees that companies have to pay when their vehicles want to access certain infrastructures. Unlike problems on city toll schemes, however, they assume that once the arc set fee is paid, all vehicles can access the arcs of that set. Mirhedayatian and Yan (2018) study different policy measures to support the use of electric vehicles in urban freight transport. In doing so, they provide a mixed-integer linear programming (MILP) formulation of a VRP with a per-day city toll scheme and a mixed fleet of conventional and electric vehicles. Electric vehicles are, however, exempt from the toll. Also focusing on a mixed fleet of conventional and electric vehicles, Hiermann et al. (2019) present a FSMTW with per-day, per-entry, distance-based, and duration-based city toll schemes as well as bans on conventional vehicles. To solve the problem heuristically, a hybrid genetic algorithm with methods for efficient route evaluations is presented.

Congestion and Time Dependency

Another aspect affecting transport in urban areas is the presence of congestion. The INRIX 2020 Global Traffic Scorecard report, for example, estimates that congestion in Germany alone leads to an annual cost of 2.3 billion euros (Pishue, 2021). Congestion, however, not only affects the costs of LSPs due to extended transport times but also contributes to an increase in vehicle emissions (Figliozzi, 2010; Ehmke et al., 2016; Zhang et al., 2011). Typically, VRPs consider travel times based on average vehicle speeds for the arcs (Cattaruzza et al., 2017). In reality, however, the expected travel times in cities are variable and time-dependent, since, for example, congestion increases during rush hours, resulting in slow-moving traffic (Ehmke et al., 2016).

Time-dependent VRPs aim to address this issue by assuming that travel time between any two vertices depends on the start time of the vehicles. An important feature for time-dependent VRPs is the first-in-first-out property of travel times, which ensures that vehicles that start later also arrive later (Ichoua et al., 2003; Figliozzi, 2012). Two commonly applied methods to account for this property are travel-time or travel-speed functions (Gendreau et al., 2015; Ichoua et al., 2003; Fleischmann et al., 2004). Multiple extensions and algorithms for solving deterministic and stochastic time-dependent VRPs have been proposed. An overview can be found in Gendreau et al. (2015). Several recent papers combine time dependence with other aspects of urban freight transport. For example, Rincon-Garcia et al. (2020) study a VRPTW with time-dependent travel times and driving hours regulations in a city context. Huang et al. (2017) model a time-dependent VRP with path flexibility considering an urban road network so that multiple paths between customers exist. Pan et al. (2021) model a time-dependent VRP with multi-trips in a city context.

Alternative and Shared Delivery Locations

In contrast to the classic VRPs, problem extensions with alternative locations and shared delivery locations (SDLs) are characterized by the possibility that more than one delivery location per customer request exists. In general, these problems can also be considered as integrated problems, as they integrate the decision of selecting the location to which customer requests should be delivered into the VRP.

Three types of applications can be distinguished in the literature. The first case is motivated by the emergence of parcel lockers and similar pickup facilities where customers can collect deliveries on their own (e.g., Orenstein et al., 2019; Dumez et al., 2021a; Grabenschweiger et al., 2021). The second type of application is also motivated by parcel deliveries. However, instead of allowing deliveries to SDLs, parcels can be delivered to customer-specific alternative locations (e.g., vehicle trunks) depending on a given time schedule (Reyes et al., 2017; Ozbaygin et al., 2017). Lastly, the third type of application is motivated by UCCs and similar third-party urban transshipment facilities where LSPs can transship their customer requests instead of performing the last-mile deliveries themselves (e.g., Baldacci et al., 2017; Alcaraz et al., 2019). With respect to the research in this thesis, which focuses on UCCs where multiple deliveries are bundled, the first and third application types are particularly relevant as in both cases SDLs exist. Nonetheless, the problems of the second case are also considered in Chapter 4 to validate the performance of the presented heuristic.

In the following, the works on VRPs with SDL are summarized. As mentioned above, several papers focus on the inclusion of parcel lockers and similar pickup facilities, and the associated decision of which customer requests to deliver to which parcel locker or to the customer directly. Despite a common motivation and several similarities, problem variants are named quite differently in the literature. Among the first to study this problem were Sitek and Wikarek (2019) and Orenstein et al. (2019). Sitek and Wikarek (2019) propose a so-called capacitated vehicle routing problem with pick-up and alternative delivery (CVRPPAD), where customers can receive their parcels at home or pick them up at a SDL. Orenstein et al. (2019) introduce a similar problem called the flexible parcel delivery problem (FPDP), where parcels must be delivered to one of several different sized parcel lockers. In their problem, customers can however not receive their parcels at home and thus only SDLs are considered. Mancini and Gansterer (2021) propose the vehicle routing problem with private and shared delivery locations (VRPPSDL), which considers both deliveries to individual private locations and SDLs. Private locations here are associated with a customer-specific time window. Grabenschweiger et al. (2021) study a very similar problem named the vehicle routing problem with heterogeneous locker boxes (VRPHLB). In their problem, they allow for differently sized parcels and parcel slots within the parcel lockers. Thus, besides the routing of vehicles and the assignment of parcels to parcel lockers, the problem also requires decisions regarding the packing of parcels into slots. The vehicle routing problem with delivery options (VRPDO), which is studied by Dumez et al. (2021a), Dumez et al. (2021b), and Tilk et al. (2021), follows a similar motivation as the previously mentioned problems. Unlike other problems, however, the problem introduces customer-specific preference levels associated with the SDLs. To account for these preferences, the problem introduces constraints on the overall customer preference satisfaction. Zhou et al. (2018) (multi-depot two-echelon vehicle routing problem with delivery options (MD-2E-VRPDO)) and Enthoven et al. (2020) (two-echelon vehicle routing problem with covering options (2E-VRP-CO)) also focus on parcel pick up points and introduce them to the 2E-VRP. However, unlike Mancini and Gansterer (2021), Grabenschweiger et al. (2021), and the works on the VRPDO, they do not consider parcel locker capacities.

The third area of application considers SDL in the form of UCCs and similar transshipment facilities for urban areas. Compared to customer pickup facilities, little research has addressed this application. The first problem to consider transshipment decisions to third-party facilities, such as UCCs, is provided by Baldacci et al. (2017). In their vehicle routing problem with transshipment facilities (VRPTF), customer requests can be transshipped to third-party transshipment facilities

(UCCs) for a distance-dependent fee. Alcaraz et al. (2019) address a related problem characterized by several problem attributes, including driver-hours regulations and incompatibility among goods. The work in this dissertation focuses on the VRPTF of Baldacci et al. (2017) and extends it by presenting new problem variants and heuristic solution methods. Chapter 4 presents the vehicle routing problem with time windows and transshipment facilities (VRPTWTF) and the fleet size and mix vehicle routing problem with time windows and transshipment facilities (FSMTWTF) with two types of cost functions. Contrary to previous problems featuring SDL, both problems present variants that incorporate duration-based costs while optimizing vehicle departure times from the depot. Chapter 5 of this dissertation extends the FSMTWTF and proposes the multi-trip multi-path fleet size and mix vehicle routing problem with time windows and transshipment facilities (MTMP-FSMTWTF). In this problem, multiple trips per vehicle and day, service-dependent loading times, and maximum shift durations shorter than the planning horizon are introduced. Moreover, two types of city tolls are included by using a multigraph representation.

Figure 2.5 summarizes the main attributes of the presented VRPs with SDLs. The *Problem variant* and *Authors* columns list the names of the problem variants and the authors who study these problems. The columns *hom.* and *het.* indicate whether the problem assumes homogeneous fleets or heterogeneous fleets including fleet composition decisions. The next five columns describe the cost components of the objective functions. The *vehicle*, *arc*, and *duration* columns indicate whether fixed vehicle costs, arc-based costs (e.g., distance-based costs) or total duration-based costs (including waiting times) are included. The following two columns, *SDL use* and *other*, specify whether the use of SDLs, such as parcel lockers or UCCs, is associated with additional costs, and whether there are other cost components considered. The remaining two columns, *SDL capacity*, and *Time windows* denote whether SDLs have a limited customer request capacity and whether time window constraints are considered.

The overview shows that in most problem variants the use of SDLs is associated with some sort of cost. These costs may be independent of the customer requests or may depend, for example, on the size of the customer requests (e.g., in the FSMTWTF). In the problems focusing on UCCs, these costs represent the fee that LSPs must pay to the UCC operator in order for the UCC to transship and deliver the customer requests to the customers. In the case of self-pickup facilities, only some problems consider costs associated with using a SDL. If costs are considered, they usually represent compensation paid to customers for collecting their deliveries themselves. Another difference can be observed regarding the inclusion of capacity constraints. Contrary to problems assuming self-pickup facilities, problems on UCCs do not include capacity constraints for the SDL. This could be due to differences in the operation of the two types of facilities. Whereas parcels at self-pickup facilities are stored for up to several days until they get picked up, UCCs are usually operated as cross-docking facilities, where goods are transshipped to other vehicles and stored for only a short time, if at all.

Two-echelon Structures

Two-echelon distribution structures describe a special case of multi-echelon systems in which a transport network is comprised of two echelons (Cuda et al., 2015). Based on Cuda et al. (2015) they can be described as follows. In the first step, freight is transported from a central depot to satellite facilities where it is stored, consolidated, or transshipped. Subsequently, the freight is delivered from the satellite facility to its destination. The 2E-VRP describes a class of problems

Table 2.5: Overview of vehicle routing problems with transshipment facilities and shared delivery locations.

Problem variant	Authors	Fleet		Cost components					SDL capacity	Time windows
		hom.	het.	vehicle	arc	duration	SDL use	other		
VRPTF	Baldacci et al. (2017); Friedrich and Elbert (2022) (Chapter 4)	✓			✓		✓			
"Rich" VRP	Alcaraz et al. (2019)		✓		✓		✓			✓
VRPTWTF	Friedrich and Elbert (2022) (Chapter 4)	✓		✓	✓	(✓)	✓			✓
FSMTWTF	Friedrich and Elbert (2022) (Chapter 4)		✓	✓	✓	(✓)	✓			✓
MTMP-FSMTWTF	Chapter 5		✓	✓	✓	✓	✓	city toll		✓
FPDP	Orenstein et al. (2019)	✓		✓	✓			penalty for parcels not delivered	✓	
CVRPPAD	Sitek and Wikarek (2019)		✓		✓		✓		✓	
VRPDO	Dumez et al. (2021a); Dumez et al. (2021b); Tilk et al. (2021)	✓			✓				✓	✓
VRPPSDL	Mancini and Gansterer (2021)	✓		✓	✓		✓		✓	✓
VRPHLB	Grabenschweiger et al. (2021)	✓			✓		✓		✓	✓
MD-2E-VRPDO	Zhou et al. (2018)	✓		✓	✓		✓	satellite facility handling cost		
2E-VRP-CO	Enthoven et al. (2020)	✓			✓		✓			

that concerns the optimal routing in two-echelon distribution structures.

The application of 2E-VRPs is commonly associated with urban freight transport and city logistics (Cuda et al., 2015; Guastaroba et al., 2016). In this context, it is emphasized that transhipping goods at satellite facilities, also called intermediate facilities, allows the use of smaller or more environmental-friendly vehicles in the city (Crainic et al., 2009; Savelsbergh and van Woensel, 2016; Anderluh et al., 2021). Crainic et al. (2009), for example, study a two-echelon distribution system for large cities in which a central depot is located at the city limits and satellite facilities are located within or near the city center. Satellite facilities are assumed to be operated on a cross-docking principle with no intermediate storage and thus may be non-permanent facilities, such as parking lots and town squares. At these satellite facilities, freight is transshipped to smaller so-called city freighters, which are better suited for urban freight transport.

In the literature, many problem variants of the 2E-VRP are studied. Anderluh et al. (2021), for example, present a multicriteria 2E-VRP in which the negative externalities of urban freight transport are considered. Using artificial city layouts, they further examine the impact of city layouts on total costs and externalities. Zhou et al. (2018) study a so-called MD-2E-VRPDO in an urban setting. In the problem, which bears resemblance to the VRPDO, customers can pick up their deliveries at pickup facilities instead of having them delivered to their homes. Enthoven et al. (2020) study a very similar 2E-VRP in an urban context. In their 2E-VRP-CO, they also extend the 2E-VRP by introducing pickup facilities, called covering locations, where customers pick up their deliveries themselves. Each customer request can be satisfied either by delivering it to the customer via a satellite facility or by delivering it to a pickup location where customers pick it up themselves. However, unlike Zhou et al. (2018), they allow split deliveries at the first echelon, and the pickup facilities are served through the first echelon instead of the second echelon. Finally, an overview of further variants, as well as modeling and solution approaches, can be found in the reviews of Cuda et al. (2015) and Guastaroba et al. (2016).

Routes with Multiple Trips

In the VRP, it is generally assumed that each vehicle may only make one trip per day or planning period. However, as Olivera and Viera (2007) argue, this assumption is unrealistic in many cases, as vehicles often make several short trips per day, especially in urban areas. Supporting this argument, Aljohani and Thompson (2020a), for example, report that 42 % of LSPs surveyed in Melbourne, Australia, perform more than one trip per vehicle per day in the city center. In their survey, a few of the questioned LSPs even state to complete three trips per vehicle per day. As a result, the possibility for multiple trips should be explicitly taken into account during vehicle route planning. The multi-trip vehicle routing problem (MTVRP), introduced by Fleischmann (1990), addresses this issue. The MTVRP is an extension of the VRP in which vehicles can perform a set of trips during each planning horizon. The number of trips a vehicle can perform is limited by the length of the planning horizon or the maximum tour duration. Two approaches for handling multiple trips in heuristic algorithms can be found in the literature. In the first, commonly used method, trips are assigned to vehicles using bin-packing techniques (see e.g., Fleischmann, 1990; Taillard et al., 1996; Olivera and Viera, 2007; Cattaruzza et al., 2014). In this approach, trips are first generated and considered as items, whose duration represents the item size. Subsequently, the trips (items) are assigned to the vehicles, which are considered as containers whose capacity corresponds to the maximum allowed tour duration (François et al., 2016). However, with the addition of constraints and extensions, such as time windows and heterogeneous fleets the difficulty of assigning trips to vehicles increases (Cattaruzza et al., 2016; François et al., 2016). To address this issue, François et al. (2016) and François et al. (2019) provide an integrated approach for the MTVRP and the MTVRPTW using multi-trip local search operators. In the integrated approach, the generation of trips (routing) and the assignment to vehicles (bin packing) are handled simultaneously. For this purpose, the ordered trips of a vehicle are represented as a giant tour that includes replenishment visits to the depot (François et al., 2016). Given the demonstrated advantage for routing problems with time windows provided by François et al. (2019), the integrated approach is used in Chapter 5 of this dissertation.

Besides heuristics solution approaches, several mathematical formulations exist for the MTVRP and its variants. These include 4-index, 3-index, and 2-index formulations (Cattaruzza et al., 2018; Neira et al., 2020). A 2-index formulation approach to model successive multi-trips as a single tour, which is followed in Chapter 5, is provided by Rivera et al. (2015). In this approach, replenishment arcs are added for each pair of customers, representing an intermediate round trip of a vehicle to the depot (Neira et al., 2020). Thus, instead of using one arc from the last customer of a trip to the depot and a second arc from the depot to the first customer of the next trip, a replenishment arc is used between the two customers (Rivera et al., 2015).

In addition to time windows, multi-trip problems are commonly combined with further problem constraints. These constraints include, service-dependent loading times (e.g., François et al., 2019; Neira et al., 2020), limited trip durations (e.g., Azi et al., 2014; Hernandez et al., 2014; Wang et al., 2014; Neira et al., 2020), and limited tour durations (e.g., François et al., 2019; Battarra et al., 2009). In this dissertation service-dependent loading times and limited tour durations are considered. Service-dependent loading times depend on the customer requests served during a trip. The loading duration is usually considered to be proportional to the sum of service time of the customer requests served in the trip (Cattaruzza et al., 2016). Limited trip duration constraints refer to the duration of each trip a vehicle performs. The limited tour duration constraint, by contrast, limits the total duration that a vehicle may spend on performing its set of trips to a duration that is shorter than the planning horizon (François et al., 2019).

2.3.4 Solution Methods for Vehicle Routing Problems

For the past decades, an abundance of solution methods has been developed for the VRP and its variants. In this section, a brief overview and classification of solution methods for the VRP are given. Hereby, the focus is especially on metaheuristics, which are particularly relevant for VRPs in urban freight transport that are characterized by numerous attributes. Figure 2.6 provides a classification of solution methods for VRPs that is derived from reviews on solution methods by Elshaer and Awad (2020), Laporte (2009), Laporte et al. (2014), and Archetti and Speranza (2014).

At the first level, solution approaches for VRPs can be divided into exact solution methods, heuristics, and other solution approaches (Braekers et al., 2016; Laporte, 2009). Exact approaches include solution methods such as branch-and-cut and branch-and-price algorithms. However, due to the size of many problem instances and the increasing number of problem attributes, such as in urban freight transport, exact solution methods face challenges (Drexl, 2012). As such, often only small problem instances can be solved to optimality (Laporte et al., 2014). Heuristics form the second class of solution methods. In contrast to exact methods, heuristics do not guarantee that an optimal solution is found but instead find good solutions in much less time (Blum and Roli, 2003). In addition to exact methods and heuristics, there are also further solution approaches, such as dynamic programming and simulation. However, these methods are used comparatively rarely (Braekers et al., 2016).

Heuristics can be further divided into constructive heuristics, metaheuristics, and matheuristics. Numerous constructive heuristics were proposed for VRPs between the 1960s and 1980s (Laporte, 2009; Vidal et al., 2013b). A central characteristic of constructive heuristics is that they follow a greedy approach (Vidal et al., 2013b). Nowadays, constructive heuristics are mainly used to generate initial or new solutions within metaheuristics (Vidal et al., 2013b; Laporte et al., 2014). Examples of constructive heuristics include the savings algorithm of Clarke and Wright (1964) and petal algorithms.

According to a recent review paper by Braekers et al. (2016), metaheuristics are the most commonly used solution method for VRPs. The term metaheuristic can be traced back to Glover (1986) and refers to a broad class of strategies that "guide" the search process (subordinate heuristics) (Blum and Roli, 2003). Metaheuristics are approximate and aim to generate (near-) optimal solutions by efficiently exploring and exploiting the search space (Blum and Roli, 2003; Osman and Laporte, 1996). Various approaches exist in the literature to classify metaheuristics (Blum and Roli, 2003). A frequently used approach is to distinguish between single-solution-based methods and population-based methods (Blum and Roli, 2003; Elshaer and Awad, 2020). Single-solution-based algorithms operate, as the name indicates, during each iteration on a single solution. Their search process can be described as a trajectory in the search space, as they move from one solution to another solution at each iteration (Blum and Roli, 2003; Laporte et al., 2014). Single-solution-based methods encompass local search-based approaches and are characterized by the necessity of escaping from local optima and avoiding cycling (Laporte et al., 2014). With regards to VRPs, among the most commonly used methods are tabu search, variable neighborhood search, iterated local search, large neighborhood search (LNS), and adaptive large neighborhood search (ALNS) (Elshaer and Awad, 2020). Population-based methods operate by contrast in each iteration on a set (population) of solutions (Blum and Roli, 2003). They are usually inspired by natural concepts and can be split into evolutionary methods, such as genetic and memetic algorithms, and swarm intelligence methods, such as ant colony optimization (Elshaer and Awad, 2020). According to Laporte et al. (2014), all successful population-based methods in the context of VRPs contain local search elements and are therefore hybrid.

The third class of heuristic solution methods is matheuristics. Matheuristics, as defined by Boschetti et al. (2009, p. 171), denote a class of heuristic algorithms that are characterized by *"[…] the interoperation of metaheuristics and mathematic programming techniques"*. Following the broad classification of Archetti and Speranza (2014), three classes can be distinguished. These classes are decomposition approaches, improvement heuristics, and branch-and-price/column generation-based approaches. Matheuristic approaches that are built on problem decompositions follow the divide-and-conquer principle and are characterized by breaking up a problem into several smaller and easier to solve subproblems (Archetti and Speranza, 2014; Maniezzo et al., 2021). Matheuristic approaches, which belong to the class of improvement heuristics, generally describe approaches that use mathematical programming models to improve a solution found by another heuristic approach. Branch-and-price/column generation-based approaches use branch-and-price or column generation to create heuristic solutions and can be divided further to restricted master heuristics, heuristic branching approaches, and relaxation-based approaches (Archetti and Speranza, 2014).

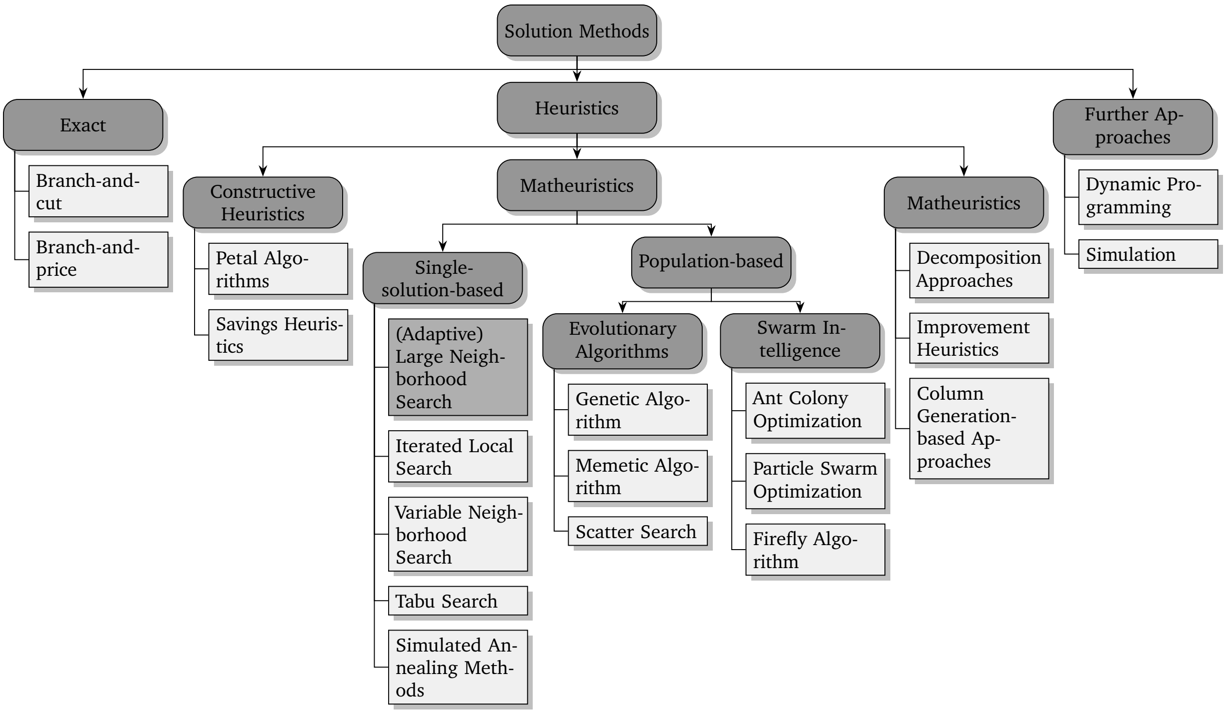


Figure 2.6: Classification of frequently applied solution methods for vehicle routing problems based on Elshaer and Awad (2020), Laporte et al. (2014), and Archetti and Speranza (2014).

In Chapters 4 and 5 of this dissertation, an ALNS heuristic, which belongs to the class of single-solution-based metaheuristics, is presented. ALNS is a widely used framework in vehicle routing that is proven to be effective for multigraph and multi-trip problems (Pisinger and Ropke, 2019; Elshaer and Awad, 2020; François et al., 2019; Ben Ticha et al., 2019a). The ALNS framework was introduced by Ropke and Pisinger (2006b) and is closely related to the LNS concept (Shaw, 1998) and the ruin and create method of Schrimpf et al. (2000). The ALNS framework is characterized by destroying the current solution at each iteration and subsequently repairing it. In doing so, multiple removal and insertion operators are available. To control the probability of operators and thus the frequency of how often they are used during the search, each destruction and repair operator is assigned a weight. During the search, these weights are dynamically adjusted based on the performance of each operator (Ropke and Pisinger, 2006b; Pisinger and Ropke, 2019). In addition to this, a randomized variable neighborhood descent (RVND) which is a variant of the variable neighborhood search is embedded into the ALNS presented in this dissertation to intensify the search. Furthermore, the presented heuristic also shares characteristics of a matheuristic by including a set partitioning (set covering) formulation to recombine routes found by the ALNS heuristic. Every time a certain number of iterations has passed, the set partitioning (set covering) problem is called to try to improve the incumbent solution of the ALNS heuristic.

2.4 Derivation of the Overall Research Design

To achieve the two overarching research objectives of developing models and solution algorithms to support the quantitative evaluation of UCCs and to provide insights into the impact of urban freight transport regulations and operational characteristics on the cost attractiveness of UCCs, four research questions (RQs) were raised, as described in Subsection 1.2.2. For each of the four questions, research propositions (RPs) are formulated, which are stated and explained grouped by their corresponding questions in the following.

RQ 1 addresses the approaches towards evaluating UCCs from the perspective of LSPs. In this context, it is proposed to differentiate between jointly-operated UCCs and third-party UCCs when evaluating UCCs. To aid the answering of RQ 1, different types of UCCs and methods to analyze UCCs are identified in Subsection 2.2.6 by reviewing the literature. The results of this analysis of the literature and the various UCC characteristics show that UCCs need to be studied differently according to their type and the assumed planning horizon. The two resulting RPs are as follows:

RP 1.1: *To strategically evaluate the cost attractiveness of jointly-operated UCCs for LSPs considering urban freight transport regulations and LSP-specific operational characteristics, scenario-based simulation modeling is an appropriate method.*

RP 1.2: *To operationally evaluate the cost attractiveness of third-party UCCs from the perspective of a LSP, an appropriate method is to integrate the decision to use UCCs into the vehicle route planning and thereby consider each customer request individually.*

RQ 2 revolves around the heuristic solution of the VRPTF and extends the problem to consider urban freight transport regulations (time windows and city tolls) and operational characteristics (heterogeneous fleets and multi-trips). RQ 2.1 and RQ 2.2 aim to extend the VRPTF and heuristically solve the resulting problem variants. Both RQs are answered by presenting heuristics with specific operators and mechanisms to address the transshipment decisions and proposed problem extensions. RQ 2.3 targets to evaluate the performance of the developed solution heuristics. This can be answered by comparing the results and runtimes of the heuristics with those of exact solution methods from the literature and commercial solvers, as well as a comparison with other heuristics from the literature on closely related problems. This gives rise to the following RPs:

RP 2.1: *The heuristic solution procedures provide solutions with low optimality gaps (compared to results from the literature and commercial solvers).*

RP 2.2: *The heuristic solution procedures provide solutions with significantly lower runtimes than exact solution methods.*

RQ 3 focuses on the comparison of the integrated VRP with the blanket decision approach. To answer RQ 3 the routing plans generated by both approaches are compared to each other in a real-world case study. In this, solution costs, as well as the UCC usage are compared between the two approaches for different problem sizes, fleets, UCC usage costs, demand levels, and time window lengths. The following two RPs are created:

RP 3.1: *The cost attractiveness and thus usage of UCCs differ between the integrated routing approach and the blanket decision approach.*

RP 3.2: *By taking transshipment decisions for each customer request individually, the integrated routing approach provides solutions with lower or equal costs compared to the blanket decision approach.*

RQ 4 and its three subquestions focus on providing insights by analyzing how urban freight transport regulations and operational characteristics affect the cost attractiveness of UCCs. RQ 4.1, which targets jointly-operated UCCs, is answered by a simulation case study in which multiple LSPs cooperate. In this process, the cost attractiveness of using the UCC is examined for each LSP individually. RQ 4.2 and RQ 4.3 are answered by real-world case studies, using the developed heuristics for the VRPTF and its variants. The following RPs are derived:

RP 4.1: *Urban freight transport regulations increase the cost attractiveness of jointly-operated UCCs for LSPs. The extent, however, differs among participating LSPs.*

RP 4.2: *Time windows and city toll regulations increase the cost attractiveness of UCCs for LSPs.*

RP 4.3: *Increases in UCC usage fees, as well as in the average demand volume of customer requests, strongly reduce the cost attractiveness of UCCs for LSPs.*

In summary, the RPs aim to provide valuable guidance for the practical implementation of UCCs as well as the related decisions of LSPs from both a methodological and an analytical perspective. As pointed out in Subsection 1.2.3, the RQs and corresponding RPs are addressed in the following three chapters. A reflection on the RQs and RPs is given in the overall conclusion in Section 6.1.

3 Simulation-based Evaluation of Urban Consolidation Centers Considering Urban Access Regulations[1]

Abstract

The negative effects of urban freight transport, such as air quality problems, road congestion, and noise emissions lead in many cities to major difficulties. A widely studied measure to reduce these negative effects are urban consolidation centers (UCCs) which aim to bundle freight flows to reduce the number of urban freight transport. However, many projects showed that the additional costs of UCCs often made it unattractive for logistics service providers (LSPs)[2] to participate in such schemes. This paper presents an agent-based simulation to assess the impact of urban access regulations on the cost attractiveness of UCCs for LSPs. A case study inspired by the Frankfurt Rhine-Main area is presented to compare deliveries of a group of LSPs with and without a UCC under various urban access scenarios. The simulation shows that regulations increase the cost attractiveness of UCCs for LSPs to varying degrees while increasing the overall traffic volume.

3.1 Introduction

Today, more than 54 % of the world's population lives in urban areas and the share of the world's urban population is expected to increase to 60 % by 2030 (United Nations, 2015). Along with the growth in urban population, the demand for urban goods and thus urban freight transport increases steadily. While urban freight transport poses an inevitable part in the economic and social system of a city, the growth in urban freight transport is accompanied by negative impacts on the urban population and attractiveness of the urban areas it serves (Ogden, 1992; Crainic et al., 2009).

Since the early 1990s, managing urban freight has become a key challenge in urban management and led to the rise of city logistics initiatives in research and practice (Allen et al., 2012; Crainic et al., 2009; Browne et al., 2005). Much of this research and many schemes in practice focus on reducing the negative impacts associated with urban freight transport (e.g., congestion, pollutant emissions, noise) by means of consolidation and collaboration strategies without negatively affecting the

[1] © 2018 IEEE. Reprinted, with permission, and slight modifications from R. Elbert and C. Friedrich (2018a). "Simulation-based Evaluation of Urban Consolidation Centers Considering Urban Access Regulations". In: *2018 Winter Simulation Conference (WSC)*. ed. by M. Rabe et al. [Piscataway, NJ]: IEEE, pp. 2827–2838. ISBN: 978-1-5386-6572-5. DOI: 10.1109/WSC.2018.8632356.

[2] In the original published manuscript, the term carrier is used instead. This has been changed to LSP for consistency.

economic and social activities within the urban area (van Duin et al., 2012; Crainic et al., 2009; Rabe et al., 2016). In this context, particular attention has been given to UCCs which are a widely studied measure in city logistics. The basic principle of a UCC is to reduce the number of urban freight transport by bundling freight in a logistics facility in the proximity of an urban area and transshipping it onto vehicles with increased load factors (Allen et al., 2012). Although more than 100 implementations of UCCs have been reported in the literature, many projects failed due to low participation and therefore financing problems (Allen et al., 2012).

A critical factor for the success of UCC schemes are urban freight transport policies (see e.g., Marcucci and Danielis, 2008; van Duin et al., 2012; Ville et al., 2013). Local administrations pursue the goal to make freight transport more sustainable and therefore support the realization of UCCs in different ways. Besides financial support in form of subsidies, regulatory measures are often adopted to promote the use of the UCC (Allen et al., 2012; Browne et al., 2005; Ville et al., 2013).

In practice, many cities already have some form of urban access regulations to regulate the traffic of heavy goods vehicles regardless of the existence of a UCC. Especially delivery time windows within city centers and pedestrian zones, in particular, represent a popular measure to regulate urban freight deliveries (Russo and Comi, 2010; Quak and de Koster, 2009). In addition, as a consequence of continuing air quality problems in urban areas, further measures such as for example truck bans and congestion charges are either already implemented or being discussed in many places.

Although UCCs and urban access regulations are intertwined through similar goals and interference, only relatively little is known about the interrelations between both. The aim of this paper is to study the cost attractiveness of LSP-led jointly-operated UCCs under various urban access regulations. For this reason, we develop an agent-based simulation model to examine the question of how urban access regulations influence the cost attractiveness of UCC schemes. In contrast to previous works, we consider an entire region, where LSPs have to perform deliveries to receivers within a city and smaller surrounding municipalities. Only transport orders located in the UCC service area can be assigned to a UCC. By using real street network data and actual retailer and LSP locations we assess the impact of a UCC and urban access regulations on the operations of LSPs in an entire region, including both urban and non-urban deliveries.

The outline of this paper is as follows: In Section 3.2 we briefly discuss the related literature on UCCs and urban access regulations. In Section 3.3 we present our simulation model on LSP-led UCCs and the implementation of urban access regulations. Section 3.4 describes the studied case and experimental setup. The results of the model and case study are discussed in Section 3.5. Finally, Section 3.6 concludes and provides pointers for future research.

3.2 Related Literature

Aspects of particular importance are the costs and financial viability of UCCs. Besides the theoretical benefits of UCC schemes, the inclusion of a UCC into the urban transport chain is accompanied by both setup costs for the UCC as well as additional operational costs caused by the transshipment such as extra handling costs. Thus, in order to be an attractive alternative for LSPs, the costs of independent last-mile deliveries have to exceed the additional costs related to the UCC (Marcucci and Danielis, 2008). Confirming this theoretical reasoning, Nordtømme et al. (2015) also identify the financial viability as the main barrier to establish a UCC in the context of a planned UCC implementation in Oslo.

Existing works analyze different factors influencing the possible costs savings of UCCs and consequently its cost attractiveness to receivers and LSPs. Roca-Riu et al. (2016) develop an analytic model featuring LSPs with different market shares to analyze the potential cost savings of UCCs. The model results reveal little impact of different market shares on the operational savings of a UCC. However, they point out the importance of other parameters, such as vehicle capacities and distances of depots and the UCC to the service area. Battaia et al. (2014) analyze the level of LSP participation at UCCs through game theory and simulation. For this purpose, they aim to determine the conditions which lead to operational savings for LSPs. Their results also show a strong influence of the distances and locations of the UCC and LSP depots relative to the city center. Janjevic and Ndiaye (2017b) provide an analytic model for the estimation of urban delivery costs and evaluation of the cost attractiveness of UCCs. With their model, they examine the cost structure of UCCs and factors, such as delivery characteristics, influencing the cost attractiveness of UCCs in a case study. Estrada and Roca-Riu (2017) also investigate the financial viability of UCC schemes. On the basis of an analytic cost model, they identify vehicle costs and other vehicle-related parameters to have only a minor impact on the financial viability of UCCs. However, they point out that a critical density of receivers exists that makes routing via the UCC cost-attractive for LSPs.

Quak and Tavasszy (2011), as well as Ville et al. (2013) identify the presence of urban freight transport policies as an essential component of viable UCCs. By issuing regulations, such as urban access restrictions, the usage of UCCs can be encouraged. In this context, van Duin et al. (2012) coin the notation of policy-oriented modeling which aims to retrace urban truck movement in the presence of different urban freight transport policies to assess its implications. Following this characterization, van Duin et al. (2012) investigate the contribution of policy measures to the successful operations of a UCC in an artificial city network with the aid of an agent-based simulation. Thereby, they examine the impacts of congestion, dynamic toll rates and subsidies by a local administration on the dynamic usage of UCCs. Their results indicate a little impact of different toll rates and a strong dependence on subsidies for UCCs to be viable. Tamagawa et al. (2010) also propose a multi-agent model for evaluating the impacts of road tolls and truck bans on different stakeholders in a test city network. They differentiate between privately owned motorways and publicly owned roads. Their results show that a reduction in motorway tolls in combination with truck bans offers a large potential to reduce negative environmental effects. Marcucci and Danielis (2008) by contrast conducted a stated-preference study to investigate the decision-making by receivers and transport operators regarding the use of a UCC. They show that among other policies and subsidies, zone-based access fees and parking restrictions have a positive effect on the UCC usage probability. Also, Wangapisit et al. (2014) examine the frequency of UCC usage with regard to the level of LSP subsidies and parking fees which incur additional costs for LSPs but not for the UCC. With the aid of an agent-based simulation, they show a positive effect of subsidies and parking management policies on the usage of the UCC.

Van Heeswijk et al. (2019a) provide an agent-based simulation model to assess the user base of a UCC under different delivery scenarios and urban freight transport policies. By considering delivery time windows, zone-based access fees and subsidies, they study the environmental and financial effects of numerous schemes using the city of Copenhagen as an example. Through a sensitivity analysis, they show that delivery time windows wider than two hours as a standalone measure do not contribute to the attractiveness of UCC schemes for LSPs. Estrada and Roca-Riu (2017) also consider delivery time windows for LSPs from which the UCC that uses cargo bikes is exempt. In their case study, they show that the total distance traveled and required fleet size for LSPs increases with the implementation of delivery time windows. Thus, the cost advantage of the UCC with exempt vehicles increases under the presence of delivery time windows. Simoni et al. (2018) analyze a scenario where access restrictions only allow electric vehicles and cargo bikes to enter the UCC service area. Their results indicate as expected a considerable reduction in vehicle emissions. Besides in the context of UCCs, the implications of urban access regulations and policies have also been studied in a broader sense in the literature from different points of view. Most notably, Quak and de Koster (2009) investigate the environmental and financial impacts of delivery time windows and vehicle restrictions on the logistics operations of two types of retailers with nationwide distribution to their stores. Similar to Estrada and Roca-Riu (2017), their results indicate an increase in the total distance traveled and thus increased delivery costs and emissions.

The overview of the related works shows that the cost attractiveness of UCCs has been a widely-studied topic in the context of UCCs. Therein, also access regulations received some attention and have been confirmed to increase the cost attractiveness of UCCs. However, many of the presented studies rely on simplified small test networks and extensive model assumptions. Moreover, so far it has not been taken into account that in the course of a delivery tour LSPs not only perform deliveries in one urban center but often also deliver goods to suburbs and other cities within the same region. In addition, it is usually assumed that LSPs and UCCs operate homogeneous fleets of delivery vehicles. However, in reality, transport operators often have a mixed fleet of vehicles. The contribution of this study is to assess the impact of urban access regulations on the cost attractiveness of jointly-operated UCCs for LSPs with both urban and non-urban deliveries and heterogeneous fleets.

3.3 Methodology

Simulation is a well-established methodology for analyzing urban logistics schemes and public policies (Maggi and Vallino, 2016). This can be explained by the advantages of simulation compared to mathematical modeling approaches which often cannot account for the complexity and heterogeneity of urban logistics systems (Taniguchi, 2001). By using simulation, we aim to identify the impact of urban access regulations on the cost attractiveness of LSP-led jointly-operated UCCs. For this purpose, we study several access regulations with and without the usage of a UCC and investigate the effects on its cost attractiveness for the participating LSPs. Contrary to other works, we also consider transport to receivers outside of the city where the last-mile delivery cannot be outsourced to the UCC.

3.3.1 Simulation Model Outline

In our simulation model, we assume an area-based, LSP-led UCC that focuses on business-to-business urban freight transport. At the core of the simulation model lies a discrete event simulation with agent-based elements. The simulation model was implemented using the simulation software AnyLogic 8.2.3 which offers discrete-event, system dynamics and agent-based modeling techniques. Similar to the framework of van Heeswijk et al. (2016) and the works of van Duin et al. (2012), the simulation model includes several urban stakeholders as agents. Namely, these agents are a UCC, receivers, and LSPs. Due to the agent-based approach of AnyLogic, we further model delivery vehicles, transport orders, and delivery tours as agents as well. The often proposed local administration agent has not been explicitly modeled since urban access regulations are set by the simulation user on a scenario basis and do not change during a simulation run. This is justified by the usual long-term focus of urban freight transport policies. Additionally, it is assumed that all cost factors remain static during each simulation run and no economies of scale are realized based on the stochastic order volumes.

3.3.2 Interactions Between Agents

The roles and interactions between the agents are an essential aspect of the simulation model. An overview of the interactions among the agents is visualized in Figure 3.1. The starting point of the simulation runs are the receivers which stochastically place transport requests (customer requests) at the LSPs. We thereby assume that all goods are in stock at the LSPs' depots and thus do not consider shippers, where the goods have to be picked up. In contrast to other approaches, the receivers can be primarily distinguished by being either located within the service area of the UCC or outside of it. Only receivers within the UCC service area can receive their delivery through the UCC. Furthermore, analogously to van Heeswijk et al. (2019a), receivers can exhibit different demand characteristics and vary in their order volume, number of order moments per week, and number and choice of preferred LSPs. The LSPs, in turn, possess different market shares, a fleet of vehicles, and a depot from where they operate. Based on the predefined strategic choice of participation at the UCC, the LSPs either deliver to all receivers in the region directly or drop their urban deliveries at the UCC. The UCC only receives shipments for receives within its service area and performs the last-mile delivery to the urban receivers using its own fleet of vehicles. Because we only assess the cost attractiveness of the UCC towards the LSPs, only monetary flows between these two agents are represented in the model. Hence, the shipping prices charged to the receivers by the LSPs are not taken into account in the analysis. Lastly, to represent urban freight transport policies by local administrations, the following urban access regulations can be applied in each simulation run:

- Delivery time windows;
- Zone-based access fees;
- Truck restrictions (e.g., no trucks >7.5 t).

In addition to the described agents above, we want to briefly outline the remaining agents. The delivery vehicles are either owned by the UCC or one of the LSPs and possess specific capacities and cost characteristics. A transport order describes a request from a receiver to a LSP to ship a specified load to its location. After performing the vehicle routing, delivery tours consisting of transport requests are assigned to delivery vehicles and subsequently executed. Following the tour completion, the delivery vehicles return to their home depot and various tour statistics are generated.

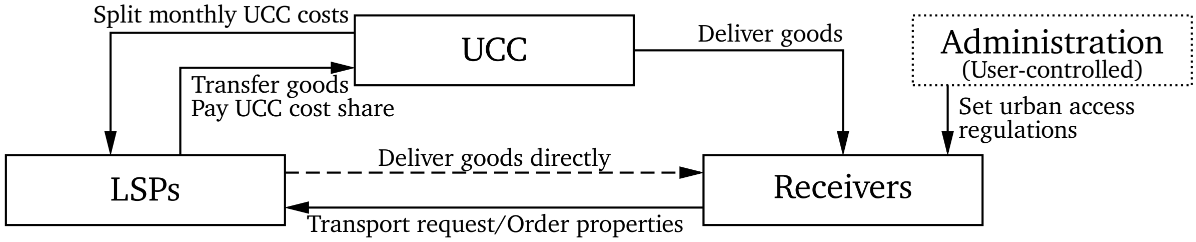


Figure 3.1: Interactions between the agents in the simulation model.

3.3.3 Cost Functions

Several cost functions are implemented to quantify the effects of the urban access regulations on the cost attractiveness of the UCC. For the description of costs, we use a similar notation as proposed in van Heeswijk et al. (2019a). Table 3.1 gives an overview of the considered costs and notations used.

Table 3.1: Overview of cost notations used in the simulation model.

Notation	Description
C_t^{UCC}	Total UCC cost in month t (€/month)
$C_{t,i}^{\text{Car}}$	Total costs of LSP i in month t (€/month)
$C_t^{\text{UCC,f}}$,$C_{t,i}^{\text{Car,f}}$	Fixed costs of the UCC or LSP i in month t (€/month)
$C_t^{\text{UCC,tr}}$,$C_{t,i}^{\text{Car,tr}}$	Transport costs of the UCC or LSP i in month t (€/month)
$C_t^{\text{UCC,h}}$	Handling costs of the UCC in month t (€/month)
C_δ	Tour operating cost of tour δ (€/tour)
c_k^{dist}	Distance-based cost rate per kilometer for deliveries with vehicle type $k \in N_k$ (€/km)
c_k^{time}	Time-based cost rate per hour for deliveries with vehicle type $k \in N_k$ (€/h)
c_k^{toll}	Costs for entering the urban area per day with vehicle type $k \in N_k$ (€/d)

A main cost component of the simulation model are transport costs. Both LSPs and the UCC make routing decisions for the last-mile distribution which affect their transport costs. To solve the underlying heterogeneous vehicle routing problem with time windows, we use the Java-based open source toolkit jsprit 1.7.2 Schröder (2017), which uses a large neighborhood search (LNS) metaheuristic that is inspired by the works of Schrimpf et al. (2000) and Pisinger and Ropke (2007).

During the simulation, each generated tour δ is executed under static travel and stochastic unloading times. The set of all tours executed during a month t are denoted by Δ_t^{UCC} for the UCC and $\Delta_{t,i}^{\text{Car}}$ for a LSP $i \in I$, where I represents the set of all LSPs. The total duration δ_{dur} of a tour consists of driving, unloading, and possible break and waiting times. The cost functions per time and distance of a tour depend on the used vehicle type k of the set of available vehicle types N_k. The costs per tour C_δ are formulated, as:

$$C_\delta = c_k^{\text{dist}} \delta_{\text{dist}} + c_k^{\text{time}} \delta_{\text{dur}} + c_k^{\text{toll}} \varrho_\delta,$$

where c_k^{dist}, c_k^{time}, and c_k^{toll} denote the distance-, time- and toll-based costs of vehicle type $k \in N_k$

and $\varrho_\delta \in \{0,1\}$ constitutes a binary variable to represent whether the tour includes deliveries to the urban area or not. The overall monthly costs of the UCC are comprised by three main cost components. The transport costs $C_t^{\text{UCC,tr}} = \sum_{\delta \in \Delta_t^{\text{UCC}}} C_\delta$ represent the sum of the costs of all tours Δ_t^{UCC} executed by the UCC within t. The monthly handling costs $C_t^{\text{UCC,h}}$ depend on the volumes handled by the UCC in t. Furthermore, fixed monthly costs $C_t^{\text{UCC,f}}$ can be assigned to the UCC. Due to the assumption that the UCC does not offer any storage services and because shipments are usually transferred within a day, the inventory costs of shipments are neglected. In summary, the monthly costs of the UCC are formulated as follows:

$$C_t^{\text{UCC}} = C_t^{\text{UCC,tr}} + C_t^{\text{UCC,h}} + C_t^{\text{UCC,f}}.$$

Second, we describe the monthly costs for the LSPs. Similar to the monthly UCC costs, the costs of a LSP $i \in I$, include transport costs $C_{t,i}^{\text{Car,tr}}$ and possible fixed costs $C_{t,i}^{\text{Car,f}}$. In addition, if the LSP participates at the UCC, represented by a binary variable $\gamma_i \in \{0,1\}$, a proportion of the monthly UCC costs is assigned to the LSP i. For simplicity, this proportion is assumed to be only dependent on the share of the number of transport requests $n_{t,i}^{\text{Car}}$ outsourced from LSP i in t of the total number of requests n_t^{UCC} processed by the UCC in t. As result, the following cost function is given for the costs of LSP $i \in I$ in t:

$$C_{t,i}^{\text{Car}} = C_{t,i}^{\text{Car,tr}} + \gamma_i C_t^{\text{UCC}} \frac{n_{t,i}^{\text{Car}}}{n_t^{\text{UCC}}} + C_{t,i}^{\text{Car,f}}.$$

Besides costs, we also measure both the total distances traveled by the UCC and LSPs and the number of vehicles entering the urban area to give an estimate of the effects on the traffic volume and environmental impacts. However, we refrain from conducting a detailed assessment of emissions due to the focus of this paper being on the financial aspects of UCCs.

3.4 Frankfurt Case Study

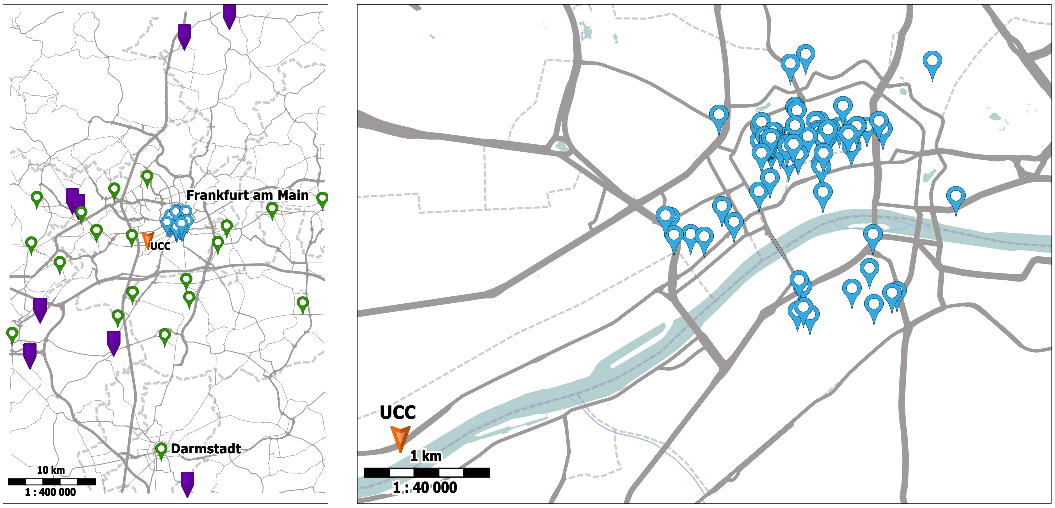
In this section, we describe a case which we used to test the simulation model and assess the impact of urban access regulations on the cost attractiveness of UCCs for LSPs. The area chosen for the case study of the simulation model is the Frankfurt Rhine-Main area. The Frankfurt Rhine-Main area is a polycentric metropolitan region consisting of almost 200 cities, towns, and rural municipalities located in the center of Germany. With a total population of more than 5.8 million, it is the third-largest metropolitan region in Germany. As a consequence of particulate matter (PM) pollution, a low-emission zone has been established in Frankfurt in 2008.

3.4.1 Data Collection and Network Design

Since there exists no real-world UCC in the Frankfurt Rhine-Main area, we modeled a fictive UCC using cost factors and data obtained from the related literature. In consequence of the fact that there is only limited or strongly varying data on UCCs and urban freight demand (van Heeswijk et al., 2019a), several assumptions regarding the parameters for the simulation study have been made.

In order to generate a network of receivers, we extracted retailer locations in specified areas from the OpenStreetMap (OSM) and randomly selected a sample to use in the case study. For the

UCC service area, 80 retail locations which are located in the city center of Frankfurt were chosen. To account for the LSPs' transport operations in the suburbs and surrounding towns, 20 additional municipalities have been selected and represented by one randomly retrieved retailer location each. Although a single UCC might not always be sufficient for a larger city, because of possible detours for LSPs to stop at the UCC (Huschebeck and Allen, 2005), we modeled for simplicity only a single UCC, which is conveniently located near two motorways in the west of Frankfurt. Similar to the selection of receivers, we extracted a sample of 8 LSP locations located west, south, and north of the UCC. Due to LSPs situated east of Frankfurt facing large detours caused by the need to drive through or around the city center to reach the UCC, we excluded those LSP locations from the selection process. An overview of the selected retail and LSP locations is given in Figure 3.2.



(a) Frankfurt Rhine-Main Area

(b) Frankfurt city center

Figure 3.2: Maps of the Frankfurt Rhine-Main area and Frankfurt city center with the UCC location (orange arrow), LSP depots (purple squares), urban receivers (blue pins) and non-urban receivers (green pins) (Map data copyrighted OSM Contributors).

Based on the selected locations, we created a time- and distance-based origin-destination matrix using the OSM-based routing engine Open Source Routing Machine from Luxen and Vetter (2011) as an input for the vehicle routing algorithm and simulation. To model urban access regulations and restrictions, we follow real regulations and reports from the literature. Regarding the length of delivery time windows, we first analyzed existing delivery time windows in Germany. Second, we compared the duration of reports and scenarios studied in the literature to create stricter scenarios. Many pedestrian zones in Germany possess delivery time windows of up to 6 hours. For example, in some parts of Frankfurt's pedestrian zone access is only allowed between 5:00 and 11:00. However, in the literature more restrictive cases can be found. For example, van Duin et al. (2010) report that the French city of La Rochelle only allowed freight delivery vehicles exceeding 3.5 t to deliver between 6:00 and 7:30. Similarly, van Heeswijk et al. (2019a) report a 2-hour time window for Copenhagen. The second restriction, which we validated with the help of the literature, are zone-based access fees (city tolls). Currently, there exists no zone-based access fee in Frankfurt. However, this measure has been frequently studied in the literature and applied or discussed elsewhere in Europe. For instance, the Swedish cities of Gothenburg and Stockholm introduced access fees up to SEK 60 and 105 (approximately 5.95 € and 10.40 €) per vehicle and day. Similarly, the Italian city of Milan charges 5 € per vehicle per day and the Norwegian capital Oslo recently adopted a toll of up to NOK 193 ($\sim$ 20.34 €) for vehicles above 3.5 t during rush hours. Lastly, the third restriction banning trucks or certain kinds of vehicles can be often found in forms of weight, dimension, or emission restrictions in real life. For example, the Hungarian capital Budapest has various limited traffic zones restricting the access for vehicles above, 3.5 t, 7.5 t, or 12 t. Similarly, we assume that vehicle access is regulated regarding vehicle weight.

3.4.2 Agent Properties

Due to the heterogeneity of freight demand in urban areas, we implemented the possibility to set different receiver profiles. Inspired by the works of van Heeswijk et al. (2019a), we modeled the following three receiver properties (i) average order volume, (ii) average order frequency, and (iii) number of supplying LSPs. Table 3.2 shows the three receiver profiles and the corresponding percentages of receivers randomly assigned to each of it. Deviating from the receiver profiles in Table 3.2, as an aggregate of the total demand within each area an increased demand is set to each of the 20 receivers which are not within the UCC service area so that the goods transported to the city center of Frankfurt amount on average to 15 % of the total amount of goods transported. Contrary to other works, we made the assumption that the UCC focuses primarily on palletized shipments due to parcel deliveries already being highly consolidated and adapted to urban policies by courier, parcel and express mail services (Ducret, 2014). Based on reported values in the literature, we set the weight range of pallets between 50 kg to 250 kg (ADEME, 2004; van Duin et al., 2013).

Table 3.2: Summary of the receiver profiles.

Profile	Order moments/week	Orders/order moment	Pallets/order	Number of LSPs	% of receivers
R1	1	1	1-3	1	20 %
R2	1-2	1-2	1-2	4	40 %
R3	2-3	1	1-2	6	40 %

An important aspect to calculate the costs of deliveries are unloading times. There are several time estimates for the dwell times during unloading at the UCC and urban receivers. For example, Churchill (2014) reports turnaround times of 5 to 20 minutes for suppliers of the London Boroughs Consolidation Centre and Ruesch (2009) states average turnaround times of 12 minutes per vehicle for the London Heathrow Airport UCC. In line with Janjevic and Ndiaye (2017b), we assume 5 minutes for waiting and administrative tasks and 1.5 minutes per pallet unloaded at the UCC. Regarding the dwell times for unloading in urban areas, Allen et al. (2000) identify a number of operational key factors, such as the distance from the vehicle parking point to the unloading point, which influence the dwell times. By analyzing 24 studies from the UK between 1999 and 2008, Allen et al. (2008) show that the average dwell times vary between 8-34 minutes. Similarly to this, Schoemaker et al. (2006) report average stop durations ranging from 21 to 34 minutes for three

Dutch cities. Following these findings, we set the range of dwell times per delivery stop between 8 and 34 minutes.

To calculate the volume-dependent handling costs of the UCC, a cost rate per unit or volume handled has to be set. Only few handling cost rates have been reported in the literature. For example, van Heeswijk et al. (2019a) suggest that the price per m^3 of parcels varies with the total throughput of the UCC to account for economies of scale and estimate a range between 7 €/m^3 to 20 €/m^3. Simoni et al. (2018) assume in contrast much lower costs of 0.025 USD/ft^3 ($\sim$0.72 €/m^3). Janjevic and Ndiaye (2017a) calculate transshipment costs of 0.58 €/parcel resulting in 5.47 €/m^3 for the stated average parcel volume of 0.106 m^3. Due to the lack of reliable data and based on the assumption that handling pallets should be cheaper than handling an equal volume of individual parcels, we estimate handling costs of 4 €/pallet.

Besides the time spent on performing deliveries, the transport costs of the UCC and LSPs strongly depend on the characteristics of the selected vehicles. Based on the works of Janjevic and Ndiaye (2017b) we selected cost parameters for two types of vehicles. Table 3.3 summarizes the vehicle properties obtained from the literature differentiating between a medium-sized truck and a semi-trailer. Both the UCC and the LSPs can choose the type of vehicles used during the heterogeneous vehicle routing problem and possess a sufficient number of vehicles to fulfill all daily transport requests and prevent backorders.

Table 3.3: Vehicle properties for LSP and the UCC.

Vehicle property	Truck (7.49 t)	Semi-trailer (39 t)
Distance-based cost [€/km]	0.31	0.41
Time-based cost [€/h]	30.85	32.01
Pallet capacity [pal]	14	34
Weight capacity [kg]	3150	25 000

3.4.3 Scenarios

For each scenario, we compare the usage of a UCC versus the case where each LSP delivers all of its shipments directly to the receivers. In the collaboration case using the UCC, each LSP delivers the urban shipments to the jointly-operated UCC and performs only the non-urban deliveries. The UCC, in turn, delivers the consolidated shipments to the urban receivers. Scenario 1 represents a situation where no urban access regulations are implemented. Scenario 2 represents a scenario with vehicle restrictions forbidding the usage of the larger vehicle within the UCC service area and delivery time windows from 8:00 until 11:00. Here we assume that receivers do not accept deliveries before 8:00, because the opening times of shops are usually after 8:00 in Frankfurt. Scenario 3 uses the same delivery time window but includes a zone-based access fee per day to enter the UCC service area instead of a restriction based on the vehicle size. Finally, scenario 4 shortens the delivery time window to 1.5 hours and in addition forbids the usage of large vehicles. Table 3.4 gives an overview of the studied scenarios.

Table 3.4: Overview of the studied scenarios.

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Delivery time window	–	8:00-11:00	8:00-11:00	8:00-9:30
Zone-based access fee	–	–	10 €	–
Truck restrictions	–	<7.5 t	–	<7.5 t

3.5 Results

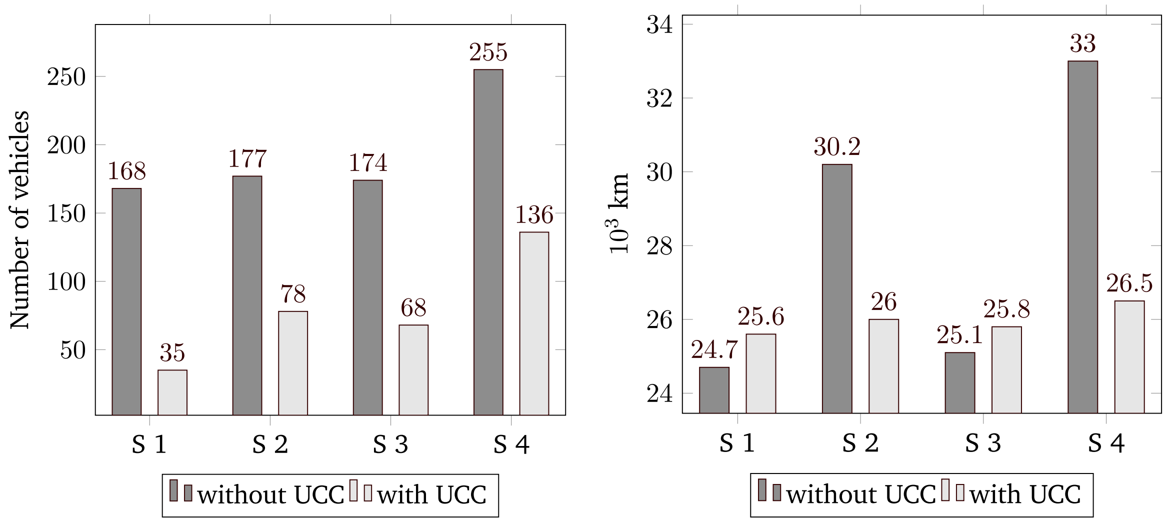
In this section, we present the results from the studied scenarios. Due to the lack of seasonal fluctuations in demand, each simulation run was performed for the period of one month, resulting in 27 days of operation simulated. For a better comparison, each scenario is evaluated using the same stochastic receiver demands.

First, we study the cost attractiveness of the UCC for each LSP under each scenario, considering the effect on the total operations of each LSP. Second, we briefly examine the number of vehicles entering the urban area and total vehicle kilometers per scenario. Table 3.5 shows that the cost attractiveness to use the UCC varies among the LSPs in each scenario. The average cost per pallet and receiver are stated for all deliveries, including deliveries outside the city of Frankfurt, which face no restrictions. The variation between the LSPs can be explained by the different locations of each LSP shown in Figure 3.2 and detours to reach the UCC, but also by the stochastic order generation. As expected, it can be seen that more restrictive scenarios lead to a higher cost attractiveness of the UCC. The comparison of scenarios 2 and 3 indicates that restricting the access for large vehicles has a bigger impact on the cost attractiveness of the UCC than the implementation of zone-based access fees. In fact, the costs when using the UCC increase compared to scenario 2, while the costs when no UCC is used decrease in comparison to scenario 2. Thus, in scenario 3 the usage of the UCC results in higher costs for all LSPs. In contrast, the results of scenario 2 indicate that the UCC is cost-attractive for two LSPs. Scenario 4 shows the highest cost attractiveness for all but one LSP and allows the assumption that the duration of delivery time windows has a high impact on the tour operations of the LSPs and thus raises the cost attractiveness of the UCC.

Table 3.5: Average cost per pallet and LSP with UCC and without UCC usage for each scenario.

	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
LSP	UCC	¬UCC	diff [%]	UCC	¬UCC	diff [%]	UCC	¬UCC	diff [%]	UCC	¬UCC	diff [%]
C1	9.67	9.16	-5.58	9.70	9.79	**0.87**	9.82	9.42	-4.19	9.75	10.01	**2.60**
C2	8.14	7.62	-6.77	8.18	7.97	-2.67	8.30	7.91	-4.92	8.24	8.35	**1.42**
C3	9.54	9.02	-5.77	9.57	9.72	**1.50**	9.66	9.39	-2.86	9.62	10.03	**4.10**
C4	8.62	8.13	-6.12	8.65	8.52	-1.54	8.75	8.38	-4.41	8.70	8.83	**1.40**
C5	7.64	7.28	-5.01	7.66	7.59	-1.06	7.75	7.49	-3.38	7.71	7.79	**0.99**
C6	7.95	7.32	-8.54	7.98	7.75	-3.04	8.12	7.58	-7.09	8.04	7.91	-1.60
C7	8.08	7.50	-7.79	8.11	7.88	-2.93	8.22	7.79	-5.52	8.17	8.28	**1.36**
C8	8.28	7.84	-5.64	8.31	8.24	-0.90	8.44	8.11	-4.05	8.37	8.57	**2.36**

The analysis of the total number of vehicles entering Frankfurt in Figure 3.3a shows that the usage of the UCC helps to reduce the number of vehicles entering the city enormously and that shorter delivery time windows increase the required number of vehicles for both the UCC and LSPs. Our analyses of the total vehicle distance traveled in Figure 3.3b further shows that the usage of the UCC leads to more vehicle kilometers when no regulations are present, due to the resulting detours for the LSPs. However, with the implementation of regulations, the total kilometers traveled increase more in the cases where no UCC is used than in the cases where the UCC is used.



(a) Number of vehicles entering the city per scenario.

(b) Total vehicle distance traveled.

Figure 3.3: Comparison of tour characteristics with and without the usage of the UCC for each scenario (S).

3.6 Conclusion

In this paper, we presented a simulation model using an actual road network and real retail locations to investigate the impact of urban access regulations on the cost attractiveness of UCCs for LSPs serving an entire region. Applied on a case study inspired by the Frankfurt Rhine-Main area, we showed that the implementation of urban access regulations offers potentials in raising the cost attractiveness of UCCs. Especially shortened delivery time windows appear to have a large impact on LSP operations and thus increase the cost attractiveness of using a UCC. However, the results also illustrated the difficulties to find scenarios where the UCC is beneficial for all LSPs. Furthermore, the analyses show that with shortened delivery time windows and vehicle size restrictions the number of vehicles and distance traveled increases, due to the usage of smaller vehicles with less capacity. Thus, the restrictions can lead to additional negative effects caused by a larger number of smaller vehicles and an increase in total kilometers traveled.

Conclusively, some limitations of this study and future areas of research can be identified. First, aspects, such as the UCC location and impacts of different receiver demand structures have not been studied in our simulation experiments and should be subject to further analyses and sensitivity analyses. In addition, cases with two or more UCCs could be investigated, especially for larger cities. Second, for future research, the study of more advanced cost-allocation methods such as the Shapley-Value or Nucleolus could be interesting to study. Third, longer time periods with seasonal demand changes could be studied and lastly, to find more viable situations for UCCs additional sources of income, such as value-added service and backhauling could be included in further studies as well.

4 Adaptive Large Neighborhood Search for Vehicle Routing Problems with Transshipment Facilities Arising in City Logistics[1]

Abstract

In this paper, we investigate vehicle routing problems with third-party transshipment facilities that arise in the context of city logistics. Contrary to classical vehicle routing problems, where each customer request is delivered directly to its destination, the problems considered in this paper feature the alternative possibility of delivering customer requests to third-party transshipment facilities, such as urban consolidation centers (UCCs), for a fee. We present an adaptive large neighborhood search (ALNS) with an embedded randomized variable neighborhood descent (RVND) as a local search component and a set partitioning problem (SPP) for the recombination of routes to solve various versions of the problem. Thereby, we consider location-dependent time windows as well as heterogeneous fleets and propose several new procedures that consider transshipment facilities within the components of our adaptive large neighborhood search. The proposed method is tested on benchmark instances from the literature as well as newly created benchmark instances. It shows promising results, leading to multiple improvements over existing algorithms from the literature. Moreover, a real-world study is presented to gain managerial insights on the impact of transshipment fees, order size, and heterogeneous fleets on the transshipment decisions.

4.1 Introduction

City logistics and last-mile deliveries give rise to numerous challenges for logistics service providers (LSPs), such as increased public attention to sustainability (Savelsbergh and van Woensel, 2016), urban access restrictions (Ville et al., 2013; Elbert and Friedrich, 2018a), and growing delivery volumes (European Commission, Directorate General for Mobility and Transport, 2019). A common approach to address these challenges is the consolidation of shipments at transshipment facilities to increase the efficiency of urban freight transport. In this context, UCCs are a widely studied concept in city logistics (Björklund and Johansson, 2018; Lagorio et al., 2016). UCCs can be defined as logistics transshipment facilities in the proximity of an urban area that consolidate urban freight transport across companies (Allen et al., 2012). Although numerous studies have been

[1] This chapter has been published with slight modifications as C. Friedrich and R. Elbert (2022). "Adaptive large neighborhood search for vehicle routing problems with transshipment facilities arising in city logistics". In: *Computers & Operations Research* 137, p. 105491. DOI: 10.1016/j.cor.2021.105491

published on UCCs and several UCCs have been implemented in cities across the world, except for a few cases (e.g., Baldacci et al., 2017), the decision on whether to outsource individual shipments to third-party transshipment facilities, such as UCCs, has rarely been included in vehicle routing problems.

Motivated by this lack of research, and to bridge the gap towards this real-world problem in city logistics, in this paper we expand the research on the vehicle routing problem with transshipment facilities (VRPTF) of (Baldacci et al., 2017) by including location-dependent time windows and heterogeneous fleets. As a generalization, this problem can be described as a vehicle routing problem that includes selecting delivery locations for customer requests from among multiple possible delivery locations, each with the possibility of different transshipment costs and time windows. These transshipment facilities could be, for example, UCCs serving an urban area, or regular third-party LSP facilities. Aligning with problem notations from the literature, we refer to our new problem variants of the VRPTF as the vehicle routing problem with time windows and transshipment facilities (VRPTWTF) and the fleet size and mix vehicle routing problem with time windows and transshipment facilities (FSMTWTF).

The purpose of this paper is twofold. First, it contributes to filling the literature gap in that it extends the body of literature on vehicle routing problems with transshipment facilities by adding time windows and heterogeneous fleets as additional attributes. Second, it presents an efficient meta-heuristic to solve these problems, which is also tested on related problems. Additionally, our computational results show that the solutions of existing VRPTF instances from literature can be improved by 0.68 % on average.

The outline of this paper is as follows: Section 4.2 gives an overview of the related literature. In Section 4.3 the problem is described. Section 4.4 presents the details of our ALNS. Section 4.5 describes how we tuned our algorithm and reports computational results on different sets of problems. Finally, Section 4.6 provides concluding remarks and pointers for further research.

4.2 Related Literature

Considering the selection of delivery locations such as transshipment facilities in vehicle routing is a generalization of the classical capacitated vehicle routing problem. To the best of our knowledge, only a few papers consider the selection of delivery locations or third-party transshipment facilities in vehicle routing. Most notably, Baldacci et al. (2017) formulate the VRPTF where customers can either be served directly from a central depot or by using a transshipment facility for a fee. In their paper, they describe various valid inequalities for the VRPTF and provide a mathematical formulation of the problem. Furthermore, they derive lower bounds from a set-partitioning based formulation of the VRPTF.

Alcaraz et al. (2019) also address the topic of using transshipment facilities for last-mile deliveries. Similar to the problem studied by Baldacci et al. (2017), they assume that some customer requests can be delivered directly or to a transshipment facility, from where a third-party subcontractor will perform the final last-mile deliveries for a fee. They study a rich vehicle routing problem that focuses on long-haul transport between regions and features several additional characteristics, such as driving hour regulations, incompatibility among goods, heterogeneous vehicles, and time windows. They present a construction heuristic method that incorporates these characteristics and adapt various classical improvement heuristics from the literature to solve their problem.

Similarly, Sitek and Wikarek (2019) study a so-called capacitated vehicle routing problem with pick-up and alternative delivery (CVRPPAD). They assume that customer requests can have alternative delivery locations such as a parcel locker or postal outlets and consider time windows and heterogeneous fleets. To solve their problem they propose an exact solution based on mathematical programming and a heuristics solution for larger problem instances. In their heuristics solution method, customer requests are assigned to routes based on a set of rules, and subsequently, a traveling salesman problem is solved for each of these routes.

Dumez et al. (2021a) also focus on different delivery locations for customers and recently introduced the vehicle routing problem with delivery options (VRPDO). In this problem, each customer can specify a number of delivery options along with a preference value. Furthermore, each delivery option can have a time window and capacity. Contrary to the VRPTF, no additional costs are associated with the shared delivery options and the focus is placed on satisfying the customer preference levels and shared location capacity constraints. In order to solve the problem, the authors present a large neighborhood search (LNS). Extending their work on the VRPDO, Dumez et al. (2021b) introduce an adapted Balas-Simonetti neighborhood to their LNS to further improve the solution quality. Moreover, Tilk et al. (2020), also address the VRPDO and present a branch-price-and-cut algorithm that solves instances with up to 50 customers and 100 options to optimality.

Focusing on a problem with home deliveries and shared delivery options, Mancini and Gansterer (2021) propose two matheuristic-based solution methods. Similar to the VRPTF, and in contrast to the VRPDO, their problem variant introduces a fee that has to be paid for each delivery assigned to a shared delivery location (SDL).

Zhou et al. (2018) consider a two-echelon vehicle routing problem (2E-VRP), where deliveries are routed through an intermediate capacitated satellite depot. Similar to Dumez et al. (2021a) and Sitek and Wikarek (2019), they assume that customers can provide different delivery options, such as receiving their parcels at their home or picking them up at an intermediate pick up facility. To solve this problem, Zhou et al. (2018) propose a hybrid multi-population genetic algorithm that is tested on real-world and artificial instances. Although the 2E-VRP is generally similar to the VRPTF, Baldacci et al. (2017) point out two significant differences between the two problems. First of all, the facilities and satellites in the 2E-VRP are assumed to be owned and operated by the same LSPs as the main depot. In the VRPTF, the facilities are operated by third-party providers that charge the LSP using its service a fee for conducting the last-mile deliveries to the customers. As a consequence, the vehicle routing from the transshipment facility to the customers is not part of the VRPTF. Second, in the 2E-VRP each customer request is generally routed through an intermediate facility, while in the VRPTF the customer requests can be either transshipped at a facility or delivered directly.

Two other closely related problems to the VRPTF that also include multiple delivery locations are the vehicle routing problem with roaming delivery locations (VRPRDL) and the very similar vehicle routing problem with home and roaming delivery locations (VRPHRDL). Reyes et al. (2017) define the VRPRDL as a routing problem where customer shipments are delivered to the trunk of their cars. Thereby, the cars are parked in different locations at different times, based on a known schedule. However, contrary to the VRPTF, no additional costs are associated with the different delivery locations and customers do not share common locations, such as a transshipment facility. Reyes et al. (2017) present a construction heuristic and an LNS-based improvement heuristic for solving this problem. The VRPHRDL introduced by Ozbaygin et al. (2017) extends the VRPRDL to allow shipments to be delivered to customers' homes during the entire planning period or, based on a predefined schedule, to the trunk of their cars. In order to solve both the VRPRDL and VRPHRDL, Ozbaygin et al. (2017) developed a branch-and-price algorithm. Later, Dumez et al. (2021a), Dumez et al. (2021b), as well as Tilk et al. (2020) also study both problems to validate their algorithms for the VRPDO, leading to new best solutions and large time improvements on the instances of Ozbaygin et al. (2017) and Reyes et al. (2017).

Although transshipment facilities such as UCCs have been a topic in city logistics for a long time, dating back to as early as the 1970s (Allen et al., 2012), only a few studies focus on whether to transship goods at a third-party transshipment facility. To the best of our knowledge, the studies on UCCs usually assume that only a single transshipment facility (UCC) exists, and that either all or no deliveries for a city are transshipped at the UCC. In reality, however, more than one transshipment facility can exist. Besides, as indicated in a survey among LSPs by Stathopoulos et al. (2012), it might be preferable to transship only some customer requests (e.g., requests with narrow time windows), while other customer requests are served directly. Moreover, the transshipment decision is often modeled to be periodical, depending on either the past performance or cost estimates (e.g., Firdausiyah et al., 2019; van Heeswijk et al., 2019a; van Duin et al., 2012).

The literature review underlines that the literature on selecting delivery locations in the context of vehicle routing is still scarce. Especially third-party transshipment facilities in connection with heterogeneous vehicles have been little studied so far. Hence we aim to expand the literature in this regard.

4.3 Problem Description

In our paper, we consider different problem variants of the VRPTF. Table 4.1 gives an overview of the considered problem variants and their properties. The VRPTWTF extends the VRPTF by including time window constraints, while the FSMTWTF is based on the fleet size and mix vehicle routing problem with time windows (FSMTW) (Liu and Shen, 1999) and extends the VRPTWTF by adding fleet size and mix decisions. For both problem variants, we distinguish between two cost functions consisting of different vehicle cost components. In the following, we describe the variant of the FSMTWTF with a rich cost function, abbreviated FSMTWTF-R, which encompasses the properties of the other problem variants studied.

Table 4.1: Overview of considered problem variants and their aspects.

Problem variant	Time windows	Fleet		Vehicle cost		
		homogeneous	heterogeneous	fixed	distance	duration
VRPTF		✓			✓	
VRPTWTF	✓	✓			✓	
FSMTWTF	✓		✓	✓	✓	
VRPTWTF-R	✓	✓		✓	✓	✓
FSMTWTF-R	✓		✓	✓	✓	✓

Expanding the notation of the VRPTF from Baldacci et al. (2017), the FSMTWTF-R considered in this paper can be described as follows. Let $G = (V, A)$ be a complete directed graph, where

$V = \{v_0\} \cup V'$ is the set of vertices and A the set of arcs. The set of vertices V' is partitioned into $V' = \{V_{\mathrm{C}}, V_{\mathrm{F}}\}$, where $V_{\mathrm{C}} = \{v_1, \ldots, v_{n_{\mathrm{C}}}\}$ is the set of customer locations and $V_{\mathrm{F}} = \{v_{n_{\mathrm{C}}+1}, \ldots, v_{n_{\mathrm{C}}+n_{\mathrm{F}}}\}$ the set of transshipment facilities. Vertex v_0 represents the depot, where goods to be delivered are stored and vehicle routes originate.

Each customer location $v_i \in V_{\mathrm{C}}$ is associated with a single customer request cr_i. These requests are characterized by a non-negative demand of q_i units to be delivered from the depot v_0 and a non-negative service time t_i^{s}. Each customer request can be delivered directly to the associated customer v_i or, if applicable, to a transshipment facility selected from its set $F_i \subseteq V_{\mathrm{F}}$ of possible transshipment facilities. Figure 4.1 gives an example of a vehicle routing problem with four transshipment facilities, where customer requests can be assigned to a single facility, multiple facilities, or no transshipment facility at all.

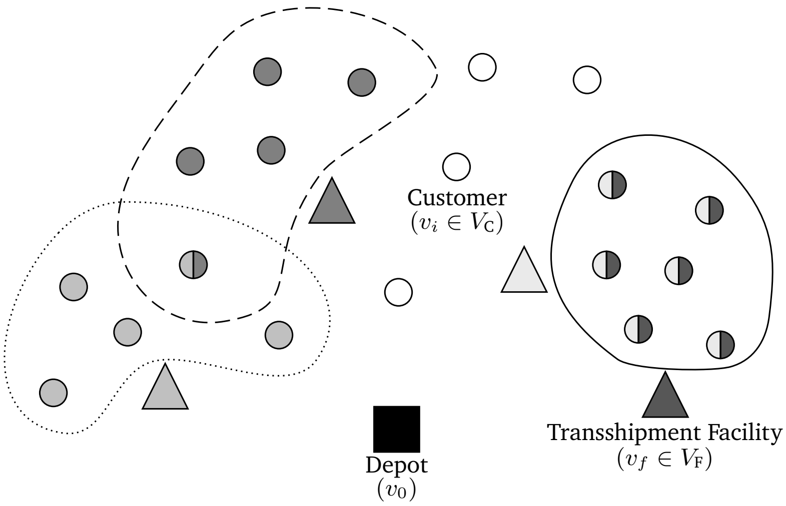


Figure 4.1: Example of a VRPTF instance with four transshipment facilities. Each transshipment facility (triangles) has a number of customer locations that it can serve, indicated by the grey scale of each locations' circle and the surrounding polygon. Some customer requests, denoted as white circles, can only be served directly and may not be transshipped.

The selected delivery location of a customer request cr_i is denoted as $cr_i^{\mathrm{l}} \in F_i \cup \{v_i\}$. Each location from V' can have a delivery time window specified by the earliest and latest time tw_i^{S} and tw_i^{E} $(0 \leq tw_i^{\mathrm{S}} < tw_i^{\mathrm{E}} < \infty)$ to be visited. In order to account for possible time savings when customer requests are consolidated and transshipped at a transshipment facility, a preparation time t_i^{p} is assigned to each location similar to the approach of Dumez et al. (2021a). This preparation time represents, for example, the time needed for parking and administrative tasks (e.g., handling delivery documents) at the locations that occur regardless of the quantity being unloaded. In contrast to this, the service time t_i^{s} is location independent and represents the time needed for unloading the goods of a customer request cr_i. The arc set A represents the links between the vertices, where d_{ij} is the distance between location v_i and v_j and t_{ij} the transport time. For distinct locations the transport time t_{ij} includes the location-dependent preparation t_i^{p}.

The fleet originating from the depot is composed of n_{Vehicles} different vehicle types, with $M = \{1, \ldots, n_{\text{Vehicles}}\}$. For each type $k \in M$, there are m_k available vehicles, each with a capacity Q_k. Additionally, fixed costs c_k^{f} as well as distance-dependent c_k^{d} and time-dependent costs c_k^{t} can be assigned to each vehicle type.

We define a route r^k as a vehicle of type k starting from and ending at the depot v_0 and visiting some locations to fulfill customer requests. Each solution s to our problem consists of a set of routes R. A route is feasible if the total load of the route, computed as the sum of demand of all customer requests assigned to it, does not exceed the vehicle capacity of the vehicle. Furthermore, for each visited location, and the customer requests assigned to it, the time window constraints must be fulfilled.

The costs c_r of a route r^k consist of four vehicle-dependent cost components. First, the distance-based costs equal the total distance traveled multiplied with the distance-based cost factor c_k^{d} of the vehicle type. Second, the duration-based costs equal the total operation time to perform the route, including times for traveling, unloading goods at the locations, and possible waiting times due to time windows, multiplied with the duration-dependent cost factor c_k^{t} of the vehicle type. To minimize the waiting times, the departure time of each vehicle from the depot can be scheduled any time during the work day. Third, the fixed cost c_k^{f} of the selected vehicle type is incurred when the vehicle is assigned to a tour. Fourth, the sum of transshipment costs for transshipping customer requests at the third-party transshipment facilities. Different transshipment cost functions can be selected for this and included in the objective function. For example, following Baldacci et al. (2017), the cost of transshipping customer requests can be based on the distance between the location of the customer and the selected transshipment facility. Alternatively, the cost for assigning a transshipment facility, such as a UCC, can also be based on the quantity q_i of the customer request cr_i. This is in line with several real-world UCCs, where the prices usually solely depend on the number of pallets and parcels to be transshipped (Janjevic and Ndiaye, 2017b). In practice, however, in order to be cost-efficient UCCs usually have a predefined service area, such as a city center, in which they operate (similar to the example in Figure 4.1).

In summary, the objective of the vehicle routing problem with transshipment facilities is to determine the assignment of customer requests to transshipment facilities and vehicles as well as a set of routes that minimizes the sum of route costs and does not violate the constraints of the vehicles, customer requests, and locations.

4.4 Adaptive Large Neighborhood Search for Vehicle Routing Problems with Transshipment Facilities

This section describes our ALNS with an embedded local search for solving the VRPTF and its extensions. ALNS is a common meta-heuristics for solving vehicle routing problems and has been introduced by Ropke and Pisinger (2006a), who initially applied it to the pickup and delivery problem with time windows. In contrast to classical neighborhoods for vehicle routing problems (VRPs), it is characterized by large moves that are performed by removal and insertion procedures. This underlying principle of removing and inserting customer requests, also called ruin and create, has been present in previous research articles. Shaw (1998) presented the LNS, where routes are ruined and subsequently repaired by inserting the unassigned customer requests. Later, Schrimpf et al. (2000) used the term *ruin and create* for a similar concept to solve several routing problems.

4.4.1 Algorithm Outline

The overall framework of our algorithm to solve the different variants of the VRPTF is reported in Algorithm 1. First, we initialize the parameters for the ALNS, such as the stop-criterion, initial weights of the removal and insertion operators, and the conditions for executing the embedded local search procedure and SPP. Second, we create an initial solution by using a regret-2 insertion procedure (see 4.4.3). After creating an initial solution, in each iteration of our ALNS, a copy s' of the incumbent solution s_t is destroyed using a removal procedure and subsequently repaired using an insertion procedure (lines 10 and 12). Both removal and insertion procedures are selected randomly based on a roulette wheel selection. Following these two steps, a local search procedure that includes new neighborhoods to modify the locations of customer requests can be invoked with probability p_{LS} to improve the current solution s' (lines 13-15). After the solution improvement phase, we check whether to store the feasible routes of the newly generated solution into the set of routes R^{pool} (line 16). If we find a route that serves the same customers as an existing route in R^{pool} using the same vehicle type with lower costs, we replace the corresponding route.

Following this, the new solution s' is accepted as the current solution depending on an acceptance criterion (lines 17-18). In case a new best solution has been found, the best solution s_{best} is updated as well (lines 19-20). Every η^{SP} iteration of the algorithm the routes of the pool R^{pool} are used to solve a SPP and the incumbent solution s_t is updated. After each call to the SPP, R^{pool} is emptied to avoid it becoming too large (lines 24-25). Furthermore, for every η^{update} iteration we update the weights (selection probabilities) of the removal and insertion procedures (lines 27-28). Following Ropke and Pisinger (2006b), we use an adaptive weight adjustment for the removal and insertion procedures that updates the weight of each procedure after η^{update} consecutive iterations (segment). The weights of each procedure w_{ij} are calculated by using the weights of the previous segment and scores obtained during the previous segment as shown in Equation 4.1. The weight $w_{i,j+1}$ of an procedure i in segment $j+1$ is calculated by

$$w_{i,j+1} = w_{ij}(1-\lambda) + \lambda \frac{\pi_i}{\theta_i}, \tag{4.1}$$

where π_i is the current score of procedure i and θ_i the number of times that the procedure i has been invoked during the last segment. The factor λ controls how strongly the procedure's historical performance from previous segments is considered during the calculation. To update the score π_i each time an insertion or removal procedure has been applied, the reward parameters ν_1, ν_2, and ν_3 are used to update the procedure's score, as shown in Equation 4.2.

$$\pi_i^{k+1} = \pi_i^k + \begin{cases} \nu_1 & \text{if a new best solution has been found} \\ \nu_2 & \text{if the found solution is better than the incumbent solution} \\ \nu_3 & \text{if the found solution is accepted but worse than the incumbent solution} \end{cases} \tag{4.2}$$

By using an adaptive weight adjustment, the selection probabilities of the removal and insertion procedures that previously led to promising solutions are increased, while the selection probabilities of unpromising procedures are reduced.

Lastly, our algorithm stops when either a maximum number of overall iterations $\eta^{\max}$ or a maximum number of iterations without improvement $\eta^{\max}_{\text{noi}}$ has been reached.

Algorithm 1 Overview of the ALNS algorithm.

function ALNS
  initializeParameters()
  $s_t \leftarrow$generateInitialSolution()
  $s_{\text{best}} \leftarrow s_t$
  $\eta \leftarrow 0$
  while $\eta < \eta^{\max}$ **and** $\eta - \eta_{\text{imp}} < \eta^{\max}_{\text{noi}}$ **do**
    $s' \leftarrow s_t$
    Randomly select a removal operator. Draw δ customers to remove from s'.
    $s' \leftarrow$ applyRemoval(s', δ)
    Randomly select an insertion operator to reinsert customers.
    $s' \leftarrow$ applyInsertion(s')
    if random() $< p_{\text{LS}}$ **then**
      $s' \leftarrow$ LS(s')
    end if
    store the routes of s' in R^{pool}
    if acceptanceCriteria$(s', s_t, s_{\text{best}})$ **then**
      $s_t \leftarrow s'$
      if $f(s') < f(s_{\text{best}})$ **then**
        $s_{\text{best}} \leftarrow s'$
      end if
    end if
    if modulo$(\eta, \eta^{\text{SP}}) = 0$ **then**
      $s_t \leftarrow$ callSetPartitioningProblem(R^{pool})
      $R^{\text{pool}} \leftarrow \emptyset$
    end if
    if modulo$(\eta, \eta^{\text{update}}) = 0$ **then**
      setNewSelectionScores()
    end if
    $\eta \leftarrow \eta + 1$
  end while
end function

4.4.2 Search Space and Objective Function

In order to allow for infeasible solutions regarding time window constraints during the search, both the removal and insertion procedures, as well as the embedded local search procedure, use the *return in time* relaxation scheme from Nagata et al. (2010). In this relaxation scheme, each time a vehicle would arrive late at a location (after the end of the location's time window) it is assumed that the vehicle can travel back in time to arrive at the end of the time window. The amount of time traveled back in time is therein denoted as *time warp* (Vidal et al., 2015) and used to penalize the objective function. Hence, similar to the approaches of Olivera and Viera (2007) and François et al. (2016), we use an augmented objective function for evaluating a solution s':

$$f^{\text{mod}}(s') = f(s') + \alpha^{\text{p}} \cdot TW(s'), \tag{4.3}$$

where $f(s')$ is the total operating cost of the solution including fixed and variable costs, $TW(s')$ denotes the sum of the time warp associated with solution s'. The Parameter α^{p} is an adaptive penalization parameter that self-adjusts during the ALNS search process. During the ALNS, we initialize α^{p} to $\alpha^{\text{p}}_{\text{min}}$ and limit it to the interval $[\alpha^{\text{p}}_{\text{min}}, \alpha^{\text{p}}_{\text{max}}]$. At the end of each iteration, α^{p} is updated based on the feasibility of the incumbent solution s_t. If the incumbent solution s_t contains no time warp, α^{p} is set to $\max\{\alpha^{\mathrm{p}}/\rho, \alpha^{\mathrm{p}}_{\mathrm{min}}\}$ to encourage our ALNS to find infeasible solutions to reduce the probability of becoming trapped in a local optimum. Otherwise, if the incumbent solution is infeasible α is set to $\min\{\alpha^{\mathrm{p}} \cdot \rho, \alpha^{\mathrm{p}}_{\mathrm{max}}\}$ to guide the search to more feasible solutions. In this process, the parameter $\rho \geq 1$ controls to what extent α^{p} is adjusted. After every η^{reset} iteration, α^{p} is set back to $\alpha^{\mathrm{p}}_{\mathrm{min}}$ so that it does not get stuck at $\alpha^{\mathrm{p}}_{\mathrm{max}}$.

4.4.3 Removal and Insertion Operators

Removal Procedures

During each of the following removal procedures, we remove δ customer requests, where δ is drawn from the interval $[\omega_{\mathrm{min}}, \omega_{\mathrm{max}}] \cdot \min(|V_{\mathrm{C}}|, 100)$. The parameters ω_{min} and ω_{max} denote thereby the minimum and maximum share of customer requests to be removed. All removed customer requests are placed in the set of absent customer requests B. The following removal procedures can be used in our ALNS:

Random removal: a removal heuristic that randomly removes δ customer requests from a given solution s' using a uniform probability distribution.

Route removal: a removal heuristic where a random route is selected and up to δ customer requests of the route are randomly removed, using a uniform probability distribution. This is repeated until δ customers are removed in total (Nagata and Bräysy, 2009).

Worst removal: a removal heuristic introduced by Ropke and Pisinger (2006b) that removes customer requests with high costs that strongly contribute to the objective function of the current solution. To do so, we calculate for each customer request cr_i the savings of removing it from s' and sort the customer requests in descending order. Subsequently, we use a randomized removal controlled by a parameter p_{worst}, as proposed in Ropke and Pisinger (2006b) to remove the customer requests. This is done repeatedly until δ requests have been removed from s'.

Historical knowledge node removal: removal heuristic that saves the lowest costs associated with each customer request and removes the δ customer requests with the highest difference between their current costs and saved historical lowest cost (Demir et al., 2012). We adapted the procedure to include the transshipment costs of customer requests.

Shaw removal: a removal heuristic that is also called related removal and was introduced by Shaw (1997), Shaw (1998). We define the similarity $S(i, j)$ between two customer requests cr_i and cr_j based on four customer request characteristics. First, their difference in demand $|q_i - q_j|$ divided by the maximum difference in demand $\max_{i \in V_{\mathrm{C}}}(q_i) - \min_{i \in V_{\mathrm{C}}}(q_i)$. Second, the distance d_{ij} divided by the maximum distance between all customer requests $\max_{i,j \in V_{\mathrm{C}}}(d_{ij})$. Third, their absolute difference of time window centers $|tw^{\mathrm{S}}_i + (tw^{\mathrm{S}}_i - tw^{\mathrm{E}}_i)/2 - tw^{\mathrm{S}}_j + (tw^{\mathrm{S}}_j - tw^{\mathrm{E}}_j)/2|$ divided by the maximum absolute difference between all time window centers. Fourth, the difference in the number of shared transshipment facilities $|F_i \cap F_j|$ divided by the maximum number of $\max_{i,j \in V_{\mathrm{C}}}(|F_i \cap F_j|)$. The last term, however, only makes a difference in instances where the possible transshipment facilities differ between customer requests. Each term is weighted by a weight factor $\chi_q, \chi_d, \chi_{TW}$ and χ_l respectively.

Cluster removal: introduced by Ropke and Pisinger (2006a), aims to remove an entire cluster of customer requests. Taking a given route, the customer requests in that route are partitioned into two clusters. Subsequently, one of these clusters is selected, and up to δ customer requests are removed. If the number of customer requests removed is smaller than δ, a random customer request from the removed customer requests is selected. For this customer request, the current nearest customer request that is not in the same route is chosen. The route of the chosen customer request is again partitioned into two clusters and the procedure continues until δ customer requests have been removed from the solution.

Distance-related removal: also called radial removal (Schrimpf et al., 2000), is a special case of our Shaw removal procedure, where only the distances between the currently assigned locations of the customer requests are used. The underlying idea of the removal procedure is to remove customer requests that are close to each other based on the distance between them. We implemented this procedure by randomly selecting a customer request and deleting it and its $\delta - 1$-closest neighbors from the solution.

Time-related removal: a removal heuristic that removes customer requests that are related in terms of the time at which they are served (Pisinger and Ropke, 2007).

Adjacent string removal: introduced by Christiaens and Vanden Berghe (2020) and showing promising results on classical vehicle routing benchmarks. String removal is based on the premise that removing only adjacent customers (e.g., as in distance-related removal) may lead to detours still being present in the destroyed route. Instead, removing adjacent strings of customer requests might be more efficient. During the procedure, either many strings with small cardinality or a few strings with a high cardinality can be removed. The upper limit of the string cardinality is thereby controlled by the parameter $L_{\max}$. As described in Christiaens and Vanden Berghe (2020), the strings can be removed using either the *string procedure* or *split string procedure*. Contrary to the basic *string procedure*, the *split string procedure* preserves a random substring of customer requests from the string of customer requests to be removed. To control the number of customer requests to be preserved, the split depth parameter β_{String} is used. The probability to select the *split string procedure* instead of the *string procedure* is controlled by the parameter α_{String}.

Insertion Procedures

During the insertion phase of our algorithm, all locations per customer request are generally evaluated. To evaluate the insertions in constant time $\mathcal{O}(1)$, we store partial route information which depends on the type of problem considered. For our problem variants that do not include duration-based costs, we use the propositions from Schneider et al. (2013) to evaluate the corresponding time window violations of the insertions. For the problem variants with duration-based costs and flexible vehicle departure times, we use the concatenation formulas described in Subsection 4.4.4 to determine the earliest and latest departures from the depot that lead to a schedule with minimum duration and time warp. Whenever a customer request is inserted into a route, the route information is updated in linear time, in relation to the number of customer requests in the route. This includes the time window violations up to and from each customer request within the route. The capacity usage is updated in constant time. Furthermore, in the case of heterogeneous fleets we use two ideas from Koç et al. (2014). First, before starting an insertion procedure, we check whether the destroyed routes can be served by smaller vehicles with lower fixed costs. Second, when inserting a customer request in a route would exceed the available vehicle capacity, we consider using a larger vehicle for the route and account for the difference in fixed costs.

In the following, we briefly describe the implemented insertion procedures:

Random order best insertions: all absent customer requests are sequentially inserted at their best insertion position in random order (Christiaens and Vanden Berghe, 2020).

Demand order best insertions: inserts the absent customer requests sequentially at their best insertion position ordered by decreasing demand (Christiaens and Vanden Berghe, 2020).

Farthest first best insertions: inserts the absent customer requests sequentially at their best insertion position ordered by decreasing distance to the depot (Christiaens and Vanden Berghe, 2020).

Closest first best insertions: inserts the absent customer requests sequentially at their best insertion position ordered by increasing distance to the depot (Christiaens and Vanden Berghe, 2020).

Regret-2 insertion: the regret-2 insertion was introduced by (Ropke and Pisinger, 2006a) in the context of ALNS. To determine the insertion position of a customer request, a regret-2-value is calculated which is defined as the difference between its second-best and best insertion position. At each step of the insertion procedure, the regret-2-values are updated and the customer request with the highest difference is inserted at its best insertion position.

Removal and Insertion Diversification

In order to randomize the removal and insertion procedures, we implement removal and insertion diversification strategies from the literature that can be used during the removal and insertion phases of our ALNS. First, we utilize the concept of adding a noise term to the objective function value during insertion (Ropke and Pisinger, 2006a). Each time an insertion position is evaluated, the insertion cost ΔC is modified with a probability p_{noise}. To do so, we draw a random factor ξ from the interval $[\xi_{\text{min}}, \xi_{\text{max}}]$ and calculate the modified insertion costs $\Delta C' = \max\{0, \Delta C(1+\xi)\}$.

Second, inspired by the algorithm of Christiaens and Vanden Berghe (2020), we implement the concept of blinks as an insertion diversification strategy. Following Dumez et al. (2021a), we also extend the concept to the removal phase. The underlying idea of the concept is to skip possible removals and insertions with a defined probability. However, contrary to the insertion blinking procedure of Christiaens and Vanden Berghe (2020), where insertion positions within a tour can be skipped, we skip the evaluation of the possible location of a customer request when checking an insertion position within a route. Based on preliminary tests, we distinguish between the original customer location and the transshipment facilities and assign a blink probability $p_{\text{Blinks-}v_i}$

for the original customer locations and a blink probability $p_{\text{Blinks-}V_F}$ for the transshipment facilities. Furthermore, we test if it is advantageous to avoid blinking on transshipment facilities when the previous or next customer request within the route is assigned to the transshipment facility to be evaluated. For the blinking of removal positions, we define $p_{\text{Blinks-Removal}}$ as the probability to skip a customer request during a removal procedure. To sum up, we implemented the following three blinking procedures for our problem:

Blinks-R: Blinking on customer requests to be removed.

Blinks-I (I): Blinking for original customer locations.

Blinks-I (II): Blinking for transshipment facilities.

Blinks-I (III): Blinking for transshipment facilities unless they equal the previous or next customer's location within the route.

4.4.4 Local Search Procedure

In order to intensify the search, the approach described in this paper combines the ALNS general search methodology with a local search method. During each iteration of our ALNS, a local search procedure can be run with a probability p_{LS} to improve the current solution s'. The local search during the ALNS is performed by a RVND (Mladenović and Hansen, 1997) which has been applied for many routing problems, especially in the context of heterogeneous fleets (see e.g., Penna et al., 2019; Subramanian et al., 2010).

The underlying idea of the RVND can be described as follows: Let $N = \{N^1, ..., N^r\}$ be the set of neighborhood structures. Each time a selected neighborhood of the set of neighborhoods N fails to improve the incumbent solution, the RVND randomly chooses another neighborhood from the same set to continue the search throughout the solution space. Algorithm 2 gives an overview of the RVND procedure. During the first step of the algorithm, the list of inter-route neighborhoods N_{Inter} is initialized (line 2). After the initial setup, for each iteration a random neighborhood $N^{(i)} \in N_{\text{Inter}}$ is selected and evaluated. Thereby, either a first- or best-improvement strategy can be utilized (line 5). If an improvement of the incumbent solution s is found, s is updated and an *IntraRouteSearch* (here also a RVND) is initiated (line 6-8). Subsequently, the list of inter-route neighborhoods N_{Inter} is refilled with all possible inter-route neighborhoods (line 9), and in the case of problems with varying fleet size and mix the available empty vehicles are updated (line 10). In contrast, if no improvement is found, $N^{(i)}$ is removed from N_{Inter}.

To evaluate the moves of the RVND efficiently, we use the concatenation strategies of Vidal et al. (2014) and Vidal et al. (2015). These strategies are based on the idea that any route generated from a classical move applied on an incumbent solution s' corresponds to a recombination of a bounded number of depot and customer request sequences of s'. As such, every new route can be expressed as a concatenation of sequences $\sigma_1 \oplus \cdots \oplus \sigma_b$. Each sequence σ can be described by six values: distance $DIST(\sigma)$, demand $Q(\sigma)$, duration $D(\sigma)$, time warp $TW(\sigma)$, and the earliest visit $E(\sigma)$ and latest visit $L(\sigma)$ to the first vertex of σ that lead to a schedule with minimum duration and time warp. Let σ_1 and σ_2 be two sequences. Using the equations of Vidal et al. (2014) and Vidal et al. (2015), the concatenation of $\sigma_1 \oplus \sigma_2$ can be formulated as:

Algorithm 2 Overview of the RVND procedure

function RVND(s)
    Initialize the inter-route neighborhood List (N_{Inter})
    while $N_{\text{Inter}} \neq \emptyset$ **do**
        $N^{(i)} \leftarrow$ Choose a random neighborhood $N^{(i)} \in N_{\text{Inter}}$
        $s' \leftarrow$ Find the best- or first-improving neighbor s' of $\in N^{(i)}$
        if $f(s') < f(s)$ **then**
            $s \leftarrow s'$
            $s \leftarrow$ IntraRouteSearch(s)
            Update N_{Inter}
            Update Fleets ▷ only for fleet-size-and-mix instances
        else
            Remove $N^{(i)}$ from N_{Inter}
        end if
    end while
end function

$$DIST(\sigma_1 \oplus \sigma_2) = DIST(\sigma_1) + d\sigma_1(|\sigma_1|)\sigma_2(1) + DIST(\sigma_2) \tag{4.4}$$
$$Q(\sigma_1 \oplus \sigma_2) = Q(\sigma_1) + Q(\sigma_2) \tag{4.5}$$
$$D(\sigma_1 \oplus \sigma_2) = D(\sigma_1) + t\sigma_1(|\sigma_1|)\sigma_2(1) + D(\sigma_2) + \Delta WT \tag{4.6}$$
$$E(\sigma_1 \oplus \sigma_2) = \max\{E(\sigma_2) - \Delta, E(\sigma_1)\} - \Delta WT \tag{4.7}$$
$$L(\sigma_1 \oplus \sigma_2) = \min\{L(\sigma_2) - \Delta, L(\sigma_1))\} + \Delta TW \tag{4.8}$$
$$TW(\sigma_1 \oplus \sigma_2) = TW(\sigma_1) + TW(\sigma_2) + \Delta TW \tag{4.9}$$
$$\text{where } \Delta = D(\sigma_1) - TW(\sigma_1) + t\sigma_1(|\sigma_1|)\sigma_2(1) \tag{4.10}$$
$$\Delta WT = \max\{E(\sigma_2) - \Delta - L(\sigma_1), 0\} \tag{4.11}$$
$$\Delta TW = \max\{E(\sigma_1) + \Delta - L(\sigma_2), 0\}. \tag{4.12}$$

Inter- and Intra-Route Neighborhood Structures

The definition of neighborhood structures is one of the main aspects in the design of local search algorithms. In order to achieve better local optima, we use both inter-route and intra-route neighborhoods in our search. To reduce the computational effort of our inter-route swap neighborhoods, we apply the pruning mechanism for vehicle routing problems with time windows from Vidal et al. (2013a). The correlation between two locations is, thereby, calculated by the weighted sum of the distance, minimum waiting time, and minimum penalty between the two locations, using the same weights as in Vidal et al. (2013a). Subsequently, for each location $l \in V'$ we store the $\epsilon = 30$ highest-correlated locations in an immutable neighbor list. Furthermore, for each move, the capacity feasibility is evaluated first and the move is discarded if it is infeasible.

We employ the following seven inter-route neighborhoods in our local search procedure:

- **Shift(1,0)** transfers a customer request from one route to another.
- **Shift(2,0)** transfers two adjacent customer requests from one route to another.

- **2-Opt*** inter-route version of the classical 2-Opt move (Potvin and Rousseau, 1995).
- **Swap(1,1)** permutation between two customer requests from different routes.
- **Swap(2,1)** permutation of two adjacent customer requests from one route by one customer request from another route.
- **Swap(2,2)** permutation of two adjacent customer requests from one route by two customer requests from another route.
- K**-Shift** transfers K adjacent customer requests from one route to the end of another route or a new route of a vehicle with lower fixed costs (Penna et al., 2013). In the case of unlimited fleets, we ensure that there is at least one empty vehicle of each type.

Regarding the intra-route neighborhoods, we implement the well-known **2-Opt** neighborhood (Lin, 1965), **Reinsertion**, **Or-opt-2**, and **Or-opt-3** (Or, 1976) neighborhoods, as well as an intra-route version of **Swap(1,1)**. In addition to these well-known general neighborhoods, we implement new specific neighborhoods for vehicle routing problems with transshipment facilities. These intra-route neighborhoods aim to modify the assignment of transshipment facilities to customer requests within a route. The underlying idea of these operators is similar to the delivery option moves of Zhou et al. (2018), where the assignment of customer requests to intermediate pickup facilities is modified with three move types. However, unlike Zhou et al. (2018), where the current position of customers within the routes is not considered, and either a single customer request or the requests of the n-closest customers to a transshipment facility are transshipped, our intra-route neighborhoods focus on the modification of the locations of successive visits within a single route.

The first three neighborhoods, named **ChangeLocation(**m**)**, aim for small changes and are based on the idea of changing the location of m consecutive customer requests, which share at least one common transshipment facility in their set of possible transshipment facilities F, to one of the common transshipment facilities or to the respective customer locations. We thereby implemented versions for $m = 1$, 2, and 3 customer requests to be changed simultaneously. Due to our observation that the decision for or against transshipping goods at a transshipment facility often depends on a critical number of customer requests per tour being assigned to the same transshipment facility, we implemented two additional moves to change the locations of more customer requests within a route r. This modification of customer locations is an important mechanism, as depending on the problem instance, the solution can become stuck in local optima, where all or most customer requests of a tour are allocated to the same transshipment facility and the previous local search moves are not large enough to leave the local optima. Likewise, it is also possible that using a transshipment facility is only cost-effective if a large portion or all customer requests in an area are assigned to it. Thus, the two moves aim to change the assigned locations of longer sequences of suitable customer requests within a tour (see Figure 4.2). The first neighborhood, **Undo-Transshipment**, filters for sequences of adjacent customer requests being assigned to the same transshipment facility and assigns each customer request to its respective customer location. The second neighborhood, **Try-Transshipment**, is its counterpart and identifies sequences of adjacent customer requests that share a common transshipment facility $v_f \in V_{\mathrm{F}}$ and assigns the customer request to the facility. In the case of problem instances where each customer request can be assigned to every transshipment facility, the sequence of customer requests changed equals the entire route. As a consequence, it is possible to limit the maximum sequence length for routes that include many customers (e.g., maximum 10 customer requests) and evaluate every substring.

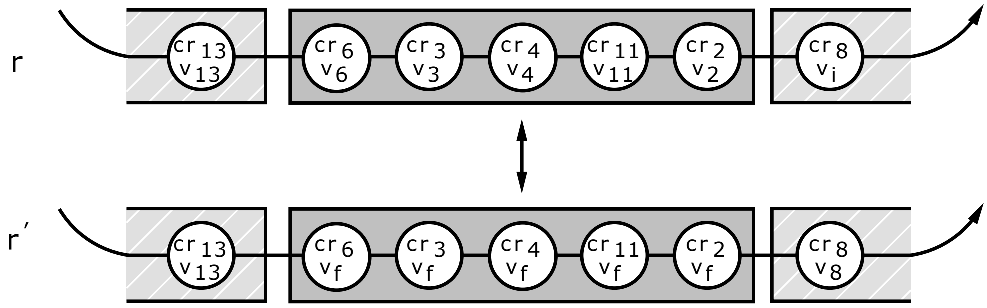


Figure 4.2: Example of the two moves for changing the location of larger parts of routes. The customer requests of the sequence $cr_6 \ldots cr_2$ share at least one possible transshipment facility $v_f \in V_\mathsf{F}$ that is neither shared by the upstream nor downstream customer requests cr_{13} and cr_8 of the tour ($v_f \notin F_{13} \cup F_8$).

With the aim to explore the location assignment of customer requests more thoroughly during the local search, we also propose *combined neighborhoods* that jointly change the assigned location as well as the visit sequence of customer requests. We thereby consider combined versions of the **Shift(1,0) Reinsertion**, and inter-route and intra-route **Swap(1,1)** neighborhoods. The combined **Reinsertion** neighborhood is very similar to the *remove a CP service* neighborhood of Zhou et al. (2018), with the exception that in the latter only customers who are currently assigned to a transshipment facility are considered. Whereas our preliminary results have shown that the addition of combined neighborhoods can lead to slight improvements in solution quality in some cases, it also significantly increases the computation times. This applies especially to instances where the customer requests have many possible transshipment locations, such as the VRPTF benchmark instances from Baldacci et al. (2017). For this reason, combined neighborhoods are not considered further in this paper.

4.4.5 Set Partitioning Problem

Every η^{SP} iteration, the pool of stored routes R^{pool} is used to build a restricted set-partitioning model to be solved by a mixed-integer linear programming (MILP) solver (see Equations (4.13)-(4.16)). Based on the notation of Subramanian et al. (2012), $R_i^{\mathrm{pool}} \subseteq R^{\mathrm{pool}}$ denotes the subset of routes that contain customer request cr_i and $R_k^{\mathrm{pool}} \subseteq R^{\mathrm{pool}}$ the subset of routes that use vehicle type m_k. The binary variable z_r indicates whether a route is included in the solution or not.

$$\min \sum_{r\in R^{\text{pool}}} c_r z_r \tag{4.13}$$

$$\text{s. t.} \sum_{r\in R_i^{\text{pool}}} z_r = 1 \quad \forall cr_i \in CR \tag{4.14}$$

$$\sum_{r\in R_k^{\text{pool}}} z_r \leq m_k \quad \forall cr_i \in CR \tag{4.15}$$

$$z_r \in \{0,1\} \quad \forall r \in R^{\text{pool}}. \tag{4.16}$$

The objective of the SP model (4.13) is to minimize the sum of the route costs. Constraint (4.14) ensures that each customer request is contained exactly once in the solution. Constraint (4.15) states the constraint for the number of available vehicles per type. However, for the fleet size and mix problem variants, constraint (4.15) is left out because the number of vehicles per type is not restricted. Furthermore, as Dumez et al. (2021b) point out, the set-partitioning constraint (4.14) can be modified to an easier to solve set-covering constraint (≥ 1 instead of $= 1$) if the triangle inequality holds true for the problem instance that is considered. If the resulting solution of the set-covering problem contains a customer request in more than one route, we remove the redundant occurrences based on a simple greedy procedure.

To reduce the computational effort and time, the solver is initialized with S_{best}, and the maximum computation time is limited to 30 seconds.

4.4.6 Solution Acceptance

Solution acceptance criteria decide whether a new solution s' is accepted to replace the incumbent solution s_t. There is a broad variety of acceptance criteria that have been tested with the ALNS framework (Santini et al., 2018). In the following, we describe two implemented acceptance criteria in our ALNS:

Threshold acceptance: threshold acceptance (TA) was introduced by Dueck and Scheuer (1990). As the name indicates, each new solution s' is accepted if the difference in solution quality $\frac{f^{\text{mod}}(s')-f^{\text{mod}}(s_t)}{f^{\text{mod}}(s')}$ is smaller than a defined threshold ζ. With each iteration, the threshold is reduced until it reaches an end value. To determine the decrease in each iteration, either linear or exponential schemes, as shown in Schrimpf et al. (2000), can be used. The linear threshold is therein calculated as $\zeta = \zeta_0(1 - \frac{\eta}{\eta^{\text{max}}})$, where ζ_0 is the initial threshold and $\frac{\eta}{\eta^{\text{max}}}$ the percentage of maximum iterations finished. The exponential threshold is calculated as $\zeta = \zeta_0 \exp(-\ln(2)\frac{\eta}{\eta^{\text{max}} ta_\alpha})$, with ta_α being a factor controlling the half-lives. The initial threshold ζ_0 is a parameter that has to be specified.

Record-to-record acceptance: record-to-record acceptance (RRA) was introduced by Dueck (1993) and is based on a similar idea to TA. However, instead of comparing the current solution s' against the incumbent solution s_t, RRA compares the difference in solution values between the current solution s' and best solution s_{best}. If $\frac{f^{\text{mod}}(s')-f^{\text{mod}}(s_{\text{best}})}{f^{\text{mod}}(s')}$ is smaller than the current threshold, the solution is accepted. As with TA, the threshold can be decreased linearly or exponentially.

4.5 Computational Results

In this section, we present the computational results for our ALNS and analyze its performance compared to other approaches in the literature. We coded our ALNS as a single-threaded code in Java 11. To solve the SPP, we used IBM Ilog CPLEX 12.10.0 as the MILP solver. All experiments were performed on an Intel Core i5-6200U CPU at 2.3 GHz with 8 GB RAM on a Windows 10 operating system.

Subsection 4.5.1 presents the process of selecting the parameters of the ALNS, including the decision of which algorithmic components to use. Following this, in Subsection 4.5.2 we derive and describe benchmark instances from the literature and compare the results where applicable. Finally, in Subsection 4.5.3 we introduce a real-world instance and analyze the impact of transshipment fees, time windows, heterogeneous fleets, and demand size on the transshipment decisions.

4.5.1 Parameter Selection

To tune the parameters of our algorithm, we used the automatic algorithm configuration tool irace (version 3.3) (López-Ibáñez et al., 2016). The irace tool implements an iterated racing procedure that provides a set of parameter configurations, so-called elite configurations, which statistically prove to be suitable. To configure our ALNS with irace, the parameters to be tuned, and their types and value ranges must be defined. Additionally, a set of training instances and the tuning budget (total number of runs to be performed) must be specified. We set the tuning budget for our algorithm to 20 000 runs with 5000 to 40 000 maximum iterations per run, depending on the problem. Each run corresponds to the execution of one sampled parameter configuration, given a random seed and a randomly selected training instance. For the training instances, we select instances of varying sizes, including instances with homogeneous and heterogeneous fleets, as well as time windows. Due to the heterogeneity of our training instances, we set irace to use an F-test with a confidence level of 0.95 as the statistical test to analyze the differences between the algorithm configurations. Table 4.2 shows the parameter types as well as their possible ranges and best-found values in irace. Thereby, we distinguish between the VRPTF and its extensions with time windows. Furthermore, we not only determined the parameters of our ALNS but also evaluated the suitability of our two acceptance criteria (see Subsection 4.4.6). In addition, we also let irace decide which removal and insertion diversification procedures to include in our ALNS. This is in line with the studies of François et al. (2019) and François et al. (2016), who argue that an *a priori selection* of algorithmic components is important when designing a ALNS.

The results of the final configurations in Table 4.3 indicate that most of the implemented removal procedures, except the route removal procedure, are beneficial for the ALNS. However, some procedures, such as the cluster and time-related removal, were selected only in the configuration for instances with time windows. Looking at the diversification mechanisms from Subsection 4.4.3, it can be observed that blinking during the ruin step (Blinks-R) seems to be advantageous for instances with time windows as well as instances without time windows. The addition of noise, however, is only selected in the configuration for VRPTF instances. Blinking on customer requests locations (Blinks (I) and Blinks (II)) is chosen in both configurations. However, the variant Blinks (III) for insertion does not appear in any elite configuration for instances with time windows. Regarding the acceptance criteria, it can be seen that TA performed better on instances without time windows, whereas RRA did better on instances with time windows.

Table 4.2: Parameters in the ALNS configuration.

Category	Parameter	Type	Authorized Range	$\neg$ TW	TW
General ALNS	η^{update}	Integer, step 100	[100, 10 000]	600	3500
	λ	Real	[0.1, 1]	0.49	0.73
	$\alpha^{\text{p}}_{\text{min}}$	Integer, step 5	$[5, 500]$	–	30
	$\alpha^{\text{p}}_{\text{max}}$	Integer, step 10	[$\alpha^{\text{p}}_{\text{min}}$, 1000]	–	900
	ρ	Real, step 0.1	[1, 2]	–	1.5
	η^{reset}	Integer, step 100	[100, 5000]	–	800
	η^{SP}	Integer, step 5000	[5000, 20 000]	5000	15 000
Removal	ω_{min}	Real	[0.05,0.25]	0.11	0.07
	ω_{max}	Real	[0.25, 0.6]	0.42	0.31
	p_{worst}	Integer	$[1, 6]$	3	3
	L_{max}	Integer	$[2, 25]$	19	15
	α_{String}	Real, step 0.1	[0.2, 0.8]	0.40	0.45
	β_{String}	Real	[0.01, 0.1]	0.03	0.03
	χ_{q}	Real	[0, 1]	0.42	0.39
	χ_{d}	Real	[0, 1]	0.25	0.11
	χ_{l}	Real	[0, 1]	0.33	0.17
	χ_{TW}	Real	[0, 1]	–	0.33
	$p_{\text{Blinks-Removal}}$	Real	[0, 0.5]	0.12	0.24
Insertion	p_{noise}	Real	[0, 0.3]	0.05	0.00
	ξ_{max}	Real	[0, 0.3]	0.15	0.00
	$p_{\text{Blinks-}v_i}$	Real	[0, 0.2]	0.02	0.01
	$p_{\text{Blinks-}V_{\text{F}}}$	Real	[0, 0.9]	0.10	0.13
Acceptance	Criterion	Categorical	{TA, RRA}	TA	RRA
	Threshold-type	Categorical	{linear, exponential}	exponential	linear
	ta_{α}	Real	[0.05, 0.3]	0.12	–
	ζ_0	Real	[0.01, 0.1]	0.02	0.07

In contrast to the previous parameters tuned by irace, the probability p_{LS} of the embedded local search was selected manually using a maximum CPU time per Instance. In this connection, on the one hand, the possible benefits of high selection probabilities and on the other hand, the additional computing effort should be weighed up. Our tests showed that values of 0.125 resulted in promising results for p_{LS}, while larger values did not improve the solution quality within the same computation time.

4.5.2 Problem Instances from the Literature

To compare our metaheuristic with existing approaches from the literature, we consider several instances for the VRPTF and similar problems, such as the VRPRDL and VRPHRDL, from the literature. As there are no instances available for variants of the VRPTF with time windows and heterogeneous fleets, we propose new instances based on classical instances for the vehicle routing problem with time windows (VRPTW) from the literature.

The instances for the VRPTF and its variants vary by the number of customers V_{C} and the number of transshipment facilities V_{F}. For each of these instances, every customer request can be assigned to every transshipment facility (i.e. $F_i = V_{\text{F}}, \forall i \in V_{\text{C}}$). The cost of assigning a customer request to

Table 4.3: Overview of selected ALNS components.

Category	Component	Configurations	
		¬ TW	TW
Removal procedures	Random removal	✓	✓
	Route removal		
	Worst removal	✓	✓
	Shaw removal	✓	✓
	Cluster removal		✓
	Historical knowledge node removal	✓	✓
	Distance-related removal	✓	✓
	Time-related removal		✓
	Adjacent string removal	✓	✓
Insertion procedures	Random order	✓	✓
	Demand order	✓	✓
	Farthest order		✓
	Closest order		✓
	Regret-2	✓	✓
Diversification	Noise	✓	
	Blinks (I)	✓	✓
	Blinks (II)	✓	✓
	Blinks (III)	✓	
	Blinks-R	✓	✓
Acceptance criteria	TA	✓	
	RRA		✓

a transshipment facility is therein calculated as the Euclidean distance d_{if} between the customer's location $v_i \in V_{\mathrm{C}}$ and the selected transshipment facility $v_f \in V_{\mathrm{F}}$. For each instance, our ALNS is run with ten different random seeds until a maximum number of iterations is reached.

VRPTF

In this section, we give an overview of our results on benchmark instances for the VRPTF and compare these to the results of Baldacci et al. (2017). Thereby, we focus on three sets of problem instances for the VRPTF that have been modified by Baldacci et al. (2017) from classical instances for the location-routing problem (LRP). These 65 instances vary between 12 to 150 customer requests and feature between 2 to 20 transshipment facilities. Instance set (I) has been derived from Akca et al. (2009) and includes 12 instances with either 30 or 40 customer requests and 12 transshipment facilities. Instance set (II) is based on the instances of Prins et al. (2004) and features instances with 20 to 100 customer requests and either 5 or 10 transshipment facilities. Finally, instance set (III) involves various instances from the LRP literature with instances varying between 12 to 150 customer requests and 2 to 20 transshipment facilities. As in Baldacci et al. (2017), the distances between locations are computed as Euclidean distances following the TSPLIB EUC_2D standard.

For our analysis, the number of iterations per instance is set to $\eta^{\max} = 5000$ iterations. However, for many smaller instances, optimal solutions can be found in less than 1000 iterations. Table 4.4

summarizes the results obtained on the three sets and compares them to the results of Baldacci et al. (2017). In the table, column #Opt. reports the number of instances on which the optimal solutions, as reported in Baldacci et al. (2017), were found. Column #Imp. reports the number of instances per set where improvement was found and column #Eq. states the number of instances where the same non-optimally proven results were obtained. Column Avg. Imp. states the average improvement in %. Lastly, column Avg. T Red. % reports the average time reduction, based on the average run time from 10 runs each. The detailed results on each instance, including the best solution values z^*, average solution values $\bar{z}$, and times $\overline{T}$ out of 10 runs can be found in Appendix 4.A.1.

Considering the reported solutions from Baldacci et al. (2017) and their stated lower bounds, it can be seen that our ALNS heuristic can find new best solutions for 38 problem instances while only taking a fraction of the computational times. For the remaining 27 problem instances, solutions identical to those reported by Baldacci et al. (2017) have been found. Of these, 23 have been proven to be optimal by Baldacci et al. (2017).

Table 4.4: Summary of the tested VRPTF data sets from Baldacci et al. (2017).

Instance set	#	#Opt.	#Imp.	#Eq.	Avg. Imp. %	Avg. T Red. %
(I) Akca et al. (2009)	12	10	0	2	0.00	85.16
(II) Prins et al. (2004)	14	3	9	2	0.81	94.73
(III) Different authors	39	10	29	0	0.85	94.66

VRPRDL and VRPHRDL

In order to validate our algorithm's performance on problem instances with time windows, we utilize the 120 instances from the VRPRDL and VRPHRDL of Reyes et al. (2017) and Ozbaygin et al. (2017) and compare our algorithm with recent studies. To be precise, we compare the results of our ALNS on the instances to those reported by Ozbaygin et al. (2017), Dumez et al. (2021a), and Tilk et al. (2020). To compare our results to those reported by Ozbaygin et al. (2017), we set the maximum number of vehicles to the number reported by Ozbaygin et al. (2017), as done in Dumez et al. (2021a), and Tilk et al. (2020). In summary, as shown in Tables 4.5 and 4.6, we can observe that the best-known values, as reported in the literature, are found for all 120 instances. Furthermore, with respect to the average solution quality and computing time $\overline{T}$, only very small differences to the current state-of-the-art algorithm from Dumez et al. (2021a) can be observed.

New Instances for the VRPTWTF and FSMTWTF

We propose new instances based on modifications of the classical instances for the VRPTW from Solomon (1987) to analyze our performance with respect to the VRPTWTF and FSMTWTF. These instances are separated into three sets, that are clustered, random, and semi-clustered, and denoted as C, R, and RC. To use these classical instances for our problem with transshipment facilities, we choose a similar approach as Baldacci et al. (2017) and derive our instances from the LRP literature. More specifically, for the transshipment facilities, we use the depots 2-6 from the location-routing problem with time windows (LRPTW) benchmark instances of Koç et al. (2016a), who used a

Table 4.5: Summary of the tested data sets for the VRPRDL.

Instance set	$\lvert V_{\mathrm{C}} \rvert$	Ozbaygin et al. (2017)	Dumez et al. (2021a)		Tilk et al. (2020)	ALNS	
		Best 1	Best 5	Avg. 5	Best 1	Best 5	Avg. 5
1-5	15	**6072.0**	**6072.0**	6072.0	**6072.0**	**6072.0**	6072.0
6-10	20	**6848.0**	**6848.0**	6848.0	**6848.0**	**6848.0**	6848.0
11-20	30	**18 595.0**	**18 595.0**	18 595.0	**18 595.0**	**18 595.0**	18 595.0
21-30	60	**37 213.0**	**37 213.0**	37 213.0	**37 213.0**	**37 213.0**	37 213.0
31-40	120	53 881.0	**53 738.0**	53 738.4	**53 738.0**	**53 738.0**	53 738.8
41-50-v1	40	29 842.0	**29 838.0**	29 838.0	**29 838.0**	**29 838.0**	29 838.0
41-50-v2	40	**21 863.0**	**21 863.0**	21 863.4	**21 863.0**	**21 863.0**	21 864.9
Sum		174 314.0	**174 167.0**	174 167.8	**174 167.0**	**174167.0**	174 169.7
$\overline{\mathrm{T}}$[s]		2961.0	17.3		148.5	16.9	
Processor		Xe-2.3G	Xe-2.57G		i7-3.5G	i5-2.3G	

discrete uniform distribution to draw additional depot locations for each of the instance sets from Solomon (1987). The central depot coordinates remain unchanged from the original Solomon instances.

With regard to the time windows and service times, the instances are adjusted as follows:

- The customer location time windows are shifted forward in time by adding the service times from the Solomon instances to the start and end times of the time windows of the VRPTW instances. This way we can model the original service times as location preparation times so that the time spent at a transshipment facility is independent of the number of customer requests. Furthermore, transshipment facilities have the same location-dependent preparation times t_i^{P} as the customer locations.
- Transshipment facilities can only be visited early during the routes so that the latest possible arrival time of all transshipment facilities equals the rounded maximum travel time between the depot v_0 and any transshipment facility ($tw_i^{\mathrm{S}} = 0$ and $tw_i^{\mathrm{E}} = \lceil \max_{i=v_0, j \in V_{\mathrm{F}}}(t_{ij}) \rceil$).

Although the VRPTW typically has a hierarchical objective function of reducing the number of vehicles first and the distance second, we refrain from doing so for the VRPTWTF, as the fleet minimization objective favors the transshipment facilities too strongly, so that the routes consist almost exclusively of visiting transshipment facilities. Instead, for each instance of the VRPTWTF, we limit the number of available vehicles to the minimum number of vehicles reported for the original instances of the VRPTW in the literature. This also gives us information on the best solution values without using any of the transshipment facilities for each instance and allows us to assess how the addition of transshipment facilities can impact costs.

The instances for the FSMTWTF are also based on the Solomon instances and use the same modifications regarding the time windows and service times. For the vehicles and their corresponding costs and capacities, we use the vehicles and cost structure A from the FSMTW instances of Liu and Shen (1999). Regarding the maximum number of iterations, we set $\eta^{\max} = 35\,000$ because it proved to be a good trade-off between run time and solution quality.

Table 4.6: Summary of the tested data sets for the VRPHRDL.

Instance set	$\lvert V_C \rvert$	Ozbaygin et al. (2017)	Dumez et al. (2021a)		Tilk et al. (2020)	ALNS	
		Best 1	Best 5	Avg. 5	Best 1	Best 5	Avg. 5
1-5	15	**5450.0**	**5450.0**	5450.0	**5450.0**	**5450.0**	5450.0
6-10	20	**5604.0**	**5604.0**	5604.0	**5604.0**	**5604.0**	5604.0
11-20	30	**15 128.0**	**15 128.0**	15 128.0	**15 128.0**	**15 128.0**	15 128.0
21-30	60	26 829.0	**26 800.0**	26 800.0	**26 800.0**	**26 800.0**	26 800.0
31-40	120	38 610.0	**37 252.0**	37 310.4	37 583.0	**37 252.0**	37 303.6
41-50-v1	40	27 997.0	**27 996.0**	27 996.0	**27 996.0**	**27 996.0**	27 996.0
41-50-v2	40	20 977.0	**20 958.0**	20 958.0	**20 958.0**	**20 958.0**	20 958.0
Sum		142 595.0	**139 188.0**	139 246.4	139 519.0	**139 188.0**	139 239.6
$\overline{\mathrm{T}}$[s]		6587.1*	17.3		2924.1	17.0	
Processor		Xe-2.3G	Xe-2.57G		i7-3.5G	i5-2.3G	

* Ozbaygin et al. (2017) did not report solution times for the instances with $\lvert V_C \rvert = 40$.

In order to validate our Algorithm's performance on the new FSMTWTF instances, we also tested our algorithm on instances for the FSMTW that have been studied by several authors from the literature. The results, summarized in Table 4.7, show that our ALNS is very competitive for the FSMTW, finding new best solutions for four instances (see Appendix 4.A.3).

Table 4.7: Summary of the tested data sets for the FSMTW.

Instance set	#	$\lvert V_C \rvert$	Vidal et al. (2014)	Koç et al. (2015)	Penna et al. (2019)	ALNS	
			Best 5	Best 5	Best 10	Best 10	Avg. 10
C1	9	100	**63 746.78**	**63 746.78**	**63 746.78**	**63 746.78**	63 746.78
R1	12	100	**48 375.38**	48 497.56	48 385.69	48 377.28	48 507.54
RC1	8	100	39 129.97	39 331.28	39 108.26	**39 099.14**	39 180.60
C2	8	100	**45 494.00**	**45 494.00**	**45 494.00**	**45 494.00**	45 494.20
R2	11	100	34 671.50	**34 653.26**	34 672.03	34 676.70	34 779.66
RC2	8	100	**33 680.83**	33 681.82	**33 680.83**	33 687.66	33 792.85
Sum			265 098.46	265 404.69	265 087.59	**265 081.53**	207 155.09
$\overline{\mathrm{T}}$			305.24	283.60	193.26	252.88	
Processor			Opt-2.2G	Xe-2.6G	i7-2.93G	i5-2.3G	

Table 4.8 and 4.9 give a summary of the results obtained for the VRPTWTF and FSMTWTF, highlighting the usage of the transshipment facilities, and comparing the results with the best-known solution values of the VRPTW and FSMTW. Furthermore, Tables 4.15 and 4.18 in Subsections 4.A.2 and 4.A.4 of the Appendix provide detailed results. The results show that for many of the instances, the number of vehicles, as well as the objective value, can be reduced, compared to the results of the VRPTW without transshipment facilities (column Avg. Gap. %). On average, the usage of transshipment facilities leads to a cost reduction of 4.08 % for the VRPTWTF. However, the potential for cost reductions seems to depend strongly on the instances. For example, for the

clustered instances (C) of the VRPTWTF no improvements are found by adding transshipment facilities. Furthermore, the results show that fewer transshipment facilities are used for the FSMTWTF than the VRPTWTF, and smaller cost improvements compared to the FSMTW are observed. Especially for the instances with longer planning horizons (C2, R2, and RC2), only a few improvements over the best solutions without transshipment facilities are found for the FSMTWTF. The relatively small cost savings on the FSMTWTF instances can be explained by the fact that the instances have, in contrast to the VRPTW, no fleet size restrictions and as such make it easier to find good solutions without using transshipment facilities.

Table 4.8: Summary of the tested data sets for the VRPTWTF.

Instance set	#	$\overline{\#r}$	$\overline{\#f}$	$\overline{\#c}$	$\overline{z^*}$	$\overline{T}$[s]	Avg. Gap. %
C1	9	10.00	0.00	0.00	828.38	84.69	0.00
R1	12	10.92	2.83	15.50	1080.62	173.88	-10.14
RC1	8	10.88	3.38	14.88	1271.40	122.03	-7.39
C2	0	3.00	0.00	0.00	589.86	132.04	0.00
R2	0	2.73	0.82	4.36	929.49	312.52	-2.15
RC2	0	3.25	1.50	9.38	1081.76	247.30	-2.99

Table 4.9: Summary of the tested data sets for the FSMTWTF.

Instance set	#	$\overline{\#r}$	$\overline{\#f}$	$\overline{\#c}$	$\overline{z^*}$	$\overline{T}$[s]	Avg. Gap. %
C1	9	19.00	1.00	1.00	7079.06	265.08	-0.06
R1	12	19.08	2.83	8.67	4013.05	313.97	-0.42
RC1	8	15.25	2.00	7.75	4859.92	400.23	-0.54
C2	8	5.00	0.00	0.00	5686.75	396.01	0.00
R2	11	5.00	0.55	2.09	3147.23	427.94	-1.94
RC2	8	11.30	0.13	1.30	4213.26	430.28	0.08

4.5.3 Real-World Instances

In this section, we give an overview of the real-world instances newly created and the computational results obtained. First, we describe how the real-world instances were created and give an overview of the attributes and data sources. Second, we report our computational results on these instances and conduct a sensitivity analysis on the impact of the transshipment costs, demand size, time windows, and vehicle fleet on the transshipment decisions. All of the newly created instances are available upon request.

Description

The instances are based on the Frankfurt-Rhine-Main metropolitan area in Germany and feature either 50 or 100 customers, eight transshipment facilities, and one central depot. The customer locations for both instance sizes are based on the real geographic coordinates of retail stores. The central depot, as well as the transshipment facilities, are based on the geographic coordinates of real facilities from LSPs and are the same for both instances. To obtain a realistic mix of customer locations within urban and non-urban areas, we retrieved the retail locations from 13 retail chains within a 30 km radius of the central depot and selected two subsets of these locations. These retail chains operate between 4 to 20 stores within the area of which 10 % to 100 % are located in urban centers. For the transshipment of goods at transshipment facilities, we assume that only the customer requests of customers located in one of the seven largest cities of the Frankfurt-Rhine-Main metropolitan area can be transshipped. For this purpose, we include eight potential transshipment facilities. Each urban area has either one or two transshipment facilities and, except for one transshipment facility, all serve only one urban area. For both instances, 60 % of the customers can be transshipped at a transshipment facility. Figure 4.3 gives an overview of the geographic distribution of all the locations.

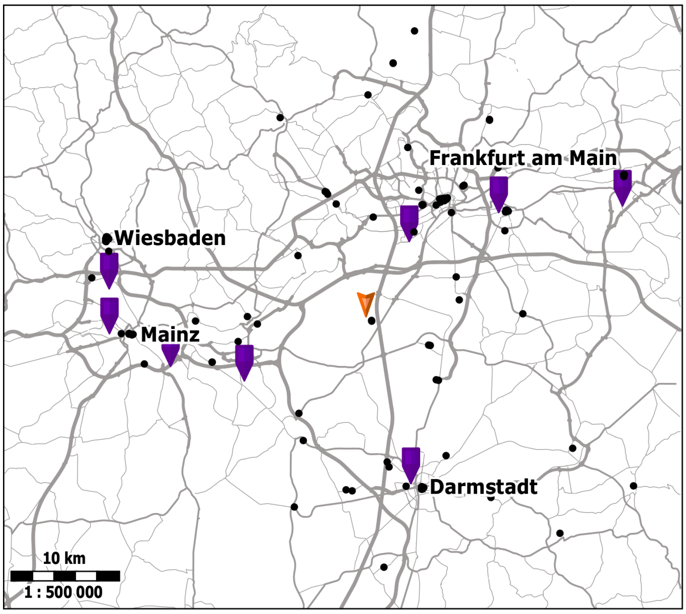


Figure 4.3: Map of the Frankfurt Rhine-Main area with the central depot (orange arrow), transshipment facilities (purple squares), and customer locations (black dots) (Map data copyrighted OpenStreetMap Contributors).

For the distances and travel times between locations, we retrieved the distances and travel times for each pair of locations both ways, using the HERE Routing API v7, with the mode specified as *truck* and *fastest* and *truckType=truck*. In this context, it is worth noting that due to the presence of truck transit bans in the region, some triangle inequality violations occur. This means that visiting a sequence of customer locations $\{v_1, v_2, v_3\}$, with v_2 being in a transit ban zone, might be shorter than the sequence $\{v_1, v_3\}$, as vehicles with at least one delivery within the transit ban zone are exempt from the ban.

While we keep the subset of locations constant for the two instance sizes, we vary the time window lengths, customer demands, transshipment costs, and vehicle fleet during our experiments to analyze how they affect the transshipment decisions. Table 4.10 gives an overview of the key characteristics of the instances created for our experiments, which we will describe in the following.

Table 4.10: Real-world instance and experiment summary.

Factor	Values
$\lvert V_{\mathrm{C}} \rvert$	$\{50, 100\}$
$\lvert V_{\mathrm{F}} \rvert$	8
$\bar{q}$	$[1, 5]$
t_i^{p}	15
t_i^{s}	$\bar{q}$
κ	$\{60, 120, 180\}$
c_{tf}	$[1, 10]$
Fleet	{homogeneous, heterogeneous}

The time windows of the customer locations are set according to the following rules:

- Customers in urban areas have to be visited in the morning due to access restrictions in the pedestrian zones so that $[tw_i^{\mathrm{S}}, tw_i^{\mathrm{E}}]$ such that $30 + t_i^{\mathrm{p}} \leq tw_i^{\mathrm{S}} \leq 90 + t_i^{\mathrm{p}}$ and $tw_i^{\mathrm{E}} = tw_i^{\mathrm{S}} + \kappa$.
- Transshipment facilities should be visited in the morning, so that $tw_i^{\mathrm{S}} = 0$ and $tw_i^{\mathrm{E}} = 120$.
- For other customers that cannot be served by a transshipment facility, the time windows $[tw_i^{\mathrm{S}}, tw_i^{\mathrm{E}}]$ are set randomly, so that $t_i^{\mathrm{p}} \leq tw_i^{\mathrm{S}} \leq 450$ and $tw_i^{\mathrm{E}} = tw_i^{\mathrm{S}} + \kappa$.

Depending on the instance, we assume for the time window length κ values of 60, 120, and 180. To analyze the impact of demand size q_i on the transshipment facility usage, we systematically vary the demand for all customers in the range of 1 to 5 pallets. We modify the demand equally for each customer ($q_i = \bar{q}$), so that the impact of demand can be analyzed more easily. In this context, we assume that the service times of customer requests correspond to the demand quantity ($t_i^{\mathrm{s}} = q_i$) while the demand independent preparation times t^{p} are assumed to be 15 minutes for all locations.

Following the literature on UCCs (see e.g., Firdausiyah et al., 2019) and the reported real-world UCCs (Janjevic and Ndiaye, 2017b), we assume that the transshipment costs are based on the quantity transshipped and thus model a price per pallet cost scheme for the transshipment facilities. Subsequently, we calculate the costs for transshipping a customer request cr_i at a transshipment facility by multiplying the cost factor per unit c_{tf} with the quantity q_i of cr_i. For our sensitivity analysis, we vary the transshipment costs per unit c_{tf} in the range of $[1, 10]$. Regarding the vehicle fleets, we test both a homogeneous fleet and a heterogeneous fleet consisting of three vehicle types. For the homogeneous fleet, we assume a single medium-sized vehicle type with a capacity of 18 demand units. For the heterogeneous fleet, we add two additional vehicle types – one smaller and one larger – with capacities of 12 and 34 demand units, respectively. Each of the three vehicle types has its distance-based and fixed usage cost, while the duration-based costs are assumed to be independent of the vehicle type. Table 4.11 summarizes the three vehicle types.

Results and Managerial Insights

In this section, we present the results of our experiments to quantify the impact of transshipment costs, demand size, time windows, number of customers, and vehicle fleet on the transshipment decisions, cost, and fleet mix. Figure 4.4 provides the percentage of transshipment facility usage for the experiments with the heterogeneous fleet, and Figure 4.5 the results for the experiments

Table 4.11: Vehicle properties for the real-world instance.

Vehicle property	Small truck ($k = 1$)	Medium truck ($k = 2$)	Large truck ($k = 3$)
Distance-based cost c_k^{d} [per km]	0.33	0.46	0.61
Duration-based cost c_k^{t} [per h]	21	21	21
Fixed cost c_k^{f} [per tour]	55.35	72.01	118.33
Capacity Q_k	12	18	34

with the homogeneous fleet. As expected, the results show that, in general, the use of the transshipment facilities declines as the usage costs per unit c_{tf} increase. Moreover, the results indicate that the demand $\bar{q}$ has a strong impact on the transshipment facility use. With increasing demand per customer request, the percentage of customer requests transshipped rapidly decreases. This relationship can be explained by the quantity-based pricing of the transshipment facilities, which reduces the potential cost savings (e.g., time and distance savings) at higher transshipment quantities per stop. It is also in line with previous research from Janjevic and Ndiaye (2017b), who showed that the cost attractiveness for using a UCC strongly decreases as the number of pallets per stop increases.

As both figures show, the length of the time windows is another important influencing factor. With smaller time window lengths κ, the use of the transshipment facilities becomes cost-attractive and increases. In particular, for a homogeneous fleet with a narrow time window length of $\kappa = 60$, the percentage of customer requests transshipped remains consistently high across the studied transshipment cost levels. Wider time windows, on the other hand, show a stronger price sensitivity so that the fraction of customer requests transshipped decreases more as transshipment costs increase.

When comparing the transshipment facility usage between the homogeneous and heterogeneous fleet, it can be observed that for customer demands of $\bar{q} = 1$ the percentage of customer requests transshipped seems to be higher for the homogeneous fleet than for the heterogeneous fleet. However, at larger demand sizes ($\bar{q} >= 2$), the fraction of customer requests transshipped is overall slightly higher for the heterogeneous fleet than the homogeneous fleet. This could be explained by the fact that in the heterogeneous case, the large trucks ($k = 3$) can load more customer requests to be delivered to the transshipment facilities, making the deliveries to the transshipment facilities more efficient and allowing for larger cost savings.

The comparison of the two instance sizes does not show a clear relationship. For runs with narrow time windows, a homogeneous fleet, and customer demand $\bar{q} \leq 3$, the fraction of orders transshipped is higher for the instance with 50 customers than for the instance with 100 customers. However, this relationship between the number of customers and the fraction of orders transshipped seems to be weaker when a heterogeneous fleet is employed and the time window length is longer.

The analysis of the resulting fleet mix for the instance with $|V_{\mathrm{C}}| = 50$, presented in Figure 4.6, and for $|V_{\mathrm{C}}| = 100$ in Figure 4.7, shows how the vehicle types deployed depend on the demand per customer, time windows, and transshipment cost. First, it can be observed that the demand sizes seem to have a strong impact. With low demand per customer ($\bar{q} \in \{1, 2\}$), the small and medium-sized trucks are preferred, while for higher values of $\bar{q}$ the large-sized trucks are used. Second, the figures show that with narrow time windows, smaller vehicles are selected more frequently. Third, with lower transshipment cost, and a consequently higher fraction of customer

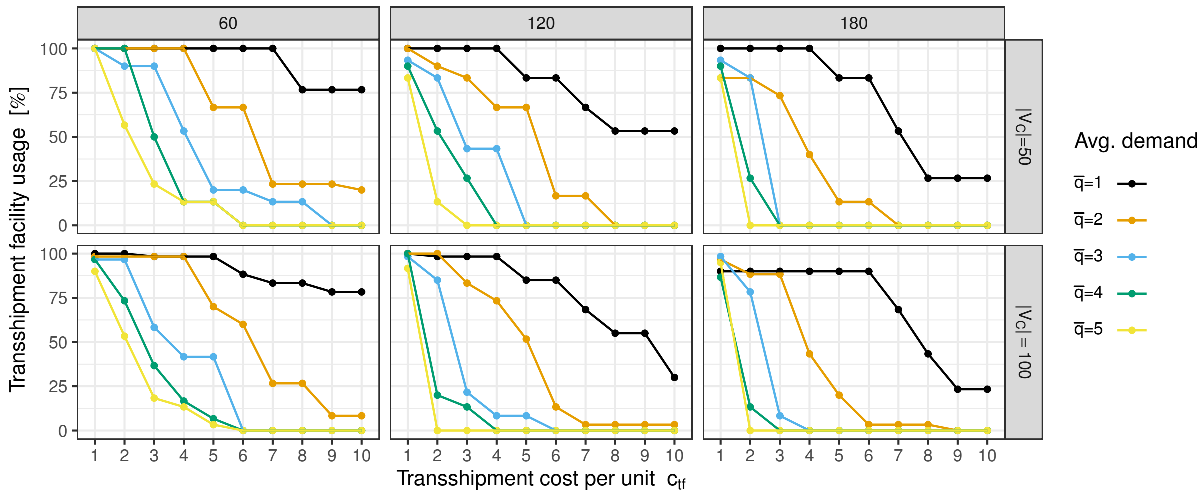


Figure 4.4: Analysis of the impact of time window length κ (columns), number of customers $|V_{\mathrm{C}}|$, demand $\bar{q}$, and transshipment costs per unit c_{tf} on the percentage of transshipment facility usage when using a heterogeneous fleet.

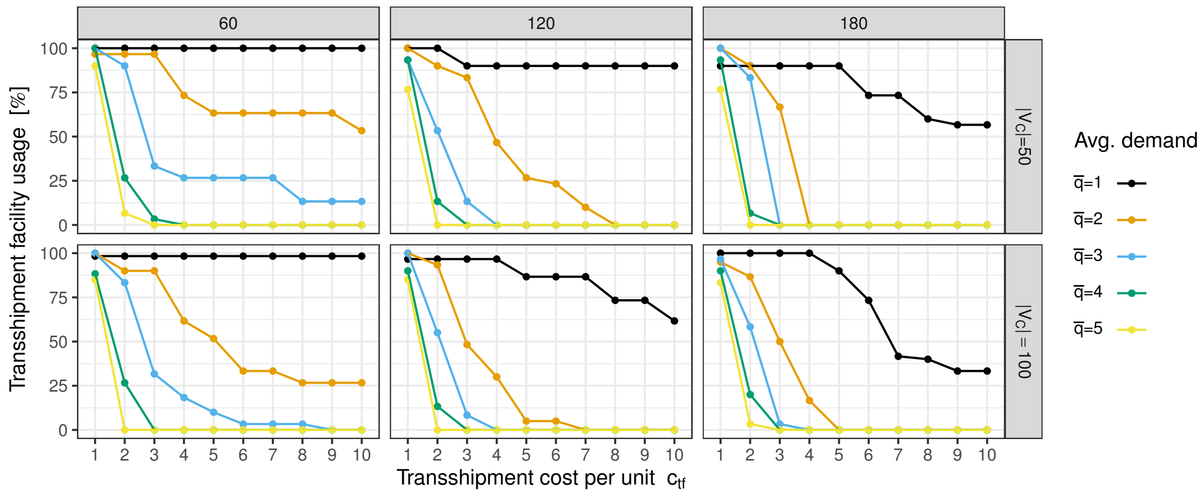


Figure 4.5: Analysis of the impact of time window length κ (columns), number of customers $|V_{\mathrm{C}}|$, demand $\bar{q}$, and transshipment costs per unit c_{tf} on the percentage of transshipment facility usage when using a homogeneous fleet consisting only of medium-sized trucks.

requests transshipped, the use of medium and large-sized vehicles increases for the demand sizes $\bar{q} \leq 4$. Finally, the comparison between instances for 50 and 100 customers shows that with the larger number of customers, not only more but also larger vehicles are employed. This may be related to the fact that the higher number of customers is also accompanied by a higher customer density and thus multiple customer requests can be more easily combined into one route.

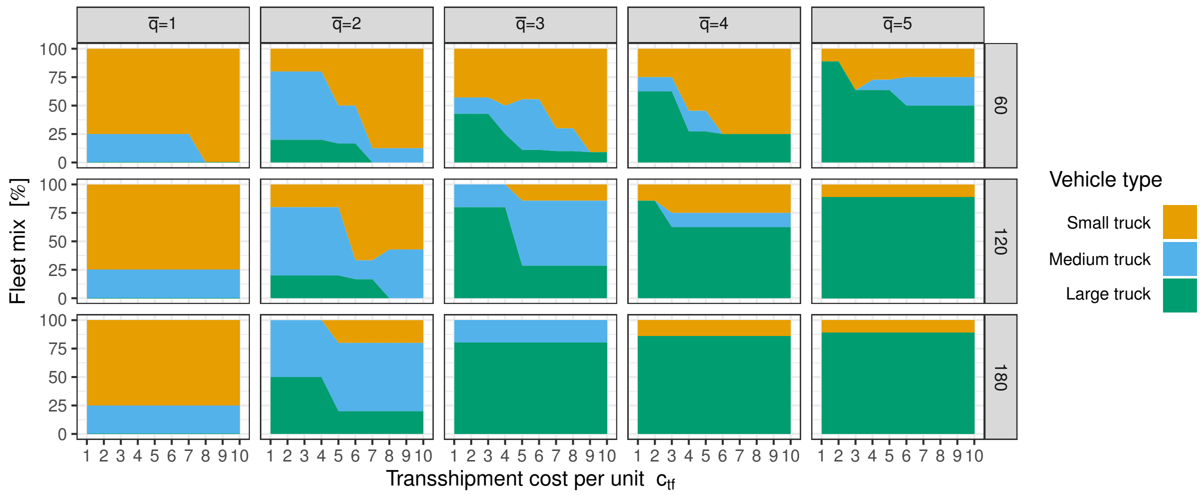


Figure 4.6: Analysis of the impact of time window length κ (rows), demand q, and transshipment costs per unit c_{tf} on the fleet mix for $|V_{\text{C}}| = 50$.

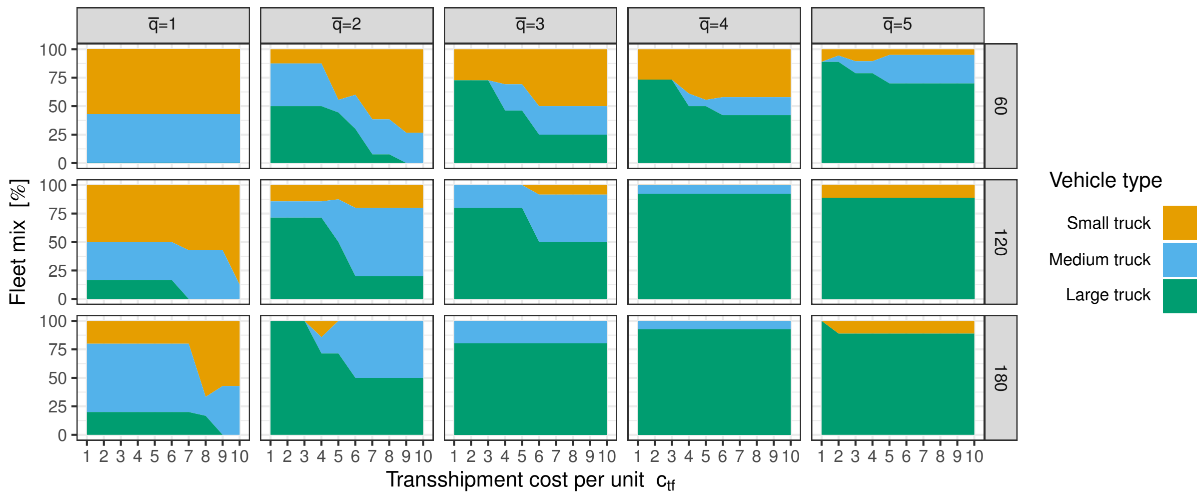


Figure 4.7: Analysis of the impact of time window length κ (rows), demand $\bar{q}$, and transshipment costs per unit c_{tf} on the fleet mix for $|V_{\text{C}}| = 100$.

Lastly, we study how the overall solution costs are impacted by the factors studied. Figure 4.8, as well as Figure 4.9, provide an overview, of how the transshipment costs per unit c_{tf} and customer demand impact the overall solution cost, separated by the two instance sizes and three time window lengths. As the transshipment costs per unit increase and thus the transshipment facility usage decreases, the overall costs per factor level combination increase, up to the point where no transshipment facility is used. Furthermore, in Section 4.B in the Appendix, we analyze the cost savings that can be achieved using the approach presented in this paper compared to the traditional approach where either all or none of the customer requests destined for an urban area are transshipped. The results reveal that, in some cases, considerable cost savings of more than 7 % are achieved when the transshipment is decided for each customer request individually. Thus, the approach presented in this paper could help LSPs to save costs in the context of UCCs.

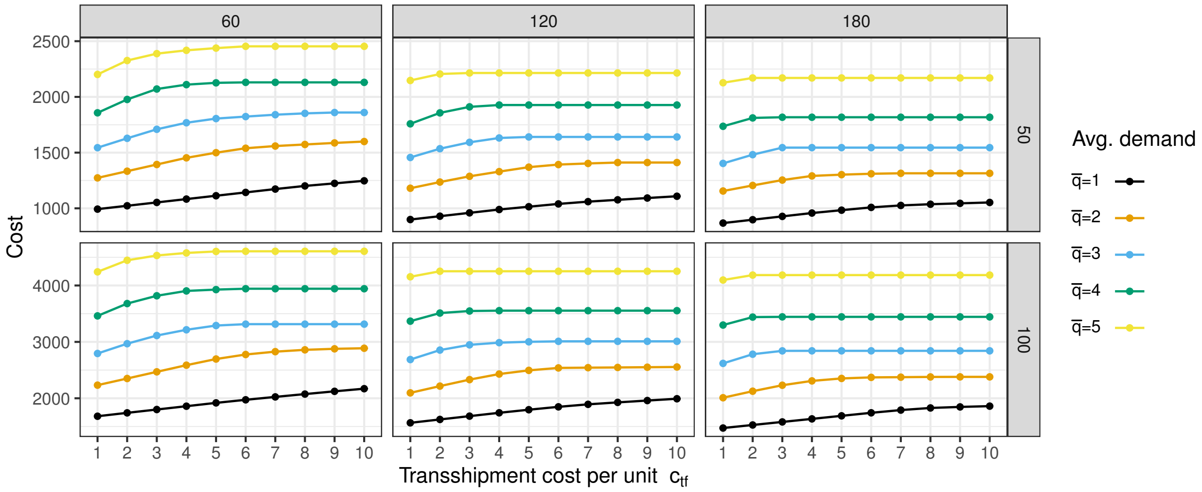


Figure 4.8: Analysis of the impact of time window length κ (columns), number of customers $|V_C|$, demand q, and transshipment costs per unit c_{tf} on the costs when using a heterogeneous fleet.

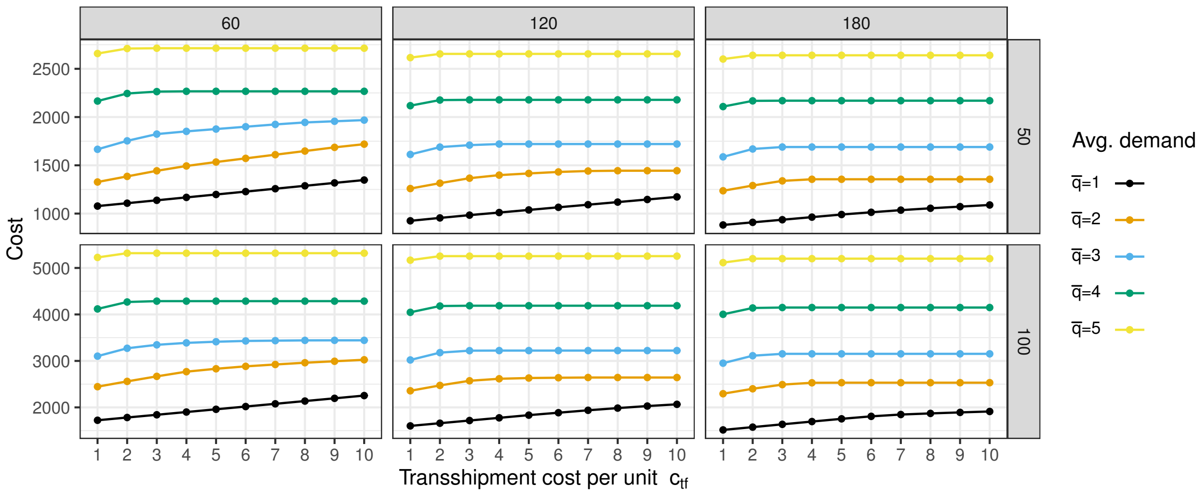


Figure 4.9: Analysis of the impact of time window length κ (columns), number of customers $|V_C|$, demand $\bar{q}$, and transshipment costs per unit c_{tf} on the costs when using a homogeneous fleet.

From the results of our analysis, we conclude that the decision of whether to tranship customer requests at a transshipment facility depends largely on the price and demand per customer request. In addition, it becomes apparent that due to the quantity-based pricing of transshipment facilities, LSPs with low demand per customer or stop would be the primary target group for transshipment facilities. Indeed, this group of LSPs has also been previously identified by Browne et al. (2005) as the potential beneficiaries of UCCs. As a consequence, initiatives using a quantity-based scheme should focus on attracting LSPs with low drop sizes per stop. Alternatively, different pricing models to attract LSPs with larger demands per stop should be developed.

Time windows, especially at the narrow time window width $\kappa = 60$ min, can increase the potential cost-benefits of using a transshipment facility. This is also consistent with other studies from the literature, which have shown that time windows must be particularly narrow to influence the decision to use transshipment facilities, such as UCCs (Elbert and Friedrich, 2018a; van Heeswijk et al., 2020). Consequently, local governments could support the use of transshipment facilities through narrow time windows. Moreover, the comparison of the two instance sizes shows that the time window widths seem to have a stronger influence when the number of customers to be visited is lower.

Concerning the fleet mix, it can be seen that depending on the demand and usage costs, but also on the time window length, the composition of the fleet changes. Especially, in the case of medium demand per customer, the share of medium and large vehicles increases when transshipment facilities become more cost-attractive. This suggests that LSPs that want to regularly use transshipment facilities for a portion of their customer requests should ideally adjust their fleet accordingly. At the same time, however, this also means that the benefits of transshipment facilities can vary greatly depending on the LSP's fleet already in place.

4.6 Conclusion and Further Research

In this article, we presented an ALNS with an embedded local search for different vehicle routing problems with transshipment facilities. The VRPTF and its variants describe an extension to the VRP where, for a fee, some customer requests can be delivered to third-party transshipment facilities, such as UCCs, instead of being delivered directly. Thereby, we extended the existing approaches on vehicle routing problems with transshipment facilities to include both time windows and heterogeneous fleets. Furthermore, we introduced new operators for removal, as well as local search moves, and insertion diversification methods that consider transshipment facilities.

To test our algorithm on various problem instances and assess the importance of different algorithmic components, we tuned the parameter of our ALNS using the irace package. Subsequently, we tested our algorithm on several instances from the literature as well as new instances derived from classical VRPTW instances and real-world data. We also used related problems, such as the VRPRDL, VRPHRDL, and FSMTW to validate the performance of our algorithm. Furthermore, we introduced new instances for the VRPTWTF and FSMTWTF, and provided solutions for these, and compared the results to the normal versions without transshipment facilities.

In comparison to the results from the literature, our algorithm seems to be very competitive. For the VRPTF our ALNS outperforms the existing exact algorithm, requiring only a fraction of the computational time. As a result, we were able to find new best solutions for 38 out of 65 VRPTF instances from the literature. For the VRPRDL and VRPHRDL, the best-known solutions reported in the literature were also found. Likewise, our algorithm also shows promising results on the well-studied FSMTW instances from the literature, obtaining new best results for four instances.

The computational results on our real-world instance, using a mixed cost function that considers distance-dependent and time-dependent costs, as well as fixed costs, show that many factors influence the decision of whether to tranship customer requests at a third-party transshipment facility. In particular, the demand per customer, and the transshipment fees charged by the third-party subcontractor, but also the length of the customer time windows have a large impact on the transshipment decisions.

For future research, more factors influencing the transshipment decisions, such as the customer structure and density could be investigated using simulation. Moreover, the ALNS could be extended by considering additional real-world characteristics, such as vehicle-dependent toll schemes and travel times, incompatibility among goods, and driving and working hour regulations.

CRediT authorship contribution statement

Christian Friedrich: Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Ralf Elbert:** Conceptualization, Supervision, Project Administration, Writing – Review & Editing.

4 Appendix

Appendix 4.A Detailed Results

4.A.1 VRPTF Instances

Table 4.12: Detailed results on set (I), based on Akca et al. (2009).

Instance	$\lvert V_C \rvert$	$\lvert V_F \rvert$	Baldacci et al. (2017)		ALNS						
			z*	T	z*	$\bar{z}$	$\bar{T}$	#r	#f	#c	Gap[%]
cr30x5a-1	30	5	621.00	8.0	621.00	621.00	3.9	5	0	0	0.00*
cr30x5a-2	30	5	665.00	20.0	665.00	665.00	4.8	5	1	2	0.00*
cr30x5a-3	30	5	575.00	29.0	575.00	575.00	4.5	5	1	2	0.00*
cr30x5b-1	30	5	727.00	10.0	727.00	727.00	4.4	5	1	1	0.00*
cr30x5b-2	30	5	826.00	79.0	826.00	826.00	4.1	6	0	0	0.00*
cr30x5b-3	30	5	788.00	1061.0	788.00	788.00	4.5	7	1	1	0.00*
cr40x5a-1	40	5	738.00	82.0	738.00	738.00	5.1	7	3	8	0.00*
cr40x5a-2	40	5	786.00	3615.0	786.00	787.20	5.7	6	4	4	0.00
cr40x5a-3	40	5	807.00	3631.0	807.00	810.20	5.1	6	1	1	0.00
cr40x5b-1	40	5	964.00	49.0	964.00	964.00	5.5	8	0	0	0.00*
cr40x5b-2	40	5	901.00	34.0	901.00	901.00	5.4	8	2	3	0.00*
cr40x5b-3	40	5	887.00	81.0	887.00	887.00	5.3	8	2	5	0.00*

* Optimality proven by Baldacci et al. (2017).

Table 4.13: Detailed results on set (II), based on Prins et al. (2004).

Instance	$\lvert V_C \rvert$	$\lvert V_F \rvert$	Baldacci et al. (2017)		ALNS						
			z*	T	z*	$\bar{z}$	$\bar{T}$	#r	#f	#c	Gap[%]
ppw-20-5-2-a	20	5	247.00	14.0	247.00	247.00	1.9	5	1	3	0.00*
ppw-20-5-2-b	20	5	189.00	5.0	189.00	189.00	2.1	3	1	2	0.00*
ppw-50-5-2-a	50	5	587.00	126.0	587.00	587.00	7.2	12	1	2	0.00*
ppw-50-5-2-b	50	5	357.00	3625.0	357.00	357.00	8.6	6	0	0	0.00
ppw-50-5-3-a	50	5	586.00	3630.0	583.00	583.20	8.3	12	1	3	-0.51
ppw-50-5-3-b	50	5	381.00	3644.0	381.00	381.00	9.8	6	0	0	0.00
ppw-100-5-2-a	100	5	1010.00	3735.0	996.00	997.80	39.8	23	1	3	-1.41
ppw-100-5-2-b	100	5	569.00	3783.0	558.00	560.30	41.7	11	0	0	-1.97
ppw-100-5-3-a	100	5	1068.00	3686.0	1065.00	1066.80	36.6	23	2	3	-0.28
ppw-100-5-3-b	100	5	612.00	3733.0	607.00	608.30	38.3	11	0	0	-0.82
ppw-100-10-2-a	100	10	1030.00	3853.0	1012.00	1018.30	41.6	24	2	5	-1.78
ppw-100-10-2-b	100	10	582.00	3809.0	574.00	577.10	70.7	11	0	0	-1.39
ppw-100-10-3-a	100	10	1055.00	424.0	1038.00	1039.50	40.6	24	3	5	-1.54†
ppw-100-10-3-b	100	10	608.00	3773.0	599.00	600.20	80.1	11	2	3	-1.50

* Optimality proven by Baldacci et al. (2017).
† Baldacci et al. (2017) report their value of 1055 to be optimal. We assume this to be an error.

Table 4.14: Detailed results on instance set (III), based on different authors.

Instance	$\lvert V_C \rvert$	$\lvert V_F \rvert$	Baldacci et al. (2017)		ALNS						
			z*	T	z*	$\bar{z}$	$\bar{T}$	#r	#f	#c	Gap[%]
Christ-50x5	50	5	514.00	130.0	514.00	519.90	7.0	5	2	2	0.00*
Christ-50x5B	50	5	533.00	3698.0	530.00	531.00	7.2	5	2	3	-0.57
Christ-75x10	75	10	783.00	3676.0	771.00	776.80	19.3	9	3	3	-1.56
Christ-75x10B	75	10	814.00	3750.0	812.00	813.00	18.3	9	4	6	-0.25
Christ-100x10	100	10	831.00	3987.0	821.00	823.20	100.0	8	0	0	-1.22
Gaskell-21x5	21	5	371.00	5.0	371.00	371.00	2.1	4	1	2	0.00*
Gaskell-22x5	22	5	554.00	145.0	554.00	550.40	2.1	3	3	4	0.00*
Gaskell-29x5	29	5	503.00	683.0	503.00	503.00	4.9	4	1	1	0.00*
Gaskell-32x5	32	5	479.00	280.0	479.00	479.00	5.3	4	1	1	0.00*
Gaskell-32x5-2	32	5	427.00	567.0	427.00	427.70	4.9	3	0	0	0.00*
Gaskell-36x5	36	5	411.00	17.0	411.00	411.40	5.6	4	1	1	0.00*
Min-27x5	27	5	3083.00	24.0	3083.00	3083.00	4.5	4	1	1	0.00*
Perl83-12x2	12	2	100.00	2.0	100.00	100.00	1.0	8	0	0	0.00*
Perl83-55x15	55	15	453.00	278.0	453.00	453.40	12.3	10	3	3	0.00*
Perl83-85x7	85	7	618.00	3736.0	617.00	617.20	20.5	11	0	0	-0.16
P111112-100x10	100	10	1346.00	3846.0	1315.00	1337.80	66.1	11	0	0	-2.36
P111122-100x20	100	20	1252.00	4138.0	1242.00	1255.40	64.0	11	1	1	-0.81
P111212-100x10	100	10	1266.00	3718.0	1256.00	1259.80	41.0	10	0	0	-0.80
P111222-100x20	100	20	1338.00	4053.0	1310.00	1316.60	60.0	11	3	3	-2.14
P112112-100x10	100	10	1236.00	3889.0	1229.00	1230.80	75.5	11	3	3	-0.57
P112122-100x20	100	20	1047.00	4177.0	1018.00	1025.40	87.4	10	3	3	-2.85
P112212-100x10	100	10	892.00	3918.0	877.00	877.00	69.1	11	1	1	-1.71
P112222-100x20	100	20	1006.00	3747.0	1000.00	1002.00	77.2	10	2	2	-0.60
P113112-100x10	100	10	1158.00	4007.0	1149.00	1157.60	68.1	10	0	0	-0.78
P113122-100x20	100	20	1190.00	3914.0	1175.00	1184.40	75.8	11	4	7	-1.28
P113212-100x10	100	10	1154.00	3717.0	1149.00	1150.00	64.0	10	1	1	-0.44
P113222-100x20	100	20	1078.00	3748.0	1071.00	1071.00	79.0	11	0	0	-0.65
P131112-150x10	150	10	1833.00	3946.0	1795.00	1807.80	53.6	16	0	0	-2.12
P131122-150x20	150	20	1769.00	4411.0	1756.00	1756.00	79.6	16	2	2	-0.74
P131212-150x10	150	10	1802.00	4147.0	1786.00	1790.20	51.7	16	2	3	-0.90
P131222-150x20	150	20	1802.00	4371.0	1775.00	1783.40	78.7	16	2	3	-1.52
P132112-150x10	150	10	1783.00	4815.0	1759.00	1780.20	97.1	16	2	2	-1.36
P132122-150x20	150	20	1541.00	4508.0	1519.00	1526.60	114.1	16	1	1	-1.45
P132212-150x10	150	10	1251.00	4073.0	1242.00	1243.40	81.3	16	0	0	-0.72
P132222-150x20	150	20	1184.00	4368.0	1171.00	1174.00	97.2	16	0	0	-1.11
P133112-150x10	150	10	1899.00	4434.0	1892.00	1900.60	83.6	16	1	1	-0.37
P133122-150x20	150	20	1498.00	4908.0	1489.00	1499.40	111.2	16	1	1	-0.60
P133212-150x10	150	10	1245.00	4510.0	1236.00	1236.80	84.8	16	0	0	-0.73
P133222-150x20	150	20	1551.00	4688.0	1509.00	1529.20	104.5	15	0	0	-2.78

* Optimality proven by Baldacci et al. (2017).

4.A.2 VRPTWTF Instances

Table 4.15: Detailed results on the VRPTWTF instance set based on Solomon (1987).

Instance	$\lvert V_C \rvert$	$\lvert V_F \rvert$	ALNS						VRPTW-	VRPTW-
			z*	$\bar{z}$	$\bar{T}$	#r	#f	#c	BKS*	Gap [%]
C101	100	5	828.94	828.94	86.4	10	0	0	828.94	0.00
C102	100	5	828.94	828.94	89.8	10	0	0	828.94	0.00
C103	100	5	828.06	828.06	90.1	10	0	0	828.06	0.00
C104	100	5	824.78	824.78	84.2	10	0	0	824.78	0.00
C105	100	5	828.94	828.94	81.3	10	0	0	828.94	0.00
C106	100	5	828.94	828.94	78.4	10	0	0	828.94	0.00
C107	100	5	828.94	828.94	81.4	10	0	0	828.94	0.00
C108	100	5	828.94	828.94	82.3	10	0	0	828.94	0.00
C109	100	5	828.94	828.94	88.3	10	0	0	828.94	0.00
R101	100	5	1400.90	1401.65	174.3	15	4	26	1650.80	-15.14
R102	100	5	1242.24	1243.05	183.1	13	3	21	1486.12	-16.41
R103	100	5	1094.32	1095.87	176.2	12	3	17	1292.68	-15.34
R104	100	5	958.28	961.43	171.8	9	2	9	1007.31	-4.87
R105	100	5	1215.11	1217.03	170.2	12	4	24	1377.11	-11.76
R106	100	5	1130.07	1133.63	177.7	11	2	17	1252.03	-9.74
R107	100	5	1008.94	1011.08	169.5	10	2	11	1104.66	-8.67
R108	100	5	920.21	922.69	164.2	9	2	9	960.88	-4.23
R109	100	5	1071.95	1073.19	180.9	11	3	16	1194.73	-10.28
R110	100	5	1005.22	1006.60	174.8	10	4	14	1118.84	-10.16
R111	100	5	996.55	1001.73	173.7	10	2	11	1096.73	-9.13
R112	100	5	923.64	927.09	170.1	9	3	11	982.14	-5.96
RC101	100	5	1502.96	1508.34	119.9	12	4	21	1696.95	-11.43
RC102	100	5	1346.32	1352.55	122.5	11	4	22	1554.75	-13.41
RC103	100	5	1221.27	1227.73	118.0	10	2	9	1261.67	-3.20
RC104	100	5	1121.73	1124.88	116.4	10	3	6	1135.48	-1.21
RC105	100	5	1368.01	1378.28	123.9	12	4	22	1629.44	-16.04
RC106	100	5	1303.20	1311.40	127.4	11	4	18	1424.73	-8.53
RC107	100	5	1195.13	1199.27	126.3	11	3	11	1230.48	-2.87
RC108	100	5	1112.55	1118.33	121.9	10	3	10	1139.82	-2.39
C201	100	5	591.56	591.56	122.4	3	0	0	591.56	0.00
C202	100	5	591.56	591.56	133.5	3	0	0	591.56	0.00
C203	100	5	591.17	591.17	134.6	3	0	0	591.17	0.00
C204	100	5	590.60	590.60	128.4	3	0	0	590.60	0.00
C205	100	5	588.88	588.88	145.3	3	0	0	588.88	0.00
C206	100	5	588.49	588.49	130.9	3	0	0	588.49	0.00
C207	100	5	588.29	588.29	132.5	3	0	0	588.29	0.00
C208	100	5	588.32	588.32	128.7	3	0	0	588.32	0.00
R201	100	5	1197.53	1198.25	303.1	4	2	10	1252.37	-4.38
R202	100	5	1139.98	1147.61	318.1	3	1	9	1191.70	0.00
R203	100	5	900.56	904.61	310.8	3	1	6	939.50	-4.14
R204	100	5	779.21	788.99	321.0	2	1	5	825.52	-5.61
R205	100	5	994.43	998.21	294.6	3	0	0	994.43	0.00
R206	100	5	900.59	903.79	300.6	3	1	3	906.14	-0.61

continued on next page

* Values taken from Nagata et al. (2010).

Table 4.15: (Continued)

Instance	$\lvert V_C \rvert$	$\lvert V_F \rvert$	ALNS						VRPTW-	VRPTW-
			z*	$\bar{z}$	$\bar{T}$	#r	#f	#c	BKS*	Gap [%]
R207	100	5	874.28	876.23	318.9	2	1	5	890.61	-1.83
R208	100	5	725.42	729.94	309.8	2	1	4	726.82	-0.19
R209	100	5	909.16	915.05	333.0	3	0	0	909.16	0.00
R210	100	5	929.70	932.77	314.8	3	1	3	939.37	-1.03
R211	100	5	885.71	886.33	313.0	2	0	0	885.71	0.00
RC201	100	5	1333.35	1338.71	234.3	4	3	22	1406.94	-5.23
RC202	100	5	1284.22	1294.07	242.4	3	2	15	1365.65	-5.96
RC203	100	5	1033.27	1041.34	238.5	3	1	7	1049.62	-1.56
RC204	100	5	798.46	801.95	240.6	3	0	0	798.46	0.00
RC205	100	5	1232.56	1244.68	227.3	4	2	10	1297.65	-5.02
RC206	100	5	1129.83	1142.32	249.5	3	1	10	1146.32	-1.44
RC207	100	5	1024.08	1028.93	256.2	3	2	10	1061.14	-3.49
RC208	100	5	818.27	828.63	289.6	3	1	4	828.14	-1.19

* Values taken from Nagata et al. (2010).

4.A.3 FSMTW Instances

Table 4.16: Detailed results on the FSMTW instances (fleet A) I.

Instance	$\lvert V_C \rvert$	BKS	Vidal et al. (2014)			Koç et al. (2015)			Penna et al. (2019)			ALNS			
			z*	$\overline{z}$	$\overline{T}$	z*	$\overline{z}$	$\overline{T}$	$z*$	$\overline{z}$	$\overline{T}$	z*	$\overline{z}$	$\overline{T}$	Gap[%]
R101	100	4314.36	4314.36	4322.04	276.60	4317.52	–	248.40	4314.36	4325.76	120.56	4314.36	4316.10	167.90	0.00
R102	100	4166.28	4166.28	4175.05	361.80	4173.84	–	358.80	4166.28	4181.25	124.45	4166.28	4186.78	111.30	0.00
R103	100	4024.14	4027.36	4034.88	321.00	4031.40	–	312.60	4024.14	4038.85	134.79	4026.23	4036.97	179.40	0.05
R104	100	3936.40	3936.40	3938.92	288.60	3946.44	–	247.20	3936.55	3948.00	113.83	3936.51	3940.41	225.50	0.01
R105	100	4122.50	4122.50	4130.71	389.40	4134.06	–	360.60	4122.50	4133.06	131.61	4122.50	4127.69	210.50	0.00
R106	100	4048.59	4048.59	4058.95	334.20	4060.05	–	307.20	4050.17	4059.07	127.47	4047.34	4071.37	215.10	-0.03
R107	100	3970.51	3970.51	3979.18	333.60	3985.12	–	286.80	3976.40	3988.73	126.16	3973.68	3983.72	255.40	0.08
R108	100	3928.12	3928.12	3932.46	280.80	3932.60	–	392.40	3928.12	3935.45	108.28	3930.17	3945.00	250.40	0.05
R109	100	4015.71	4015.71	4020.93	288.00	4024.83	–	367.20	4015.71	4023.34	128.21	4011.97	4021.19	205.90	-0.09
R110	100	3961.68	3961.68	3966.47	389.40	3973.51	–	312.60	3961.68	4023.34	114.65	3960.55	3967.05	236.70	-0.03
R111	100	3964.99	3964.99	3973.49	316.80	3988.00	–	307.20	3971.90	3989.84	127.58	3968.81	3985.81	155.90	0.10
R112	100	3917.88	3918.88	3926.32	295.20	3930.19	–	282.60	3917.88	3927.20	105.96	3918.88	3929.29	182.90	0.03
C101	100	7093.45	7093.45	7093.45	177.60	7093.45	–	148.20	7093.45	7093.59	167.56	7093.45	7093.45	124.10	0.00
C102	100	7080.17	7080.17	7080.17	128.40	7080.17	–	159.00	7080.17	7080.17	134.68	7080.17	7080.17	136.30	0.00
C103	100	7079.21	7079.21	7079.21	125.40	7079.21	–	120.60	7079.21	7079.21	119.00	7079.21	7079.21	164.20	0.00
C104	100	7075.06	7075.06	7075.06	131.40	7075.06	–	118.20	7075.06	7075.06	101.36	7075.06	7075.06	165.10	0.00
C105	100	7093.45	7093.45	7093.45	199.80	7093.45	–	159.00	7093.45	7093.60	154.47	7093.45	7093.45	111.00	0.00
C106	100	7083.87	7083.87	7083.87	136.80	7083.87	–	130.20	7083.87	7083.87	140.25	7083.87	7083.87	151.60	0.00
C107	100	7084.61	7084.61	7084.61	133.80	7084.61	–	143.40	7084.61	7084.61	142.94	7084.61	7084.61	154.10	0.00
C108	100	7079.66	7079.66	7079.66	131.40	7079.66	–	118.20	7079.66	7079.66	124.35	7079.66	7079.66	179.90	0.00
C109	100	7077.30	7077.30	7077.30	122.40	7077.30	–	131.40	7077.30	7077.30	107.98	7077.30	7077.30	170.50	0.00
RC101	100	5150.86	5150.86	5154.95	312.60	5173.47	–	308.40	5150.86	5160.03	121.21	5150.86	5151.78	225.30	0.00
RC102	100	4974.82	4987.24	5000.28	288.60	5018.83	–	255.60	4974.82	4999.64	122.10	4974.82	4988.66	215.70	0.00
RC103	100	4804.61	4804.61	4821.61	424.80	4850.20	–	388.20	4804.61	4837.40	122.75	4804.61	4821.56	155.80	0.00
RC104	100	4717.63	4717.63	4724.10	318.00	4725.40	–	317.40	4721.44	4734.77	94.74	4717.63	4725.97	223.20	0.00
RC105	100	5035.35	5035.35	5035.76	334.20	5048.86	–	286.80	5036.50	5047.72	119.73	5035.35	5041.05	170.50	0.00
RC106	100	4921.13	4936.74	4944.74	337.80	4964.13	–	317.40	4921.13	4941.27	118.48	4919.43	4932.82	173.90	-0.04
RC107	100	4787.59	4788.69	4795.35	304.80	4825.60	–	250.20	4787.59	4807.65	107.49	4787.59	4797.27	165.00	0.00
RC108	100	4708.85	4708.85	4709.09	286.80	4724.79	–	277.80	4711.31	4726.02	86.50	4708.85	4721.49	158.30	0.00

Table 4.17: Detailed results on the FSMTW instances (fleet A) II.

Instance	$\lvert V_C \rvert$	BKS	Vidal et al. (2014)			Koç et al. (2015)			Penna et al. (2019)			ALNS			
			z^*	$\bar{z}$	$\overline{T}$	z^*	$\bar{z}$	$\overline{T}$	z^*	$\bar{z}$	$\overline{T}$	z^*	$\bar{z}$	$\overline{T}$	Gap[%]
R201	100	3446.78	3446.78	3446.78	390.60	3446.78	–	367.80	3446.78	3452.08	320.01	3446.78	3455.82	338.5	0.00
R202	100	3297.42	3308.16	3308.16	460.80	3297.42	–	447.60	3308.16	3313.28	342.72	3308.86	3315.73	275.8	0.35
R203	100	3141.09	3141.09	3141.09	339.00	3141.09	–	368.40	3141.09	3143.21	321.32	3141.09	3141.19	310.0	0.00
R204	100	3018.14	3018.14	3018.83	417.60	3018.14	–	376.80	3018.14	3019.95	296.69	3018.14	3020.78	367.1	0.00
R205	100	3218.97	3218.97	3220.56	384.00	3218.97	–	382.80	3218.97	3228.75	305.08	3218.97	3225.15	269.1	0.00
R206	100	3146.34	3146.34	3150.61	618.00	3146.34	–	488.40	3147.41	3155.39	325.90	3146.84	3152.32	314.6	0.02
R207	100	3077.36	3077.58	3080.64	522.00	3077.36	–	388.20	3077.58	3082.82	313.42	3080.13	3111.44	302.9	0.09
R208	100	2997.24	2997.24	2999.35	322.20	2997.25	–	380.40	2997.24	2999.97	282.11	2998.70	3030.32	258.0	0.05
R209	100	3119.56	3122.42	3123.30	382.20	3119.56	–	299.40	3122.42	3129.93	301.95	3122.42	3122.42	269.6	0.09
R210	100	3170.41	3174.85	3178.57	415.80	3170.41	–	328.20	3174.31	3181.35	331.93	3174.85	3179.74	250.1	0.14
R211	100	3019.93	3019.93	3021.67	546.00	3019.93	–	475.80	3019.93	3022.78	285.35	3019.93	3024.76	327.5	0.00
C201	100	5695.02	5695.02	5695.02	222.60	5695.02	–	207.60	5695.02	5695.02	345.40	5695.02	5695.02	415.9	0.00
C202	100	5685.24	5685.24	5685.24	226.80	5685.24	–	190.20	5685.24	5685.24	287.90	5685.24	5685.24	354.2	0.00
C203	100	5681.55	5681.55	5681.55	252.60	5681.55	–	257.40	5681.55	5681.79	271.20	5681.55	5681.55	345.1	0.00
C204	100	5677.66	5677.66	5677.66	256.20	5677.66	–	238.20	5677.66	5677.88	281.35	5677.66	5677.66	346.3	0.00
C205	100	5691.36	5691.36	5691.36	238.80	5691.36	–	207.60	5691.36	5691.36	300.58	5691.36	5691.56	357.8	0.00
C206	100	5689.32	5689.32	5689.32	229.20	5689.32	–	178.20	5689.32	5689.32	270.71	5689.32	5689.50	388.6	0.00
C207	100	5687.35	5687.35	5687.35	254.40	5687.35	–	246.00	5687.35	5687.35	294.10	5687.35	5687.40	395.6	0.00
C208	100	5686.50	5686.50	5686.50	231.60	5686.50	–	213.60	5686.50	5686.50	265.14	5686.50	5686.50	387.1	0.00
RC201	100	4374.09	4374.09	4378.21	355.20	4376.82	–	308.40	4374.09	4380.07	193.35	4374.09	4402.00	329.6	0.00
RC202	100	4244.63	4244.63	4244.65	277.80	4244.63	–	255.60	4244.63	4246.90	203.69	4244.63	4266.07	297.0	0.00
RC203	100	4170.17	4171.47	4170.17	463.80	4170.17	–	368.40	4170.17	4177.62	196.96	4171.90	4187.56	324.7	0.04
RC204	100	4087.11	4087.11	4087.11	347.40	4087.11	–	328.20	4087.11	4094.04	171.97	4087.11	4098.03	315.7	0.00
RC205	100	4291.93	4291.93	4295.41	327.60	4293.73	–	251.40	4291.93	4294.56	197.21	4295.33	4306.24	393.6	0.08
RC206	100	4251.88	4251.88	4253.57	307.20	4251.88	–	256.20	4251.88	4257.78	207.92	4251.88	4259.31	367.3	0.00
RC207	100	4182.44	4185.98	4186.43	289.20	4182.44	–	338.40	4185.98	4188.14	192.60	4185.98	4192.18	307.2	0.08
RC208	100	4075.04	4075.04	4076.27	244.80	4075.04	–	318.60	4075.04	4077.57	166.98	4076.74	4081.47	311.0	0.04

4.A.4 FSMTWTF Instances

Table 4.18: Detailed results on the FSMTWTF instances (fleet A).

Instance	$\|V_C\|$	$\|V_F\|$	ALNS						FSMTW	
			z*	$\bar{z}$	$\bar{T}$	#r	#f	#c	BKS	Gap[%]
C101	100	5	7085.43	7086.00	301.2	19	1	1	7093.45	-0.11
C102	100	5	7076.65	7076.96	270.5	19	1	1	7080.17	-0.05
C103	100	5	7075.66	7076.23	295.1	19	1	1	7079.21	-0.05
C104	100	5	7071.20	7073.33	276.4	19	1	1	7075.06	-0.05
C105	100	5	7085.43	7085.78	253.2	19	1	1	7093.45	-0.11
C106	100	5	7081.30	7081.51	233.6	19	1	1	7083.87	-0.04
C107	100	5	7082.95	7083.25	224.2	19	1	1	7084.61	-0.02
C108	100	5	7077.39	7077.80	286.6	19	1	1	7079.66	-0.03
C109	100	5	7075.03	7076.00	244.9	19	1	1	7077.30	-0.03
R101	100	5	4230.29	4244.20	310.6	19	4	20	4314.36	-1.95
R102	100	5	4142.25	4160.42	336.7	19	3	14	4166.28	-0.58
R103	100	5	3994.49	4008.85	324.6	19	4	9	4024.14	-0.74
R104	100	5	3936.00	3945.02	281.3	19	1	1	3936.40	-0.01
R105	100	5	4096.17	4112.08	290.5	20	4	11	4122.50	-0.64
R106	100	5	4026.28	4039.20	322.6	19	4	14	4047.34	-0.52
R107	100	5	3964.29	3980.89	304.9	19	3	7	3970.51	-0.16
R108	100	5	3926.31	3940.01	319.2	19	2	3	3928.12	-0.05
R109	100	5	3996.48	4015.36	304.0	19	3	11	4011.97	-0.39
R110	100	5	3959.76	3968.13	314.9	19	2	5	3960.55	-0.02
R111	100	5	3963.68	3979.37	333.1	19	3	8	3964.99	-0.03
R112	100	5	3920.55	3933.73	325.3	19	1	1	3917.88	0.07
RC101	100	5	5076.28	5089.05	340.7	17	4	19	5150.86	-1.45
RC102	100	5	4929.53	4944.06	406.8	16	3	13	4974.82	-0.91
RC103	100	5	4799.78	4815.85	403.9	14	2	5	4804.61	-0.10
RC104	100	5	4718.12	4728.29	399.4	12	0	0	4717.63	0.01
RC105	100	5	4961.39	4974.60	389.4	16	2	10	5035.35	-1.47
RC106	100	5	4901.37	4910.90	414.5	16	3	9	4919.43	-0.37
RC107	100	5	4784.00	4797.72	432.7	16	2	6	4787.59	-0.07
RC108	100	5	4708.85	4716.94	414.4	15	0	0	4708.85	0.00
C201	100	5	5695.02	5695.02	427.2	5	0	0	5695.02	0.00
C202	100	5	5685.24	5685.24	345.5	5	0	0	5685.24	0.00
C203	100	5	5681.55	5698.11	378.5	5	0	0	5681.55	0.00
C204	100	5	5677.66	5677.66	372.8	5	0	0	5677.66	0.00
C205	100	5	5691.36	5703.20	415.9	5	0	0	5691.36	0.00
C206	100	5	5689.32	5689.71	414.3	5	0	0	5689.32	0.00
C207	100	5	5687.35	5693.33	422.1	5	0	0	5687.35	0.00
C208	100	5	5686.50	5695.73	391.8	5	0	0	5686.50	0.00
R201	100	5	3426.73	3454.40	427.8	5	1	4	3446.78	-0.58
R202	100	5	3295.10	3301.80	430.4	5	1	3	3297.42	-0.07
R203	100	5	3128.06	3130.58	426.1	5	1	5	3141.09	-0.41
R204	100	5	3014.24	3054.73	386.1	5	1	4	3018.14	-0.13
R205	100	5	3220.81	3227.40	443.4	5	0	0	3218.97	0.06
R206	100	5	3146.34	3152.83	437.6	5	0	0	3146.34	0.00

continued on next page

Table 4.18: (Continued)

Instance	$\lvert V_C \rvert$	$\lvert V_F \rvert$	ALNS						FSMTW	
			z*	$\bar{z}$	$\overline{T}$	#r	#f	#c	BKS	Gap[%]
R207	100	5	3074.01	3078.19	410.9	5	1	4	3077.36	-0.11
R208	100	5	2998.70	3001.31	420.8	5	0	0	2997.24	0.05
R209	100	5	3122.42	3124.04	428.9	5	0	0	3119.56	0.09
R210	100	5	3173.14	3178.09	442.4	5	1	3	3170.41	0.09
R211	100	5	3019.93	3023.70	452.9	5	0	0	3019.93	0.00
RC201	100	5	4377.28	4384.76	414.6	12	1	10	4374.09	0.07
RC202	100	5	4249.62	4265.53	432.6	13	0	0	4244.63	0.12
RC203	100	5	4174.00	4178.18	453.6	11	0	0	4170.17	0.09
RC204	100	5	4087.11	4093.10	438.5	9	0	0	4087.11	0.00
RC205	100	5	4294.15	4305.14	419.3	12	0	0	4291.93	0.05
RC206	100	5	4261.20	4274.22	446.4	11	0	0	4251.88	0.22
RC207	100	5	4185.98	4208.76	415.3	12	0	0	4182.44	0.08
RC208	100	5	4076.74	4079.49	421.9	9	0	0	4075.04	0.04

Appendix 4.B Cost Savings of Deciding the Transshipment per Customer Request

The decision to use a transshipment facility, such as a urban consolidation center (UCC), to transship customer requests is typically made for all requests together, as pointed out in our review of the literature on UCCs in Section 4.2. This means that logistics service providers (LSPs) either use the transshipment facility entirely for all of their urban deliveries or do not use it at all. In the vehicle routing problem with transshipment facilities (VRPTF) and its variants presented in this paper, however, the decision to transship customer requests at a transshipment facility is made individually for each customer request. This section examines the cost and transport plan differences of deciding whether to transship customer requests individually, rather than transshipping either all or none of the customer requests destined for an urban area. To do this, we compare the minimum costs of transshipping either all customer requests destined for the urban areas or transshipping no customer requests to the cost when deciding the transshipment individually. In this context, we compare the costs per fleet, the number of customers, time window length, and demand for each experiment in the real-world study. The costs of deciding the transshipment individually per customer request correspond to those reported in Figures 4.8 and 4.9.

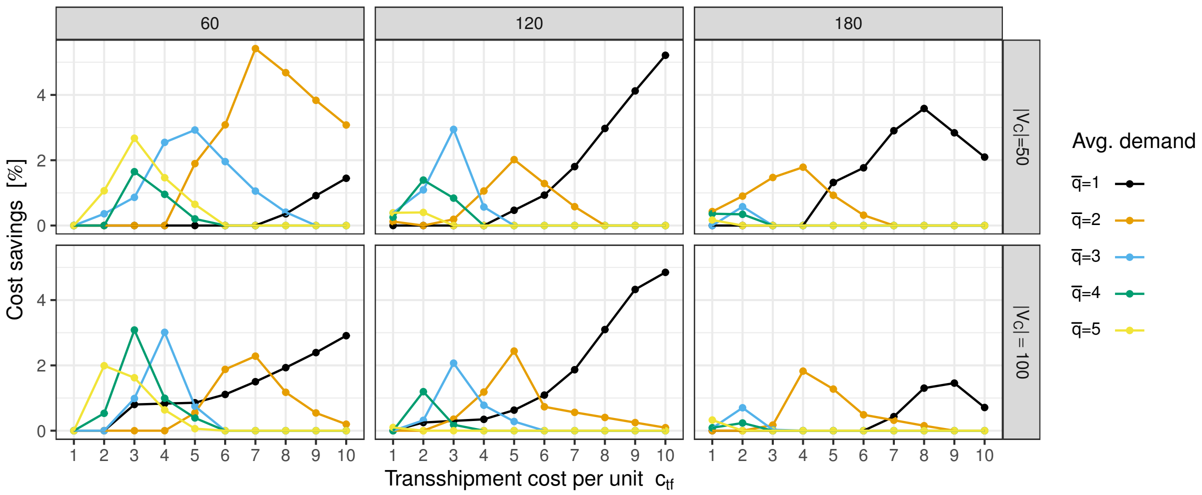


Figure 4.10: Cost savings of deciding the transshipment per customer request for different time window lengths κ (rows), demands $\bar{q}$, and transshipment costs per unit c_{tf} when using a heterogeneous fleet.

Figure 4.10 and Figure 4.11 show the percentage of cost savings resulting from deciding the transshipment individually per customer request for the heterogeneous and homogeneous fleet. The results show that individual transshipment per customer request, depending on the instance, can yield cost savings of up to 7.7 % compared to the approach of transshipping either all or none of the customer requests. Cost savings, however, can only be achieved if the solutions differ between the two approaches. If the use of transshipment facilities is either very unattractive or attractive from a cost perspective, both approaches can produce the same solutions. For example, for $\bar{q} = 5$ and $c_{\text{tf}} \leq 6$, no transshipment facility is used in any experiment, so the costs do not differ

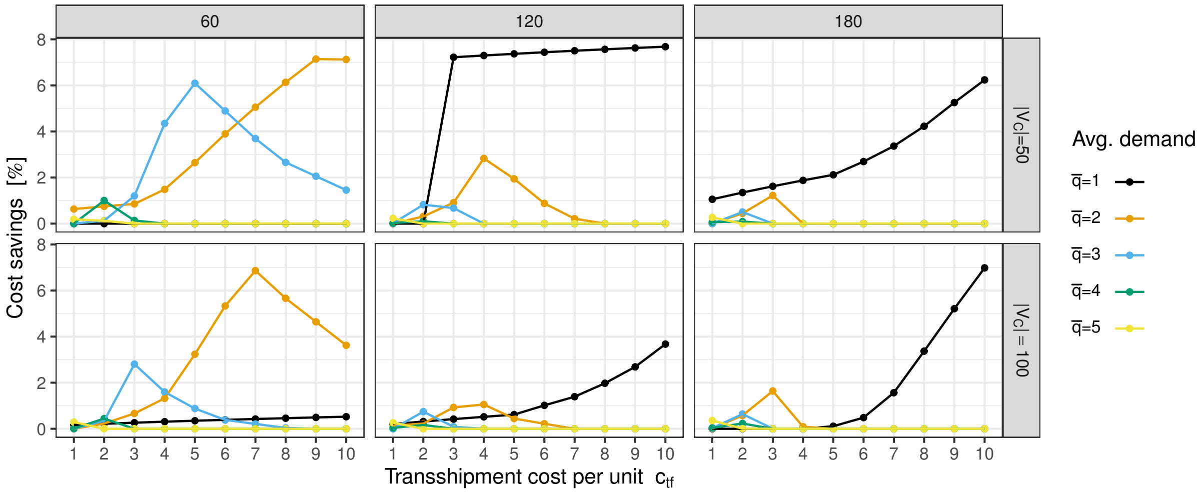


Figure 4.11: Cost savings of deciding the transshipment per customer request for different time window lengths κ (rows), demands $\bar{q}$, and transshipment costs per unit c_{tf} when using a homogeneous fleet.

for either of the two approaches. Similarly, for example, for $\bar{q} = 1$, $\kappa = 60$, and homogeneous fleet, all customer requests are transshipped to a transshipment facility in both approaches. On average cost savings of 0.55 % for heterogeneous fleets and 0.82 % for homogeneous fleets can be observed. In summary, the results demonstrate that the approach presented in this paper can lead to considerable cost savings in a number of cases, especially when the decision to use transshipment facilities is not clear-cut.

In addition to the cost savings, we also compare the change in transshipment facility usage. To this end, we compare the usage percentage between the results of the two approaches. Figure 4.12 shows the comparison for the case of a heterogeneous fleet, while Figure 4.13 shows the comparison for the case of a homogeneous fleet. In both figures, the y-axis represents the difference in transshipment facility usage, which is calculated by *% usage integrated - % usage blanket*. Thus, values > 0 indicate that more customer requests are assigned to transshipment facilities with the integrated approach than when using a blanket decision. Conversely, data points < 0 indicate that fewer customer requests are transshipped using the integrated approach. Data points at 0 signify that the solutions do not differ with respect to the percentage of transshipment facility usage.

The results of the two figures show that the use of the transshipment facilities differs between the two approaches depending on the factors. Especially for the experiments with a heterogeneous fleet, numerous differences can be seen in both directions, ranging from −76.70 % to 66.67 %. However, for both fleets, there seems to be little or no difference for the $\bar{q} = 4$ and $\bar{q} = 5$ demands since the transshipment facilities are only used in these cases when the transshipment costs are very low. Overall, the transshipment facility use is slightly lower for both the heterogeneous and homogeneous fleet when using the integrated approach (−1.78 % and −3.20 %).

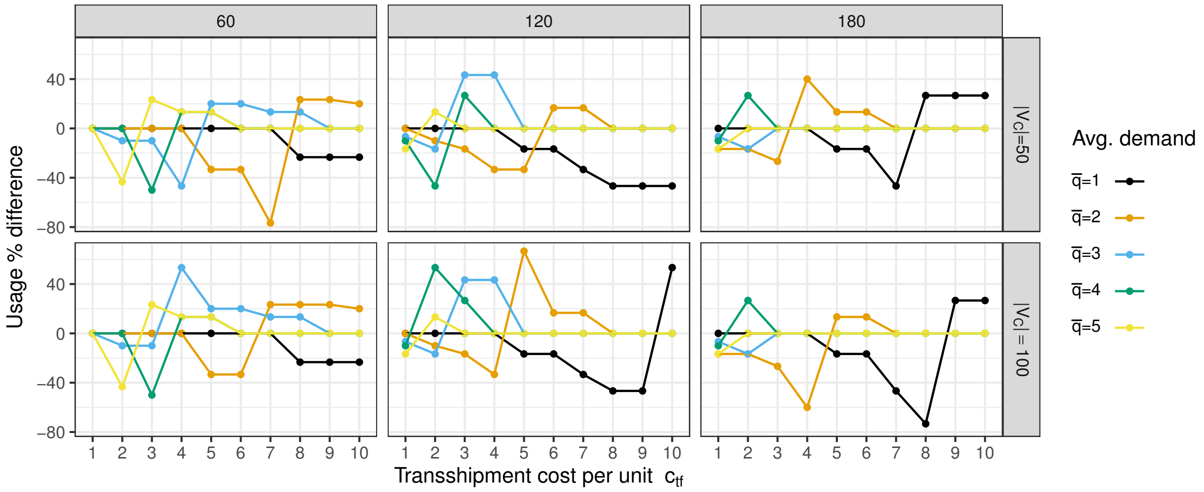


Figure 4.12: Transshipment facility usage difference for different time window lengths κ (rows), demands $\bar{q}$, and transshipment costs per unit c_{tf} when using a heterogeneous fleet.

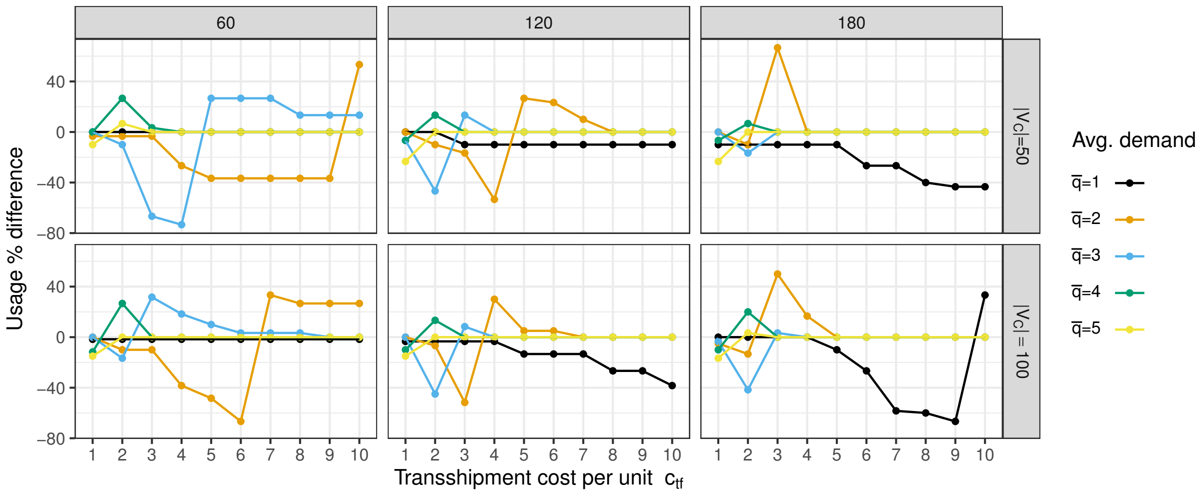


Figure 4.13: Transshipment facility usage difference for different time window lengths κ (rows), demands $\bar{q}$, and transshipment costs per unit c_{tf} when using a homogeneous fleet.

5 Urban Consolidation Centers and City Toll Schemes – Investigating the Impact of City Tolls on Transshipment Decisions[1]

Abstract

Around the world, many cities are struggling with the negative effects of urban freight transport, such as congestion and emissions. To mitigate these negative effects, both innovative solutions, such as urban consolidation centers, and regulations, such as city toll schemes and delivery time windows, can be adopted. In this paper, we investigate the impact of city toll regulations on the vehicle routing and transshipment decisions of logistics service providers. We present a mixed-integer linear programming formulation and an adaptive large neighborhood search heuristic that address the interdependent decisions of vehicle routing and the use of urban consolidation centers, taking into account city toll schemes and time window constraints. In this context, we consider heterogeneous fleets, multiple trips per vehicle, and use a multigraph to address the trade-off between fastest and cheapest paths. We validate the adaptive large neighborhood search by comparing it with the mixed-integer linear programming model on test instances with up to 20 customers. To analyze how city toll schemes affect the cost attractiveness of urban consolidation centers and the fleet composition of logistics service providers, we conduct an extensive computational study featuring real-world instances that provide managerial insights for both local administrations and logistics service providers. Our results show that both per-day and per-entrance tolls can be used by local administrations to support the use of urban consolidation centers and that the number of truck entries into urban areas can be reduced. However, our results also indicate that due to the transshipment fee per unit load, the cost attractiveness of using urban consolidation centers is considerably lower for logistics service providers with larger delivery quantities per stop.

5.1 Introduction

Urban freight transport is an inevitable part of cities, with both positive and negative effects on cities and their inhabitants (OECD, 2003; Savelsbergh and van Woensel, 2016). Managing urban freight transport is, therefore, a challenging task for both logistics service providers (LSPs) and local administrations. As a result, a variety of policy measures have been proposed to mitigate the negative impacts of urban freight transport on congestion, the environment, and traffic safety, while assuring its effectiveness and efficiency (e.g., Lindholm, 2013).

[1]This chapter is based on the working paper of the same name, which has been submitted for peer review in a journal.

According to Dolati Neghabadi et al. (2019), two types of policy measures to mitigate the negative effects of urban freight transport can be distinguished. On the one side, policy measures can be categorized as innovative solutions that often revolve around consolidation and collaboration across LSPs to reduce the number of trucks used in urban freight transport. One of the most studied and widely implemented measures in this category are urban consolidation centers (UCCs) (Lagorio et al., 2016; Björklund and Johansson, 2018). UCCs refer to transshipment facilities located near an urban area with the purpose of consolidating freight flows from multiple LSPs destined for that area. Instead of delivering their shipments directly to the urban area, LSPs can deliver their shipments for a fee to a UCC, which in turn handles the deliveries within the urban area (Allen et al., 2012; Björklund and Johansson, 2018). The goal of UCCs is to increase the efficiency of urban freight transport. On the other side, policy measures can be categorized as regulations that are imposed by local administrations. These regulations for example include delivery access time windows for pedestrian zones, vehicle-type-based access restrictions, and city toll schemes (e.g., Muñuzuri et al., 2005; Holguín-Veras et al., 2020).

As regulations, such as city toll schemes and time windows, can increase the urban delivery costs significantly (see e.g., Quak and de Koster, 2007; Holguín-Veras et al., 2020), LSPs have to consider regulations within their fleet and route planning (Zhang et al., 2019). It is therefore not surprising that regulations also pose a critical factor in the decision-making of LSPs whether to use a UCC (Marcucci and Danielis, 2008; Elbert and Friedrich, 2018a; van Heeswijk et al., 2020). Local administrations which are interested in high usage of UCCs to reduce urban freight traffic can, in turn, employ regulatory measures to increase the attractiveness of transshipping deliveries at a UCC (Quak and Tavasszy, 2011; Allen et al., 2012; Björklund et al., 2017; Akgün et al., 2020). Consequently, the impact of city toll schemes and time windows on the usage of UCCs is investigated in a few simulation studies and shown to increase the cost attractiveness of UCCs for LSPs (Elbert and Friedrich, 2018a; van Heeswijk et al., 2019a; Firdausiyah et al., 2019; van Heeswijk et al., 2020).

Although there exists some research to include city toll schemes into vehicle routing on the one side (Wen and Eglese, 2015; Zhang et al., 2019; Hiermann et al., 2019), and transshipment decisions, such as transshipping deliveries at a UCC, on the other side (Baldacci et al., 2017; Friedrich and Elbert, 2022), no approach combines both aspects in vehicle routing and analyzes the interactions between the two. Moreover, while it seems intuitive to use vehicles more than once per day in the presence of a per-day city toll scheme to increase the utilization of vehicles, no approach exists yet that considers multi-trip routing in the context of toll schemes.

We study in this article how city toll schemes influence fleet compositions, routing decisions, and decisions on whether to tranship shipments at a UCC. To do so, we develop a mixed-integer linear programming (MILP) formulation for the multi-trip fleet size and mix vehicle routing problem with time windows, transshipment facilities, and toll schemes on a multigraph. Due to the complexity of the problem, only small problem instances can be solved to optimality using the MILP formulation. Thus, to provide high-quality solutions for real-world instances, we develop an adaptive large neighborhood search (ALNS) heuristic with an embedded local search component. Using the developed ALNS, we investigate the trade-offs between UCC usage fees and toll pricing for three real-world cases with varying parameter settings. Based on the results of the three real-world cases and insights gained from them, we identify three possible ways to exploit our findings in practice:

- UCC operators and local administrations could assess how to set UCC fees and city toll schemes to incentivize UCC usage.

- LSPs could learn how to adapt their fleet and route planning to different city toll regulations and transshipment possibilities to save costs.
- Local administrations could conclude under which regulatory conditions which vehicle types would be used more frequently to estimate the effects on local emissions and freight traffic.

The remainder of this paper is structured as follows. Section 5.2 reviews the related literature. Section 5.3 presents the problem description and mathematical model. Section 5.4 describes our ALNS. Next, Section 5.5 briefly addresses the parameter configuration and validation of the algorithm. Section 5.6 presents a real-world study, and Section 5.7 concludes.

5.2 Related Literature

Our research relates to the literature on UCCs as well as to the literature on the vehicle routing problem and its variants. In the following, we describe the relevant literature per area.

5.2.1 Urban Consolidation Centers

The research on UCCs and similar third-party transshipment facilities for urban deliveries covers many different topics in the literature, ranging from studies on stakeholder acceptance and organization, environmental and social aspects, down to studies analyzing the design of UCC systems. For a broad overview of different topics studied in the context of UCCs, we refer to the review paper by Björklund and Johansson (2018). Considering the scope of our article, in the following, we will limit our review of the literature on UCCs to two research areas. First, we will briefly review the research on analyzing UCCs in the presence of regulatory measures. Second, we will give an overview of the modeling of transshipment decisions in vehicle routing.

Many studies, as the review by Björklund and Johansson (2018) points out, deal with economic considerations of UCCs. One of the key issues identified for the economic success of UCCs is the willingness of LSPs to use UCCs (see e.g., Quak and Tavasszy, 2011; Allen et al., 2012; Kin et al., 2016). In this context, the cost attractiveness of UCCs is one of the most important criteria for the decision of LSPs to use a UCC (Janjevic and Ndiaye, 2017b). Cost attractiveness in this context means that for a LSP the costs of using a UCC must not exceed the cost savings from using it (e.g., time, distance, or toll savings) (Marcucci and Danielis, 2008; Janjevic and Ndiaye, 2017b). The potential cost savings for LSPs depend on various factors. These factors include, for example, geographical aspects (e.g., UCC and LSP locations), operational characteristics (e.g., vehicle fleet and delivery request structure), cost factors (e.g., handling costs), and regulatory conditions (Browne et al., 2005; Quak and Tavasszy, 2011; Kin et al., 2016). In the following, we will focus especially on the analysis of the impact of regulations on the cost attractiveness of UCCs.

The impact of regulations on the success of UCC is investigated using various approaches, including qualitative studies as well as simulation models, and quantitative models. Often, however, the effects of regulations are not quantified and only individual regulations (e.g., access time windows) are considered rather than a combination of measures. We limit the discussion to studies that present quantitative models for analyzing the impact of regulations on UCC usage.

An agent-based model is presented by van Duin et al. (2012) to analyze under which circumstances UCCs can be a valuable addition to city logistics. In their model, they consider time windows as well as a zone-based entry toll. Additionally, they only consider deliveries within a city toll zone and assume that LSPs can decide daily to either tranship all or no deliveries to the UCC. As a consequence, no special consideration of the city toll and transshipment decisions are made within the vehicle routing problem solved in their simulation. With their model, they study two toll rates. The results obtained show that both toll rates hardly affect UCC usage.

Elbert and Friedrich (2018a) also developed an agent-based simulation model to investigate the cost attractiveness of UCCs for LSPs. In their model, they consider time windows, zone-based entry tolls, and vehicle-type-based restrictions. Unlike previous studies, they broaden the perspective by including not only urban deliveries in their model, but also deliveries destined for non-urban customers that cannot be transshipped. Using a case study, the authors compare different scenarios where LSPs either use the UCC for all urban deliveries or deliver directly. The results obtained show that narrow access time windows in combination with vehicle-type-based restrictions increase the cost attractiveness of UCCs the most.

Firdausiyah et al. (2019) propose an agent-based simulation model in which LSPs use reinforcement learning to decide on a daily basis whether to use a UCC or perform all deliveries directly. In their decision-making, the LSP agents solve two vehicle routing problems with soft time windows. In the first problem, all customer requests are transshipped to the UCC. In the second problem, all customer requests are delivered directly. By comparing the results of both problems, the decision of whether to use the UCC is made. A unique characteristic here is that for direct deliveries, the parking duration and the resulting duration-dependent parking costs are assumed to be stochastic.

Another agent-based simulation model, aiming to analyze urban consolidation centers from a multi-actor perspective, is presented by van Heeswijk et al. (2020). In their model, at each tactical decision epoch, LSPs can decide whether to use a UCC for all of their deliveries. Contrary to other studies, they include for the recipients of deliveries the option to mandate their LSP to deliver their customer requests through a UCC. With their model, they systematically study among other aspects, the effect of access time windows, zone-based city tolls, and UCC pricing on the UCC usage of receivers and LSPs. Their results show that both zone-based entry fees, as well as access time windows, can be effective regulations to support the UCC usage of LSPs.

Although several studies examine the cost attractiveness of UCCs for LSPs considering urban regulations, the transshipment decision to use UCCs, and the vehicle routing of LSPs are simplified by assumptions. A common assumption is that LSPs can only either tranship all deliveries for an urban area or make all deliveries themselves (see e.g., van Duin et al., 2012; Elbert and Friedrich, 2018a; Firdausiyah et al., 2019). In reality, however, LSPs could cherry-pick some customer requests to be delivered directly and decide to tranship the remaining customer requests at a UCC. This is also suggested by a survey conducted by Stathopoulos et al. (2012), which indicates that LSPs that showed interest in using a UCC stated that they would only tranship part of their urban deliveries at a UCC.

5.2.2 Transshipment Facilities in Vehicle Routing Literature

The research on UCCs and third-party transshipment facilities in the vehicle routing literature is still rather limited. Baldacci et al. (2017) introduce the vehicle routing problem with transshipment facilities (VRPTF). In the VRPTF, similarly to the concept of UCCs, deliveries can be transshipped for a fee to a third-party transshipment facility that performs the final delivery. Friedrich and Elbert (2022) propose an ALNS for the VRPTF and extend the problem further by including time windows and heterogeneous fleets, as well as different objective functions, including combinations of en-route duration as well as arc-based and fixed vehicle costs. Alcaraz et al. (2019) also address third-party transshipment facilities for urban deliveries. They present a rich vehicle routing problem for long-haul transport with transshipment options for last-mile deliveries. They develop a construction algorithm followed by a set of improvement heuristics and propose the use of a discrete event simulation to create time schedules that comply with driving time and break regulations.

Similar to the VRPTF is the vehicle routing problem with delivery options (VRPDO), which is addressed by Dumez et al. (2021a), Dumez et al. (2021b), and Tilk et al. (2021). In the VRPDO, the receivers of deliveries can specify different delivery locations, including shared delivery locations. However, unlike the VRPTF, there is no transshipment fee for the shared delivery locations, as it is assumed that receivers pick up the deliveries themselves. Instead, in the VRPDO each delivery option has a preference value assigned to it by its receiver and a certain level of customer satisfaction must be ensured. Mancini and Gansterer (2021) also propose a similar problem, which features private and shared delivery locations for parcel pick ups. As in the VRPTF, LSPs must pay compensation for each customer request that is assigned to a shared location. They present two matheuristic approaches to solve the problem.

In summary, the literature on vehicle routing problems with transshipment facilities is still scarce and focuses mostly on algorithmic contributions. In addition, city toll schemes, which are a common regulation in practice, have not yet been included and so their impact on transshipment decisions remains unclear.

5.2.3 Urban Freight Transport Regulations and Multigraph Modeling in Vehicle Routing

One of the most prevalent regulatory measures in urban freight transport operations are time windows (Holguín-Veras et al., 2020). In the case of urban freight transport, time windows may be imposed either as regulation by local administrations or established through a delivery agreement between the LSP and the recipient of the delivery. In the first case, local administrations stipulate that certain areas, such as a pedestrian zone, may only be accessed by delivery vehicles during defined hours of the day (e.g., morning hours) (Muñuzuri et al., 2005). In the second case, in which the recipient and LSP agree upon a time window together, a retail store, for example, might require that the deliveries take place before its opening hours or during a fixed time of the day, to schedule the required staff for unloading operations (Spliet and Desaulniers, 2015). The vehicle routing problem with time windows (VRPTW) and its variants are among the most studied problems in the vehicle routing literature. Since VRPTWs are difficult to solve and only small problem instances can be solved exactly in reasonable computation time (Kallehauge, 2008; Baldacci et al., 2012), many heuristic solution methods are proposed in the literature. For an overview of different heuristic solution methods for the VRPTW, we refer to Bräysy and Gendreau (2005a), Bräysy and Gendreau (2005b), and Desaulniers et al. (2014).

City toll schemes, of which a number of different forms exist, are another frequently encountered regulation in practice. Zhang et al. (2019), as well as Hiermann et al. (2019), provide an overview of different city toll schemes across various cities around the world. According to both overviews, city toll schemes can be distinguished into tolls paid per entry into the toll zone, tolls paid per day, tolls paid per distance traveled (e.g., approximated by gantries), or tolls paid per time spent in the toll zone. To the best of our knowledge, Wen and Eglese (2015) were the first to consider a zone-based city toll in vehicle routing. In their problem, they consider time windows, time-dependent travel times, and an access toll that is paid once per day for entering an urban area. To solve the problem they propose a tabu search heuristic that uses two time-dependent cost matrices. In one cost matrix entering the toll zone is forbidden and in the other, the toll zone can be entered for a fee. Zhang et al. (2019) build on the approach of Wen and Eglese (2015) and extend it by considering additional toll schemes. Besides a toll paid per day, they also consider city toll schemes, where the toll is paid per entrance, time, or gantry. In their algorithm, whenever a path between two vertices crosses a toll zone and the corresponding toll has not been paid on that route, the algorithm compares the cost of taking a detour around the zone with the cost of crossing the zone. However, this can lead to sub-optimal solutions as, for example, in the case of a per-day toll, it may be that paying the toll is only advantageous if the toll zone is crossed more than once during the day. Instead, in order to account for multiple road-network information, such as distances, travel times, and zone-based tolls in vehicle routing problems, multiple paths between vertices must be considered, since a single best-path might not be definable (Vidal et al., 2020). As such, Hiermann et al. (2019) use a multigraph formulation to consider multiple paths between vertices. With their algorithm, they analyze the effects of different toll schemes. Contrary to previous studies they assume a heterogeneous fleet of conventional and electric vehicles and add a vehicle-type-based access restriction. Using three real-world instances they analyze the impact of different access regulations on fleet compositions and emissions.

Multigraph formulations are one approach to incorporate road-network information in vehicle routing problems. Ben Ticha et al. (2018) provide a comprehensive overview of vehicle routing problems with road-network information, in which they distinguish between two alternative approaches for handling road network information and multiple paths between vertices. The first approach consists of using a road network graph that resembles a real road network. Such an approach is taken, for example, by Letchford et al. (2014) and Ben Ticha et al. (2019b). The second, more widely applied approach is using a multigraph, where every non-dominated path between every pair of vertices is represented as an arc. As we use a multigraph in our paper, we will focus in the following solely on models using multigraphs in vehicle routing problems.

Garaix et al. (2010) study multigraph representations in the context of an on-demand transport problem. They introduce a branch-and-price algorithm as well as an insertion heuristic to solve the considered problem. They show that any change regarding the order of the customers in a route also requires a re-optimization of the selection of arcs between each pair of successive customers. As a consequence, they introduce the NP-hard fixed sequence arc selection problem (FSASP) to determine the optimal arc selection of a given tour. To solve the FSASP, Garaix et al. (2010) treat the problem as a shortest path problem with resource constraints (SPPRC), and apply a dynamic programming algorithm based on Irnich and Desaulniers (2005). Lai et al. (2016) consider a heterogeneous vehicle routing problem on a multigraph and propose a tabu search to solve the problem. They develop a polynomial-time heuristic inspired by knapsack heuristics for the FSASP to search the neighborhoods efficiently and select the arcs. Ben Ticha et al. (2017) introduce a branch-and-price algorithm for the VRPTW on a multigraph. Ben Ticha et al. (2019a) also study a VRPTW and present an ALNS heuristic. To select the arcs during the removal and insertion phases of their ALNS, they use an incremental data structure and propose a dynamic programming algorithm to solve the FSASP.

5.2.4 Multi-Trip Routing

Multi-trip vehicle routing problems (MTVRPs) have been addressed in the literature on vehicle routing problems since the initial paper of Fleischmann (1990). As François et al. (2019) and Pan et al. (2021) point out, multi-trip problems are particularly applicable to the field of urban logistics. This can be explained, among other things, by the often short distances between the depots and the customers and the usually rather small vehicles in use. In addition, multiple trips could be particularly beneficial when combined with transshipment facilities, as the transshipment of customer requests saves time that could be used for additional trips during a work shift.

Over the last three decades, multiple variants and extensions, as well as solution methods, have been studied in the literature (Cattaruzza et al., 2018). The extensions most related to the problem considered in this work are time windows, service-dependent loading times (see e.g., Hernandez et al., 2016; François et al., 2019), and tour duration constraints (see e.g., Battarra et al., 2009; François et al., 2019). In the following, we briefly address the exact and heuristic solution approaches for related variants of the multi-trip vehicle routing problem with time windows (MTVRPTW). Within the field of exact solution methods, several approaches can be found. For example, Neira et al. (2020) develop a two-index node insertion as well as a two-index arc insertion model. Hernandez et al. (2016) develop two branch-and-price algorithms that are based on set covering formulations. Further models from the literature are summarized by Neira et al. (2020). With respect to heuristic solution methods, two main approaches can be distinguished. The first, routing–packing decomposition approach decomposes the problem into the creation of individual trips and subsequent assignment (scheduling) of trips to vehicles (see e.g., Battarra et al., 2009). The second, integrated approach, which is proposed by François et al. (2019), combines both tasks by applying operators directly on a multi-trip representation of the problem. The results of François et al. (2019) suggest that it outperforms the routing–packing decomposition approach in the presence of time windows.

5.3 Problem Description and Model

In this section, we first define and describe the integrated problem studied in this paper. We then present a mathematical formulation of the problem

5.3.1 Problem Setting

The problem considered in this paper aims to jointly optimize the fleet size and composition, customer-to-vehicle-assignments, delivery-transshipment-decisions, location-visit-sequence, and path choices between successive visits from the perspective of a single LSP. For this purpose, we extend the algorithm of Friedrich and Elbert (2022) for the fleet size and mix vehicle routing problem with time windows and transshipment facilities (FSMTWTF) by including city toll schemes and multigraph modeling. Furthermore, we extend the problem to allow for multiple vehicle trips during the planning horizon, so that vehicles can return to the depot during their work shift to reload. We refer to the resulting problem as the multi-trip multi-path fleet size and mix vehicle routing problem with time windows and transshipment facilities (MTMP-FSMTWTF).

Figure 5.1 visualizes a simple example, where some customers are located in a city toll zone

τ while other customers are located outside of the zone. Figure 5.1a on the left shows the case without transshipment facility, where all customers must be served directly. Figure 5.1b on the right shows the case, where requests from customers located in the city toll zone are transshipped at a transshipment facility for a fee, while requests of customers outside of the city toll zone are served directly. To avoid the city toll costs, there is, whenever possible, an alternative path that circumvents the toll zone. For example, when visiting a customer outside of the city, the LSP can decide whether to take the direct path through the toll zone and pay the toll or to take a detour and avoid paying the toll. Two types of city tolls are distinguished in this paper:

- Per-day toll scheme: For each vehicle that accesses a toll zone during a day, a fee is accrued. This fee is independent of the number of times a vehicle traverses through the toll zone during a day. Real implementations of this toll scheme can be found for example in London, Milan, or Durham (Transport for London, 2021a; Comune di Milano, 2021; Durham County Council, 2020).
- Per-entrance toll scheme: Each time a vehicle enters a toll zone, an entry-based toll fee is accrued. Examples of a real implementation of this toll scheme can be found in Stockholm and Gothenburg in Sweden, as well as in Oslo, Norway. However, in Sweden limitations on the maximum toll cost per hour and day are added and in Norway, a limit on the maximum amount of toll to be paid per month exists (Swedish Transport Agency, 2020; The Norwegian Public Roads Administration, 2019).

While the per-entrance toll scheme can be directly included in the variable routing costs (Hiermann et al., 2019), the daily toll fee, in turn, only accrues the first time a vehicle enters a toll zone. Overall, multiple toll zones can be defined in our proposed problem, leading to the possibility that the paths between two vertices can cross multiple toll zones.

The transshipment facilities in our problem resemble third-party UCCs, which can be used by the considered LSP to outsource its urban deliveries. Since the UCC consolidates deliveries across multiple LSPs, we only consider deliveries to the UCC and no outgoing consolidated deliveries. Moreover, we make the following assumptions regarding the transshipment facilities:

- It is assumed that the transshipment facilities are located outside of the city toll zone, so that LSPs can avoid entering the toll zones, and thus toll costs, by transshipping their urban deliveries.
- Given that the transshipment facilities are intended to be used by a variety of LSPs in practice, we assume that the transshipment facilities can be visited by an unlimited number of vehicles and that there are no capacity constraints on the volumes to be transshipped.
- Transshipment costs are paid per customer request transshipped and depend on the quantity of the customer requests.

5.3.2 Mathematical Model

In this section, we present the mathematical formulation for the MTMP-FSMTWTF. Our formulation is based on the classical vehicle flow arc-based formulation of the VRPTW (Cordeau et al., 2002)

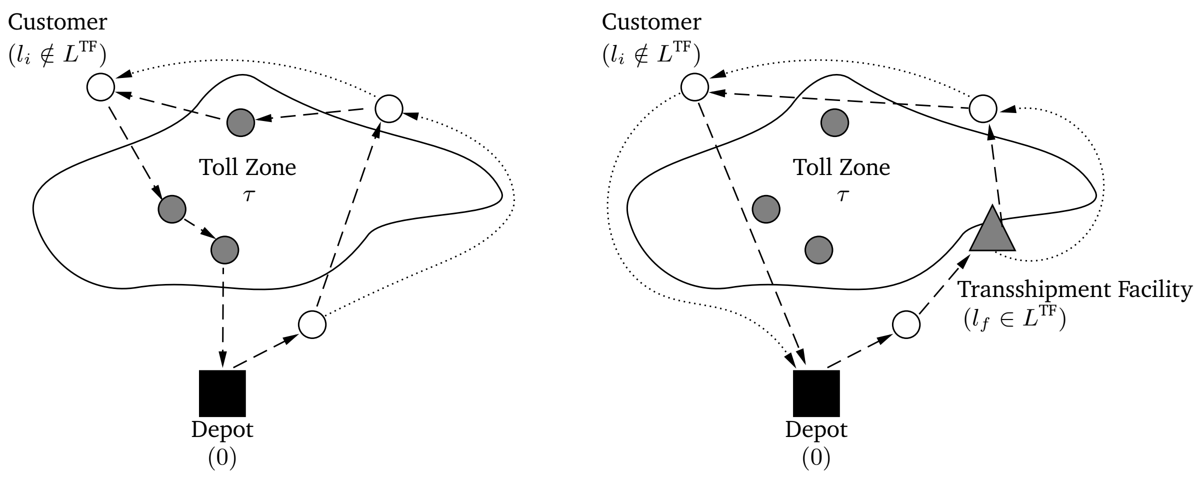


Figure 5.1: Example of a problem instance with a single city toll zone, transshipment facility, and multiple paths. In the left Figure, all customers are served directly. In the right Figure, requests whose customers are within the toll zone are transshipped at the transshipment facility (triangle). Some customers, denoted as white circles, are outside of the city toll zone and must be served directly. To add the possibility to avoid entering the toll zone, multiple paths between non-urban vertices exist.

and further uses several problem-specific extensions from the literature. In particular, we build on the models for the VRPDO from Tilk et al. (2021) and Dumez et al. (2021a), the fleet size and mix vehicle routing problem with time windows (FSMTW) model of Bräysy et al. (2008), VRPTW multigraph formulations by Ben Ticha et al. (2017), and the MTVRPTW model of Neira et al. (2020). All set definitions of the mathematical model are summarized in Table 5.1, and parameter descriptions are provided in Table 5.2.

Following the notation of the VRPDO from Tilk et al. (2021), let N be the set of customer requests and L the set of locations. Additionally, set $O \subset N \times L$ describes the set of delivery options. Each delivery option $o \in O$ corresponds to a customer request n_o and a selected location $l_o \in L$ for that customer request (e.g., a transshipment facility or the customer's location). Together they form the tuple (n_o, l_o).

Every customer request $n \in N$ has a non-negative freight demand of q_n units to be delivered from the depot $l_0 \in L$. Moreover, each customer request n is associated with a service time s_n and a loading time βs_n which represent the duration required for unloading the delivery goods independent of the delivery location and the duration for loading the goods into the vehicle at the depot. It is assumed that the loading time of customer requests is proportional to the service time s_n by a factor β. For each customer request n, exactly one delivery option o from its set of available delivery options $O_n^N = \{(n_o, l_o) \in O : n_o = n\}$ must be selected to fulfill the request.

Regarding the relationship between delivery options and locations, $O_l^L = \{(n_o, l_o) \in O : l_o = l\}$ defines the set of options belonging to location $l \in L$. We distinguish between individual customer locations that are unique to a customer ($|O_l^L| = 1$) and a set of shared locations (e.g., transshipment

Table 5.1: Set notations for the mathematical model of the MTMP-FSMTWTF.

Set	Definition
A	Set of arcs $A = \bigcup_{k \in K} A_k$
A'	Set of replenishment arcs $A' = \bigcup_{k \in K} A'_k$
E	Set of shared location entry vertices $E = \{e_l : l \in L^{\text{TF}}\}$
F	Set of shared location exit vertices $F = \{f_l : l \in L^{\text{TF}}\}$
H	Set of vehicle types
K	Set of heterogeneous vehicles $K = K_1 \cup K_2 \cdots \cup K_m$
L	Set of locations
L^{TF}	Set of shared locations $L^{\text{TF}} = \{l \in L : \lvert O_l^L \rvert > 1\}$
N	Set of customer requests
O	Set of delivery options $O \subset N \times L$
T	Set of toll zones
V	Set of vertices $V = V^{\text{opt}} \cup E \cup F$
V^{opt}	Set of vertices excluding entry and exit vertices $V^{\text{opt}} = \{0, 0'\} \cup O$

facilities) $L^{\text{TF}} = \{l \in L : |O_l^L| > 1\}$ to which multiple customer requests can be assigned. For each location, $l \in L$ a time window $[a_l, b_l]$ is given, which defines the time interval during which deliveries can take place at the vertex. Contrary to the prevailing definition of time windows in the literature, we define in line with the VRPDO that all deliveries for a location l must be unloaded before the time window end b_l. This can be explained by the fact that the total unloading time spent at a transshipment facility stop is unknown in advance, as it depends on the number of customer requests unloaded there. For the locations of the start and end depot l_0 and $l_{0'}$ we assume that $a_0 = a_{0'} = 0$ and that $b_0 = b_{0'}$ denote the end time of the working day.

As the service time s_n of each customer request $n \in N$ is assumed to be independent of the location selected, we introduce a location-dependent preparation time t_l^{prep}, similar to Friedrich and Elbert (2022) and Dumez et al. (2021a). This preparation time allows accounting for administrative tasks and other processes at the locations visited that are independent of the quantity being delivered or loaded. To consider the preparation time in the formulation, it is included in the travel times to every option location $l_o \in L$ as well as to intermediate visits at the depot for reloading. However, for successive visits at the same location, the preparation time is incurred only once.

Let the set $K = K_1 \cup K_2 \cdots \cup K_m = \{1, \ldots, n_K\}$ represents the set of heterogeneous vehicles originating from the depot location l_0. Each subset $K_h \subset K$ represents the set of vehicles belonging to the same type $h \in H$. For every vehicle, $k \in K$, Q_k denotes the vehicle capacity, and c_{f}^k the fixed cost of using vehicle k during the planning period. Analogously to the fixed costs, cost factor c_{t}^k represents the cost per time-unit of vehicle k and c_{d}^k represents the cost per distance-unit traveled. Moreover, vehicles have a maximum shift duration $D_{\max}^k$, including loading, traveling, waiting, and service times, which may not be exceeded. It is assumed that vehicles can start their shift at any time during the working day to minimize en-route waiting times. Lastly, let T resemble the set of toll zones. For each toll zone $\tau \in T$, c_τ^k describes the per-day toll cost factor of vehicle k visiting the toll zone τ. All vehicles $k \in K_h$ of the same vehicle type $h \in H$ share the same cost and capacity

Table 5.2: Overview of parameter definitions for the mathematical model of the MTMP-FSMTWTF.

Parameter	Definition
a_l	Time window start of location $l \in L$
b_l	Time window end of location $l \in L$
$c^k_{(ij)^p}$	Cost of using arc $(i,j)^p_k$ of vehicle $k \in K$
$c'^k_{(ij)^p}$	Cost of using replenishment arc $(i,j)^p_{'k}$ of vehicle $k \in K$
c^k_{d}	Cost per distance-unit of vehicle $k \in K$
c^k_{f}	Fixed cost of using vehicle $k \in K$
c^k_{t}	Cost per time-unit of vehicle $k \in K$
c^{TF}_o	Transshipment cost of option $o \in O$
c^k_τ	Toll cost factor of vehicle $k \in K$ for visiting the toll zone $\tau \in T$
D^k_{max}	Maximum shift duration of vehicle $k \in K$
Q_k	Capacity of vehicle $k \in K$
q_n	Demand quantity of customer request $n \in N$
s_n	Service time of customer request $n \in N$
t^{prep}_l	Location-dependent preparation time of location $l \in L$
β	Loading time factor
$\tau^k_{(ij)^p}$	Indicates if arc $(i,j)^p_k$ of vehicle $k \in K$ visits toll zone $\tau \in T$
$\tau'^k_{(ij)^p}$	Indicates if replenishment arc $(i,j)^p_{'k}$ of vehicle $k \in K$ visits toll zone $\tau \in T$

characteristics (i.e., $(Q_k, D^k_{\text{max}}, c^k_{\text{f}}, c^k_{\text{d}}, c^k_{\text{t}}, c^k_\tau) = (Q_h, D^h_{\text{max}}, c^h_{\text{f}}, c^h_{\text{d}}, c^k_{\text{t}}, c^h_\tau) \quad \forall k \in K_h, \forall h \in H)$.

Let $r = \{0, o_1, \dots, o_h, 0'\}$ represent a vehicle route that starts from depot vertex 0, visits a sequence of delivery options, including possible replenishment visits at the depot, and ends at the end depot vertex $0'$. For a route r to be feasible, it must satisfy the time window constraints of the visited delivery options, as well as the capacity constraint Q_k and maximum shift duration constraint D^k_{max} of the assigned vehicle $k \in K$. The cost c_r of the route r are defined as the sum of the fixed vehicle costs, duration-based costs, distance-based costs, and toll costs. The objective of the MTMP-FSMTWTF is to determine an optimal mix of the heterogeneous vehicle fleet and to find a cost-minimal set of feasible routes that covers exactly one option $o \in O^N_n$ for each customer request $n \in N$.

We model the considered problem on a vehicle-dependent location-based directed multigraph $G = (V, A)$, where V is the set of vertices and A the set of feasible arcs. A straightforward approach to consider delivery options is to introduce an option-based graph, where each delivery option is represented by a vertex (Tilk et al., 2021). This results in the set of vertices $V^{\text{opt}} = \{0, 0'\} \cup O$, where vertices 0 and $0'$ denote the start and end depot, respectively. Likewise, the corresponding option-based arc set $A^{\text{opt}} \subset V^{\text{opt}} \times V^{\text{opt}}$ denotes the set of all feasible connections between the vertices. However, to exploit the fact that multiple customer requests can be transshipped at the same transshipment facility, we use a location-based graph as proposed by Tilk et al. (2021). The idea behind the location-based graph is to reduce the number of arcs, by introducing an artificial entry and exit point for each shared location. Thus, entering and exiting a shared location $l \in L^{\text{TF}}$ is only possible through its entry and exit vertices e_l and f_l. The sets $E = \{e_l : l \in L^{\text{TF}}\}$ and $F = \{f_l : l \in L^{\text{TF}}\}$ denote the sets of all entry and exit vertices. As a consequence, the set of vertices can be described by $V = V^{\text{opt}} \cup E \cup F$. The set of arcs A for all vehicle types H is denoted by $A = \bigcup_{h \in H} A_h$. Extending the formulation for the set of arcs from Tilk et al. (2021), by allowing multiple vehicle-dependent paths, the set of feasible arcs A_k ($A_k = A_h \forall k \in K_h$) for a vehicle k can be formally described by:

$$
\begin{aligned}
A_k \subseteq & \{(i,j)_k^p \in A_k^{\text{opt}} : l_i, l_j \notin L^{\text{TF}}, p = 1, \ldots, m_{ij}^k\} \\
& \cup \{(e_l, j)_k^p \in E \times V^{\text{opt}} : l = l_j, p = 1, \ldots, m_{e_l j}^k\} \\
& \cup \{(i, f_l)_k^p \in V^{\text{opt}} \times F : l = l_i, p = 1, \ldots, m_{i f_l}^k\} \\
& \cup \{(f_l, j)_k^p \in F \times V^{\text{opt}} : l_j \notin L^{\text{TF}}, j \neq 0, p = 1, \ldots, m_{f_l j}^k\} \\
& \cup \{(i, e_l)_k^p \in V^{\text{opt}} \times E : i \neq 0', l_i \notin L^{\text{TF}}, p = 1, \ldots, m_{i e_l}^k\} \\
& \cup \{(f_l, e_l')_k^p \in F \times E : l \neq l', p = 1, \ldots, m_{f_l e_l'}^k\}.
\end{aligned}
$$

Therein, $(i,j)_k^p$ represents the p-th path linking vertex i and j for vehicle $k \in K$, where $p = 1, \ldots, m_{ij}^k$ and m_{ij}^k is the number of efficient paths between i and j for vehicle k. Each path $(i,j)_k^p$ is associated with a distance $d_{(ij)^p}^k$ and a travel time $t_{(ij)^p}^k$, as well as the set of visited toll zones $T_{(i,j)^p}^k = \{\tau \in T : \tau_{(ij)^p}^k = 1\}$. Therein, $\tau_{(ij)^p}^k$ is a constant that is 1 if arc $(i,j)_k^p$ enters or is located inside of toll zone $\tau \in T$ and 0 if not. For every pair i and j, and vehicle $k \in K$, we summarize all efficient paths linking vertex i and j for vehicle $k \in K$ as a set $A_{(i,j)}^k = \{(i,j)_k^p : p = 1, \ldots, m_{ij}^k\}$. An arc $(i,j)_k^p \in A_{(i,j)}^k$ between a pair (i,j) is considered to be efficient, if it is non-dominated in terms of travel time $t_{(ij)_k^p}$ and cost $c_{(ij)_k^p}$ and, in the presence of a daily toll, the set of toll zones visited.

It should be noted that by restricting the entry and exit of transshipment facilities to the transshipment facility's entry and exit vertices, each vehicle can visit each transshipment facility only once at most. This can be justified by the time windows of the transshipment facilities, which, depending on their length, make several successive trips to the same transshipment facility either infeasible or uneconomical anyway. However, to allow for multiple visits of the same vehicle to the same transshipment facility, either the option-based arc-sets A_k^{opt} can be used instead of A_k, or copies of each entry and exit vertice can be added for each additional possible visit.

To represent multi-trips in the model, we follow the arc-insertion approach from Neira et al. (2020). This means that we add parallel replenishment arcs for all arcs between direct customer locations and entrance and exit vertices. These replenishment arcs represent a round trip using one of the available paths from one location to the depot and one path from the depot to the next location. We denote $(i,j)'^p_k$ as the $p-$th replenishment arc from i to j and subsequently denote the set of replenishment arcs for vehicle $k \in K$ as A'_k. A formal description of A'_k, similar to A_k, can be found in Appendix 5.B.

Model 1 presents the mathematical model for the MTMP-FSMTWTF with toll zones and the objective to minimize the total costs. Following decision variables are defined for the model:

- u_o is a binary variable that indicates whether option $o \in O$ is included in the solution.
- $x_{(ij)^p}^k$ is a binary variable that indicates whether vehicle $k \in K$ uses arc $(i,j)_k^p \in A_{(i,j)}^k$.

- ${x'}^{k}_{(ij)^p}$ is a binary variable that indicates whether vehicle $k \in K$ uses replenishment arc $(i,j)^p_{'k} \in {A'}^k_{(i,j)}$.
- z^k_τ is a binary variable that indicates if vehicle $k \in K$ enters toll zone $\tau \in T$.
- y^k_i: is a continuous variable that describes the arrival time of vehicle $k \in K$ at vertex i.
- g^k_i is a real variable that denotes the cumulative service time of vehicle $k \in K$ from the end of a trip up to vertex i.
- λ^k_{ij} is the product flow of vehicle $k \in K$ from vertex i to j.

$$\begin{aligned}
\min \quad & \sum_{k\in K}\sum_{j\in V\setminus\{0'\}}\sum_{p=1}^{|A^k_{(0,j)}|} x^k_{(0j)^p} c^k_{\mathrm{f}} + \sum_{k\in K}(y^k_{0'} - y^k_0 + \beta g^k_0)c^k_{\mathrm{t}} + \sum_{k\in K}\sum_{(i,j)^p_k\in A_k} x^k_{(ij)^p} c^k_{(ij)^p} && (5.1)\\
& + \sum_{k\in K}\sum_{(i,j)^p_{'k}\in A'_k} {x'}^k_{(ij)^p} {c'}^k_{(ij)^p} + \sum_{o\in O} u_o c^{\mathrm{TF}}_o + \sum_{k\in K}\sum_{\tau\in T} z^k_\tau c^k_\tau
\end{aligned}$$

$$\begin{aligned}
\text{s. t.} \quad & \sum_{o\in O^N_n} u_o = 1 && \forall n \in N \quad (5.2)\\
& \sum_{k\in K}\sum_{j\in V, j\neq o}\lambda^k_{jo} - \sum_{k\in K}\sum_{j\in V, j\neq o}\lambda^k_{oj} = q_o u_o && \forall o \in O \quad (5.3)\\
& \sum_{j\in V, j\neq i}\lambda^k_{ji} - \sum_{j\in V, j\neq i}\lambda^k_{ij} = 0 && \forall k \in K, \forall i \in E \cup F \quad (5.4)\\
& \lambda^k_{ij} \leq Q_k \sum_{p=1}^{|A^k_{(i,j)}|} x^k_{(ij)^p} && \forall k \in K, i \in V \setminus \{0,0'\}, \forall j \in V \quad (5.5)\\
& \lambda^k_{0j} \leq Q_k \left(\sum_{p=1}^{|A^k_{(0,j)}|} x^k_{(0j)^p} + \sum_{i\in V}\sum_{(i,j)^p_{'k}\in {A'}^k_{(i,j)}} {x'}^k_{(ij)^p} \right) && \forall k \in K, \forall j \in V \setminus \{0,0'\} \cup F \quad (5.6)\\
& \sum_{i\in V}\sum_{k\in K}\sum_{p=1}^{|A^k_{(i,o)}|} x^k_{(io)^p} + \sum_{i\in V}\sum_{k\in K}\sum_{p=1}^{|{A'}^k_{(i,o)}|} {x'}^k_{(io)^p} = u_o && \forall o \in O \quad (5.7)\\
& \sum_{j\in V}\sum_{p=1}^{|A^k_{(0,j)}|} x^k_{(0j)^p} = 1 && \forall k \in K \quad (5.8)\\
& \sum_{i\in V}\sum_{p=1}^{|A^k_{(i,0')}|} x^k_{(i0')^p} = 1 && \forall k \in K \quad (5.9)
\end{aligned}$$

$$\sum_{i\in V}\sum_{p=1}^{|A^k_{(i,j)}|} x^k_{(ij)^p} + \sum_{i\in V}\sum_{p=1}^{|A'^k_{(i,j)}|} x'^k_{(ij)^p} - \sum_{i\in V}\sum_{p=1}^{|A^k_{(j,i)}|} x^k_{(ji)^p}$$

$$-\sum_{i\in V}\sum_{p=1}^{|A'^k_{(j,i)}|} x'^k_{(ji)^p} = 0 \qquad \forall k \in K; \forall j \in V \setminus \{0, 0'\} \quad (5.10)$$

$$g^k_i \geq g^k_j + s_i - M\left(1 - \sum_{p=1}^{|A^k_{(i,j)}|} x^k_{(ij)^p}\right) \qquad \forall k \in K, \forall i, j \in V, i \neq j \quad (5.11)$$

$$g^k_i \geq s_i \sum_{p=1}^{|A'^k_{(i,j)}|} x^{k'}_{(ij)^p} \qquad \forall k \in K, \forall i, j \in V, i \neq j \quad (5.12)$$

$$\beta g^k_0 \leq y^k_0 \qquad \forall k \in K \quad (5.13)$$

$$y^k_i + s_i + t^k_{(ij)^p} - y^k_j \leq M\left(1 - x^k_{(ij)^p}\right) \qquad \forall (i,j)^p_k \in A \quad (5.14)$$

$$y^k_i + s_i + t'^k_{(ij)^p} + \beta g^k_j - y^k_j \leq M\left(1 - x'^k_{(ij)^p}\right) \qquad \forall (i,j)^p_{'k} \in A' \quad (5.15)$$

$$a_i\left(\sum_{j\in V}\sum_{p=1}^{|A^k_{(j,i)}|} x^k_{(ji)^p} + \sum_{j\in V}\sum_{p=1}^{|A^{k'}_{(j,i)}|} x'^k_{(ji)^p}\right) \leq y^k_i \qquad \forall i \in V, \forall k \in K \quad (5.16)$$

$$y^k_i \leq (b_i - s_i)\left(\sum_{j\in V}\sum_{p=1}^{|A^k_{(i,j)}|} x^k_{(ij)^p} + \sum_{j\in V}\sum_{p=1}^{|A'^k_{(i,j)}|} x'^k_{(ij)^p}\right) \qquad \forall i \in V, \forall k \in K \quad (5.17)$$

$$y^k_{0'} - y^k_0 + \beta g^k_0 \leq D^k_{\text{max}} \qquad \forall k \in K \quad (5.18)$$

$$\sum_{j\in V}\sum_{p=1}^{|A^k_{(i,j)}|} x^k_{(ij)^p}\tau^k_{(ij)^p} + \sum_{j\in V}\sum_{p=1}^{|A'^k_{(i,j)}|} x'^k_{(ij)^p}\tau'^k_{(ij)^p} \leq z^k_\tau \qquad \forall \tau \in T; k \in K; \forall i \in V \quad (5.19)$$

$$x^k_{(ij)^p} \in \{0,1\} \qquad \forall (i,j)^p_k \in A \quad (5.20)$$

$$x'^k_{(ij)^p} \in \{0,1\} \qquad \forall (i,j)^p_{'k} \in A' \quad (5.21)$$

$$u_o \in \{0,1\} \qquad \forall o \in O \quad (5.22)$$

$$z^k_\tau \in \{0,1\} \qquad \forall k \in K, \forall \tau \in T \quad (5.23)$$

$$y^k_i \in \mathbb{R}^+ \qquad \forall i \in V, \forall k \in K \quad (5.24)$$

$$g^k_i \in \mathbb{R}^+ \qquad \forall i \in V, \forall k \in K \quad (5.25)$$

$$\lambda^k_{ij} \in \mathbb{R}^+ \qquad \forall i, j \in V, \forall k \in K \quad (5.26)$$

The objective function (5.1) minimizes the total route costs. The first term represents the fixed vehicle costs, where $\sum_{j\in V\setminus\{0'\}}\sum_{p=1}^{|A^k_{(0,j)}|} x^k_{(0j)^p} = 1$ indicates that a vehicle k is used in the solution and thus incurs fixed costs. The second term denotes the duration-based costs for every vehicle used, with c_{t}^{k} being the vehicle-dependent cost per time unit. These costs may represent driver costs, for example. The third term represents the sum of arc costs $c_{(ij)^p}^{k}$, which includes the vehicle-dependent distance costs (i.e., $c_{\mathrm{d}}^{k} d_{(ij)^p}^{k}$), as well as possible toll costs for entry-based toll schemes. Analogously, the next term represents the arc costs for replenishment arcs. Next, the fifth term states the sum of transshipment facility usage costs, where c_o^{TF} are the transshipment cost of option $o \in O$ ($c_o^{\mathrm{TF}} = 0 : l_o \notin L^{\mathrm{TF}}$). Note that for the sake of conciseness, we simplify some of the sum indices in the model, since, for example, $o \in O$ in the fourth linear term of the objective function could be replaced by $o \in O : l_o \in L^{\mathrm{TF}}$. Lastly, the sixth term represents the toll costs per day, where c_τ^k are the cost per day for vehicle k to visit toll zone $\tau \in T$.

Constraints (5.2) state that for each customer exactly one option $o_n \in O_n^N$ has to be selected. Constraints (5.3) and (5.4) represent the vehicle product flow constraints for delivery options and transshipment facility entrance and exit vertices. The next two constraints (5.5) and (5.6) denote the capacity constraints at the delivery options and the depot likewise. The next constraints (5.7) ensure that if an option u_o is selected, it must be visited at least once. Constraints (5.8) and (5.9) ensure that each route starts and ends at the depot, whereas constraints (5.10) ensure the continuity of the routes. Constraints (5.11) to (5.13) are adapted from Neira et al. (2020) and impose lower and upper bounds to the cumulative service times. Note that the service time is accumulated backwards from the last location visited in a trip and that $s_i = s_{n_i}\ \forall i \in O$ and 0 otherwise. The big-M parameter in Constraint (5.11) can be replaced by $\sum_{n \in N} s_n + \max_{n \in N} s_n$.

Constraints (5.14) and (5.15) ensure that the arrival times at two vertices allow for the time spent at the departure vertex and travel times between the two vertices. In the case of replenishment arcs, the cumulated loading time at the depot must be considered as well. The big-M parameters can be replaced by $\max_{i \in V} b_i + \max_{i,j \in V} t_{(ij)^p}^{k}$ in constraints (5.14), and by $\max_{i \in V} b_i + \max_{i,j \in V} t_{(ij)^p}^{\prime k} + \beta \sum_{i \in V} s_i$ in constraints (5.15).

The next two constraints (5.16) and (5.17) ensure that the time window constraints are fulfilled. Constraints (5.18) impose the maximum shift duration constraints for each vehicle. Constraints (5.19) are adapted from Reinhardt et al. (2016) and ensure, in the case of a per-day toll scheme, to track which toll zones are visited by each vehicle. The product of the binary variable $x_{(ij)^p}^{k}$ and constant $\tau_{(ij)^p}^{k}$ indicates whether a vehicle k visits τ. Similarly, for all replenishment arcs $(i,j)_{\prime k}^{p} \in A_k^{\prime}$, $\tau_{(ij)^p}^{\prime k}$ indicates if the replenishment arc traverses through toll zone τ. Finally, constraints (5.20) to (5.26) define the value space of the variables.

5.4 Solution Methodology

Due to the high complexity of the problem at hand, we propose an ALNS heuristic with embedded local search as a solution method to solve real-world instances efficiently in a reasonable time. ALNS refers to an optimization framework, which was developed by Ropke and Pisinger (2006b) and is widely used in the area of vehicle routing problems. At its core, the ALNS framework is characterized by destroying a given solution using different removal operators and subsequently repairing it using an insertion operator.

5.4.1 Algorithm Outline

The structure and operators of the algorithm are based on the ALNS for the FSMTWTF from Friedrich and Elbert (2022). However, due to the addition of multi-trips, service-dependent loading times, multi-paths, and toll schemes, the design and implementation of the two algorithms differ significantly. In this section, we present the general outline of the algorithm. An overview of the notations used to describe the ALNS and its components is provided in Table 5.9 in the Appendix 5.A. Further details about how the multigraph and multi-trip features are handled in the algorithm are described in Subsection 5.4.2 and 5.4.4.

Algorithm 3 outlines the flow of the algorithm. At the beginning of the algorithm (line 2), an initial solution S_t is generated, using a regret-2 insertion procedure (see Subsection 5.4.5). Following this, during each iteration, the incumbent solution S_t is copied and assigned to the solution S' (line 6). In the next step, a random number of customer requests is removed from the solution S' by a single removal operator and added to the set of unassigned customer requests B (line 7). Subsequently, the destroyed solution S' is repaired by a single insertion operator using the contents of set B (line 8). The removal and insertion operators to be used in an iteration are randomly selected by a roulette-wheel mechanism. After the solution is repaired, a local search can be used to intensify the search (lines 9-11). The probability for this is controlled by the probability parameter $p_{\text{localSearch}}$. In the next step, the feasible routes of the solution S' are stored in the route pool R^{pool}. If a feasible route serves the same customers at a lower cost, using the same vehicle type as an already stored route in R^{pool}, the stored route is replaced. Following this, the current solution S' is evaluated by a record-to-record acceptance (RRA) criterion which can escape local optima by accepting worse solutions (lines 13-18). If the solution is accepted, the incumbent solution S_t is updated. If the S' is better than the so-far best solution S_{best}, the best solution S_{best} is also updated. Next, every η^{SPP} iteration we use the routes stored in R^{pool} to try improving the incumbent solution by solving a set partitioning problem (SPP) with S_{best} as the start solution. After the SPP is solved, the incumbent solution S_t and best solution S_{best} are updated and the route pool R^{pool} is emptied. Lastly, every η^{update} iteration we update the selection probabilities of the removal and insertion operators based on their performance (lines 23-25). Once the maximum number of iterations $\eta^{\max}$ is reached, the algorithm terminates.

5.4.2 Search Space and Route Representation

Since the consideration of infeasible solutions regarding time window constraints leads to solutions of significantly higher quality (Vidal et al., 2015), we apply the *returns in time* relaxation scheme from Nagata et al. (2010). In this relaxation scheme, infeasible solutions are penalized, depending on the extent of their time window violation. Therein, the weighting of the penalty is dynamically adjusted during the search (see Subsection 5.4.3). Furthermore, following François et al. (2019), we also allow violations regarding the maximum shift duration $D^k_{\max}$, which we denote as overtime. The overtime per vehicle is defined as $OT_k = \max\{0, y^k_{0'} - y^k_0 - D^k_{\max}\}$.

As for the representation of routes, similar to François et al. (2019), we use an integrated approach to implement multi-trips, where routes composed of multiple trips are modeled as a sequence of vertices, including copies of the depot for reloading during the route.

Algorithm 3 Overview of the ALNS algorithm.

function ALNS($p_{\text{localSearch}}, \eta^{\text{SPP}}, R^{\text{pool}}, \eta^{\text{update}}$)
    $S_t \leftarrow$ generateInitialSolution()
    $S_{\text{best}} \leftarrow S_t$
    $\eta \leftarrow 1$
    while $\eta < \eta^{\max}$ **do**
        $S' \leftarrow S_t$
        $S', B \leftarrow$ applyRemoval(S')
        $S' \leftarrow$ applyInsertion(S', B)
        if random() $< p_{\text{localSearch}}$ **then**
            $S' \leftarrow$ applyLocalSearch(S')
        end if
        store the routes of S' in R^{pool}
        if isAccepted(S',S_{best}) **then**
            $S_t \leftarrow S'$
            if $f(S')$ is feasible $\wedge$ $f(S') < f(S_{\text{best}})$ **then**
                $S_{\text{best}} \leftarrow S'$
            end if
        end if
        if η **mod** $\eta^{\text{SPP}} = 0$ **then**
            $S_t, S_{\text{best}} \leftarrow$ solveSetPartitioningProblem($R^{\text{pool}}, S_{\text{best}}$)
            $R^{\text{pool}} \leftarrow \emptyset$
        end if
        if η **mod** $\eta^{\text{update}} = 0$ **then**
            setNewSelectionScores()
        end if
        $\eta \leftarrow \eta + 1$
    end while
end function

5.4.3 Acceptance Criterion

Since our algorithm allows invalid solutions regarding the time window constraints, we use, as in Friedrich and Elbert (2022) and François et al. (2019), an augmented objective function to evaluate solutions. The augmented objective value $f_{\text{mod}}(S')$ of a solution S' is calculated as:

$$f_{\text{mod}}(S') = f(S') + \alpha^{\text{p}}(TW(S') + OT(S')), \tag{5.27}$$

where $f(S')$ is the non-augmented objective value of solution S', $TW(S')$ represents the sum of time window violation (i.e. time warp), and $OT(S')$ the sum of overtime. The degree to which infeasible solutions are penalized depends on the adaptive parameter α^{p}. At the beginning of the search, α^{p} is initialized as $\alpha^{\text{p}}_{\text{min}}$. After each iteration, α^{p} is adjusted based on the feasibility of the incumbent solution S_t. If the incumbent solution S_t is feasible, α^{p} is reduced to $\max\{\alpha^{\text{p}}/\rho, \alpha^{\text{p}}_{\text{min}}\}$. On the other hand, if S_t is infeasible, α^{p} is increased to $\min\{\alpha^{\text{p}}\rho, \alpha^{\text{p}}_{\text{max}}\}$. To prevent α^{p} from remaining static over a longer period, α^{p} is set to $\alpha^{\text{p}}_{\text{min}}$ after every η^{reset} iteration. This adaptive mechanism allows the algorithm to explore infeasible solutions to escape local optima as well as to redirect the search back into the feasible regions.

The acceptance criterion in the ALNS decides whether a new solution S' is accepted as the new incumbent solution. A RRA criterion based on Dueck (1993) is used. With the RRA, a solution S' is only accepted if its solution value is lower than the solution value of the current best solution S_{best}

or does not exceed it by more than a certain percentage. Accordingly, a solution S' is accepted if $\frac{f_{\text{mod}}(S')-f_{\text{mod}}(S_{\text{best}})}{f_{\text{mod}}(S')} < \zeta_\eta$, where ζ_η denotes the threshold parameter at iteration η. The threshold parameter ζ_η depends on the current iteration η of the ALNS and is calculated as $\zeta_\eta = \zeta_0(1 - \frac{\eta}{\eta_{\max}})$. Hereby, ζ_0 represents a defined start threshold and $\frac{\eta}{\eta_{\max}}$ is the current portion of the total number of iterations executed so far.

5.4.4 Arc Selection and Label Pre-processing

In order to evaluate the cost and feasibility of routes during the algorithm exactly, the arcs, which connect each vertex of the route with its immediate successor, must be selected optimally. This can be achieved by solving a FSASP (Garaix et al., 2010). As proposed by Garaix et al. (2010), the FSASP can be expressed as a SPPRC using a subgraph of G that consists only of the route's vertices and the arcs connecting them to their successors (Hiermann et al., 2019; Irnich and Desaulniers, 2005).

Let $L^h_{[i,j]}$ correspond to the label of a sequence of vertices visited by a vehicle of type h starting from vertex i and ending at vertex j, including possible replenishment visits at the depot represented by copies of the depot vertex. Each label is defined by a number of resources, denoted as $R(L^h_{[i,j]}) = \{T^{\text{Q}}(L^h_{[i,j]}), T^{\text{DUR}}(L^h_{[i,j]}), T^{\text{TW}}(L^h_{[i,j]}), T^{\text{S}}(L^h_{[i,j]}), T^{\text{E}}(L^h_{[i,j]}), T^{\text{L}}(L^h_{[i,j]}), T^{\text{T}}(L^h_{[i,j]}), T^{\text{AC}}(L^h_{[i,j]}), T^{\text{Cost}}(L^h_{[i,j]})\}$, where $T^{\text{Q}}(L^h_{[i,j]})$ is the demand and $T^{\text{DUR}}(L^h_{[i,j]})$ and $T^{\text{TW}}(L^h_{[i,j]})$ represent the duration and time window violation. Moreover, $T^{\text{S}}(L^h_{[i,j]})$ denotes the cumulative service time, and $T^{\text{E}}(L^h_{[i,j]})$ and $T^{\text{L}}(L^h_{[i,j]})$ represent the earliest and latest starts of the sequence that lead to a schedule with minimum duration and time warp. Lastly, $T^{\text{T}}(L^h_{[i,j]})$ are the set of toll zones visited, and $T^{\text{AC}}(L^h_{[i,j]})$ and $T^{\text{Cost}}(L^h_{[i,j]})$ represent the arc-based and total cost.

In standard labeling procedures, whenever a vertex $j+1$ is appended to a sequence of vertices $\{i,\dots,j\}$, each non-dominated label $L^h_{[i,j]}$ is extended, using all parallel arcs $(j,j+1)^p_h \in A^h_{(j,j+1)}$ between j and $j+1$ (Hiermann et al., 2019; Ben Ticha et al., 2019a). In the case of service-dependent loading times, forward labeling, extending labels from the route start, becomes more challenging as pointed out by Hernandez et al. (2016). Each time a vertex is appended to a sequence of vertices, the service-dependent loading time and thus the departure at the depot from which the trip to which the vertex is appended originates must be updated. As a consequence, Hernandez et al. (2016) suggest using a backward extension of labels instead, where vertices are extended from the route end $0'$ and each vertex is added to the beginning of the sequence.

When it comes to metaheuristics, such as ALNS, a large number of sequences must be evaluated during the search (Ben Ticha et al., 2019a). Thus, to speed up the evaluation of moves during the removal and insertion phases and local search of the ALNS, we pre-process and store labels of subsequences for every vehicle type $h \in H$ and route r of solution S'. For every delivery option vertex i, visited by route r let $\mathcal{D}_i$ represent the depot from which the trip containing i originates and let $\mathcal{D}'_i$ be the depot where the trip containing vertex i ends. If vertex i belongs to the first trip of route r, $\mathcal{D}_i$ equals the depot vertex 0. Likewise, if i belongs to the last trip of route r then $\mathcal{D}'_i$ equals the depot vertex $0'$. Similar to François et al. (2019), we distinguish between four labels to be pre-processed for every vertex i and vehicle type $h \in H$:

- $L^h_{[0,i]}$, from the start depot 0 included to vertex i included

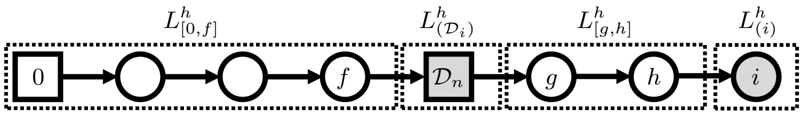


Figure 5.2: Example of how a sequence of vertices is decomposed when a vertex is appended to a label using a forward labeling algorithm.

- $L^h_{[i,0']}$, from vertex i included to the destination depot $0'$ included
- $L^h_{(\mathcal{D}_i,i]}$, from the depot $\mathcal{D}_i$, where the trip that contains vertex i starts, excluded to vertex i included
- $L^h_{[i,\mathcal{D}'_i)}$, from vertex i included to the depot $\mathcal{D}'_i$, where the trip that contains i ends, excluded

Similar to (Ben Ticha et al., 2019a), the labels of the four types of subsequences are incrementally updated after each insertion or removal. Due to the multigraph formulation, multiple non-dominated labels may exist for the same sequence of vertices. Labels for sequences $L^h_{[i,0']}$ and $L^h_{[i,\mathcal{D}'_i)}$ are updated using a backward labeling algorithm, whereas labels of sequences $L^h_{[0,i]}$ and $L^h_{(\mathcal{D}_i,i]}$ are updated using a forward algorithm.

Figure 5.2 shows an example of how a label is updated after an insertion using the forward labeling algorithm for a single vehicle type $h \in H$. Let $\{0, \ldots, f, (\mathcal{D}_i), g, h, j, \ldots 0'\}$ represent the sequence of vertices visited in a route and let i be a vertex to be inserted between vertices h and j. Due to the service-dependent loading time, each time a vertex is added to a sequence, a new label copy must be created with an updated loading time for the origin depot $\mathcal{D}_i$ of the trip to which i is added. Subsequently, the stored label of the sequence up to the vertex before the depot $\mathcal{D}_i$ is concatenated with the updated label copy of the depot $\mathcal{D}_i$ and the label of the sequence following the depot $\mathcal{D}_i$ up to the inserted vertex i. Referring to the example in Figure 5.2, this means that if we append the vertex i to the partial sequence $\{0, \ldots, f, (\mathcal{D}_i), g, h\}$, with $\mathcal{D}_i$ being the origin depot of the trip in which vertex i is to be inserted, then the label $L^h_{[0,i]}$ is obtained by concatenating the following labels:

$$L^h_{[0,i]} = L^h_{[0,f]} \oplus L^h_{(\mathcal{D}_i)} \oplus L^h_{(\mathcal{D}_i,h]} \oplus L^h_{(i)}, \tag{5.28}$$

with $T^{\mathrm{DUR}}(L^h_{(\mathcal{D}_i)}) = \beta T^{\mathrm{S}}(L^h_{(\mathcal{D}_i,i]})$, and $T^{\mathrm{S}}(L^h_{(\mathcal{D}_i,i]})$ being the sum of the service times from vertex g to vertex i. In contrast to this, label $L^h_{[i,0']}$ from the inserted vertex i to the route's destination depot $0'$ can be obtained by simply extending the label $L^h_{[j,0']}$ from the vertex j following i backwards (i.e., $L^h_{[i,0']} = L^h_{(i)} \oplus L^h_{[j,0']}$).

To evaluate local search moves (see Subsection 5.4.6), which are more complex than the insertions and removals of the ALNS operators, we preprocess by contrast labels between all vertices of a sequence. Because this calculation requires more computing time, it is performed only during the local search. To this end, a backward labeling method is used because it is more efficient in computing the labels of all subsequences.

In order to perform the concatenations of labels, we employ the concatenation equations from Vidal et al. (2015) with modifications for multi-trips from François et al. (2019) and additional modifications to consider toll costs. For conciseness, let L_1^h and L_2^h be two labels, with i being the last vertex of L_1^h and j the first vertex of L_2^h. Then the concatenation of the two labels can be calculated by the following equations:

$$T^{\text{DUR}}(L_1^h \oplus L_2^h) = T^{\text{DUR}}(L_1^h) + t^h_{(ij)^p} + T^{\text{DUR}}(L_2^h) + \Delta^{\text{WT}} \tag{5.29}$$

$$T^{\text{E}}(L_1^h \oplus L_2^h) = \max\{T^{\text{E}}(L_2^h) - \Delta, T^{\text{E}}(L_1^h)\} - \Delta^{\text{WT}} \tag{5.30}$$

$$T^{\text{L}}(L_1^h \oplus L_2^h) = \min\{T^{\text{L}}(L_2^h) - \Delta, T^{\text{L}}(L_1^h)\} + \Delta^{\text{TW}} \tag{5.31}$$

$$T^{\text{TW}}(L_1^h \oplus L_2^h) = T^{\text{TW}}(L_1^h) + T^{\text{TW}}(L_2^h) + \Delta^{\text{TW}} \tag{5.32}$$

$$T^{\text{T}}(L_1^h \oplus L_2^h) = T^{\text{T}}(L_1^h) \cup T^h_{(i,j)^p} \cup T^{\text{T}}(L_2^h) \tag{5.33}$$

$$T^{\text{AC}}(L_1^h \oplus L_2^h) = T^{\text{AC}}(L_1^h) + c^h_{(ij)^p} + T^{\text{AC}}(L_2^h) \tag{5.34}$$

$$T^{\text{Cost}}(L_1^h \oplus L_2^h) = T^{\text{AC}}(L_1^h \oplus L_2^h) + T^{\text{DUR}}(L_1^h \oplus L_2^h)c_{\text{t}}^h + \sum_{\tau \in T^{\text{T}}(L_1^h \oplus L_2^h)} c^h_\tau. \tag{5.35}$$

Equation (5.29) calculates the time of the resulting label, with $\Delta^{\text{WT}} = \max\{T^{\text{E}}(L_2^h) - \Delta - T^{\text{L}}(L_1^h), 0\}$. Therein, Δ defined as $T^{\text{DUR}}(L_1^h) - T^{\text{TW}}(L_1^h) + t^h_{(ij)^p}$. Equations (5.30) and (5.31) determine the earliest and latest start time leading to a schedule with minimum duration and time warp. Equation (5.32) calculates the time window violation of the resulting label, with $\Delta^{\text{TW}} = \max\{T^{\text{E}}(L_1^h) + \Delta - T^{\text{L}}(L_2^h), 0\}$. Next, Equation (5.33) determines the set of toll zones visited, with $T^h_{(i,j)^p}$ being the set of toll zones visited on the arc $(i,j)^p_h$. Finally, Equations (5.34) and (5.35) determine the arc-based cost and total cost of the resulting label. In addition to these equations, the additional resources $T^{\text{S}}(L_1^h \oplus L_2^h)$ and $T^{\text{Q}}(L_1^h \oplus L_2^h)$ are calculated by $T^{\text{S}}(L_1^h \oplus L_2^h) = T^{\text{S}}(L_1^h) + T^{\text{S}}(L_2^h)$ and $T^{\text{Q}}(L_1^h \oplus L_2^h) = T^{\text{Q}}(L_1^h) + T^{\text{Q}}(L_2^h)$.

In the course of the labeling algorithm, dominance criteria are applied to remove dominated labels and reduce the growth of the number of labels. Based on Hiermann et al. (2019), a label L_2^h is dominated by another label L_1^h with the same sequence of vertices, if the following applies:

$$T^{\text{Cost}}(L_1^h) + \alpha^{\text{P}}(T^{\text{OT}}(L_1^h) + T^{\text{TW}}(L_1^h)) \leq T^{\text{Cost}}(L_2^h) + \alpha^{\text{P}}(T^{\text{OT}}(L_2^h) + T^{\text{TW}}(L_2^h)) \tag{5.36}$$

$$T^{\text{E}}(L_1^h) + T^{\text{DUR}}(L_1^h) \leq T^{\text{E}}(L_2^h) + T^{\text{DUR}}(L_2^h). \tag{5.37}$$

Equation (5.36) states that the cost and penalties of L_1 must be smaller than the cost and penalties of L_2. Analogously to the overtime calculations for routes, the overtime associated with a label $T^{\text{OT}}(L_1^h)$ can be calculated by $\max\{0, T^{\text{DUR}}(L_1^h) - D^h_{\text{max}}\}$. Equation (5.37) compares the earliest possible end times of the two labels.

5.4.5 Removal and Insertion Operators

The presented ALNS consists of several removal and insertion operators. In Subsection 5.4.5, we present the removal operators included in the ALNS. In Subsection 5.4.5, we describe the insertion operators of the ALNS.

Removal Operators

Each iteration of the ALNS, a random number δ of customer requests are removed from the solution S'. The number of requests to be removed is taken from the uniform interval $[\omega_{\text{min}}, \omega_{\text{max}}] \cdot \min(|N|, 100)$, where ω_{min} indicates the minimum share and ω_{max} the maximum share of customer requests to be removed from the solution. Each time a request is removed, we update the loading times of the preceding depot and solve an SPPRC to determine the optimal selection of arcs. In case there will be two adjacent depots in a tour after a customer is removed, one of the depots will be removed as well. Similarly to François et al. (2019), the trips of the route can be iteratively merged after a removal operation takes place, based on a probability p_{merge}. Likewise, a parameter $p_{\text{trySmallerVehicle}}$ can control the shift of entire routes to an empty smaller vehicle instead, if feasible. In the following we describe the implemented operators:

- **Random removal** (Ropke and Pisinger, 2006b): removes customer requests randomly.
- **Worst removal** (Ropke and Pisinger, 2006b): removes customer requests based on how strong they contribute to the current solution cost. The selection of customer requests to be removed is randomized as proposed in (Ropke and Pisinger, 2006b) through a randomization parameter p_{worst}.
- **Smallest trip removal**: inspired by François et al. (2019) but adapted to allow randomization by using a randomization parameter p_{trip} as in the worst removal operator.
- **Cluster removal** (Pisinger and Ropke, 2007): given a selected route, the customer requests of this route are partitioned into two clusters. Then, one of the two clusters is selected and up to δ customer requests of the cluster are removed from the route. If the number of removed customer requests is smaller than δ, a random customer request is selected from the removed customer requests and the route of the customer request closest to it is chosen. This procedure is repeated until δ customers have been removed in total.
- **Historical knowledge node removal** (Demir et al., 2012): stores for each customer request the lowest cost obtained so far. Customer requests are subsequently removed in decreasing order of the difference between their current cost and best-memorized cost.
- **Distance-related removal** (Ropke and Pisinger, 2006b): removes customer requests that are related to each other in terms of the minimum distance between the selected options of the customers for the vehicle type of the route.
- **Shaw removal** (Shaw, 1997): a removal based on the relatedness of customer requests, where $R(ij)$ denotes the relatedness between customer requests i and j. The relatedness of two customer requests is calculated based on the differences in demand, the shortest distance between their customer's locations, the difference in time window centers at the customer location, and the number of possible transshipment facilities in common. We use the same factors as proposed in Friedrich and Elbert (2022) to weigh each term.
- **Time-related removal** (Pisinger and Ropke, 2007): removes customer requests that are served around the same time.

- **Toll-zone/UCC removal**: removes customer requests that are located within the same toll zone and thus can be served by the same UCC.
- **Adjacent string removal** (Christiaens and Vanden Berghe, 2020): removes multiple adjacent sequences (strings) of customer requests, where parameter L_{max} controls the maximum sequence length. Based on the probability α_{string}, subsequences of customer requests can be preserved during the removal. Hereby, the length of the sequences is controlled by β_{string}.

Insertion Operators

The insertion operators try to repair the destroyed solutions by inserting customer requests into the routes of the destroyed solution. In this process, each insertion position and each delivery option are generally evaluated for every customer request. To speed up the evaluation of insertion positions, we use sets of pre-processed labels (see Subsection 5.4.4) that are updated after each insertion.

Given the possibility of multiple trips per route, we consider four insertion modes based on François et al. (2019) when evaluating the insertion of a customer request:

1. insert the customer request only
2. insert a replenishment depot followed by the customer request
3. insert the customer request followed by a replenishment depot
4. insert a replenishment depot followed by the customer request and another depot

Insertion positions are always evaluated using the first type first, as it leads to the lowest cost increase. If, however, an insertion with mode 1 is not possible due to vehicle capacity constraints, the possibilities for insertion are evaluated with modes 2 and 3 and the better option is used. As long as the capacity of the customer request to be inserted is smaller than that of the vehicle, modes 2 and 3 always provide a feasible solution in terms of capacity constraints, since with the two schemes a new trip can be created at the end or beginning of the evaluated route, respectively. If this is the only case of how a feasible solution is found in terms of capacity, mode 4 is evaluated at last.

To facilitate the exploration of different fleet mixes during the search, entire routes can be assigned to new empty vehicles during the insertion phase. If for a customer and route under evaluation no insertion is found that is better than the best-found insertion from all previously evaluated routes for that customer, the vehicle of the current route can be switched to a different feasible vehicle type to reevaluate the insertion. Regardless of the evaluation results of the assigned vehicle of a route, this switch can also be performed with a probability $p_{\text{insertSwitch}}$.

Three insertion operator types are considered in the ALNS. The first operator type **best insertion** is adapted from Christiaens and Vanden Berghe (2020) and sorts all customer requests to be inserted by some criteria. Subsequently, the customer requests are inserted sequentially at their best positions. We consider a random, decreasing demand, farthest first (i.e., decreasing distance to the depot), and a closest first (i.e., increasing distance to the depot) sorting criterion.

The second operator type is a **regret-2 insertion** (Ropke and Pisinger, 2006b). With the regret-2 insertion, the best and second-best insertion position is determined for each job to be inserted.

Subsequently, the request with the highest difference between its second-best and best insertion position is inserted at its best position. After each step, the insertion costs are updated for every remaining request to be inserted. Lastly, a **greedy insertion** operator is implemented, which iteratively inserts the customer with the lowest insertion costs at its best position.

Removal and Insertion Diversification

To diversify the removal and insertion operators within the ALNS, we use the concept of blinks (Christiaens and Vanden Berghe, 2020). The idea of the blinks concept is to skip the evaluation of some insertion positions during insertion based on a fixed probability. Similarly, customer requests to be removed can be skipped during the removal phase (Dumez et al., 2021a). In our ALNS, both types of blinking are used. Parameter $p_{\text{blinksRemoval}}$ defines the probability of each customer request to be skipped in the blinking procedure during the removal phase. Regarding the blinks during the evaluation of insertion positions, we distinguish between blinking on the customer location and the possible transshipment facilities, as done in Friedrich and Elbert (2022). One reason for this is that if, for example, there are many possible transshipment facilities for each customer request, the number of transshipment facilities to be evaluated, and thus computation time can be reduced. Here, the parameter p_{blinksTF} denotes the blinking probability for transshipment facilities and $p_{\text{blinksDirect}}$ the blinking probability for direct deliveries.

In addition to blinking at the location level, we newly introduce blinking at the vehicle level. The idea behind this is to skip the evaluation of insertion positions for the currently assigned vehicle of a route and instead try to insert the customers using a different type of vehicle for that route. The probability of forcing this type of blinking is controlled by the $p_{\text{blinksVehicle}}$ parameter.

5.4.6 Local Search Procedure

Based on a probability $p_{\text{localSearch}}$ a local search is applied to the solution generated by the ALNS insertion operator to improve it. For the implementation of the local search, the algorithm uses a randomized variable neighborhood descent (RVND) (Mladenović and Hansen, 1997), in which the neighborhoods are explored in random order. In the RVND, a best-improvement strategy is followed, that is, each neighborhood is studied exhaustively and the best improvement is selected. To speed up the evaluation of moves during the local search, we use a correlation measure to prune neighborhoods, similar to the measure described in Vidal et al. (2014), and restrict the search to moves that lead to at least one promising arc. In this method, the correlation between two delivery options is calculated by the minimum weighted sum of the transport cost, waiting time, and time-warp usage between the two delivery option locations. For each location, the 30 locations with the highest correlation are stored in an immutable neighbor list. Moreover, we utilize a cache memory that records move evaluations, as long as the routes involved in the move remain unchanged.

In the local search, we use several classical neighborhood structures as well as neighborhoods from Friedrich and Elbert (2022) to modify the transshipment decisions. Table 5.3 gives an overview of the implemented inter-route and intra-route neighborhoods. The **shift(1,0)** and **shift(2,0)** inter-route neighborhood describe the transfer of one or two adjacent customer requests from one route to another. The **2-Opt*** neighborhood is an inter-route version of the classical 2-Opt move (Potvin and Rousseau, 1995). The **swap(1,1)**, **swap(2,1)**, and **swap(2,2)** neighborhoods describe the permutation of one or two adjacent customer requests from one route by one or two adjacent customer requests from another route. In the **K-Shift** neighborhood, a subsequence of customer requests is transferred from one route to the end of another route with lower vehicle fixed cost (Penna et al., 2013). All inter-route neighborhoods, except for the **2-Opt*** Neighborhood, are also implemented as a composite version, as proposed in (Friedrich and Elbert, 2022). That means that when evaluating moves which feature customer requests that have more than one delivery option ($|O_n^N| > 1$), all delivery options $o \in O_n^N$ for that customer request will be evaluated during the move evaluation.

Regarding the intra-route neighborhoods, we implemented the **reinsertion** neighborhood, where a single customer request is moved to another position within the same route, as well as two **Or-opt** neighborhoods (Or, 1976), where either two or three adjacent customer requests are removed and reinserted at another position of a route. Furthermore, we use an intra-route version of the **swap(1,1)** neighborhood. To modify the transshipment decisions of customer requests, we use the neighborhoods proposed by Friedrich and Elbert (2022) where the locations of subsequences of customer requests within a route are modified so that they are transshipped together at the same shared location or delivered directly instead.

Table 5.3: Overview of implemented inter- and intra-route neighborhoods.

Category	Neighborhood
Inter-route neighborhoods	shift(1,0) shift(2,0) 2-Opt* swap(1,1) swap(2,1) swap(2,2) K-Shift
Intra-route neighborhoods	2-Opt reinsertion Or-opt-2 Or-opt-3 swap(1,1) changeLocation(m) undo-transshipment try-transshipment

5.4.7 Set Partitioning Problem

During the ALNS, every η^{SPP} iteration, the algorithm attempts to generate a new best solution from the stored routes of the pool R^{pool}. To do this, a restricted set partitioning model is constructed from the stored routes, which is solved by an MILP solver (see Equations (5.38)-(5.41)). Similar to the notation of Subramanian et al. (2012) and Friedrich and Elbert (2022), $R_o^{\text{pool}} \subseteq R^{\text{pool}}$ denotes the subset of routes that contain the delivery option o, and the binary variable μ_r indicates whether or not route $r \in R^{\text{pool}}$ is included in the solution.

The objective of the model (5.38) aims to minimize the sum of route costs c_r. The constraints (5.39) ensure that each customer is served exactly once in the solution. In the case of a limited fleet, constraint (5.40) is added to ensure that the maximum number of vehicles per type is not exceeded. Hereby, $R^{\text{pool}}_h \subseteq R^{\text{pool}}$ denotes the subset of routes that use vehicles of type $h \in H$, and $|K_h|$ is the maximum number of vehicles for type h.

$$\min \quad \sum_{r \in R^{\text{pool}}} c_r \mu_r \tag{5.38}$$

$$\text{s. t.} \quad \sum_{o \in O^N_n} \sum_{r \in R^{\text{pool}}_o} \mu_r = 1 \qquad \forall n \in N \tag{5.39}$$

$$\sum_{r \in R^{\text{pool}}_{K_h}} \mu_r \leq |K_h| \qquad \forall h \in H \tag{5.40}$$

$$\mu_r \in \{0, 1\} \qquad r \in R^{\text{pool}}. \tag{5.41}$$

To reduce the computation times, we limit the maximum runtime of the solver to 20 seconds. Furthermore, we initialize the solver with S_{best} as the starting solution.

5.4.8 Update of Operator Probabilities

During each iteration of the ALNS, the selection of the removal and insertion operators is based on a roulette-wheel selection (Pisinger and Ropke, 2007). Every operator i has a corresponding weight w_i, which depends on the operator's past performance. The performance of an operator is measured using a score π_i, which is updated after each iteration in which the operator is used. To update the score π_i of an operator, one of the coefficients ν_1, ν_2 or ν_3 is added to it. In case a new best solution is found the score is updated by $\pi_i \leftarrow \pi_i + \nu_1$, whereas $\pi_i \leftarrow \pi_i + \nu_2$ holds when the incumbent solution S_t is improved. If the current solution S' is accepted, although it is worse than S_t, $\pi_i \leftarrow \pi_i + \nu_3$ applies. After every η^{update} iteration, the weight w_i of every operator i is updated by the following statement:

$$w_i \leftarrow w_i(1 - \upsilon) + \upsilon \frac{\pi_i}{\theta_i}, \tag{5.42}$$

where υ is a parameter to control how strong the previous weight impacts the new weight and θ_i is the number of times that the operator was used during the last segment. After each adjustment, all scores are reset.

5.5 Algorithm Configuration and Validation

In Subsection 5.5.1, we briefly discuss the parameter configuration of the ALNS. Subsection 5.5.2 validates the performance of our algorithm by comparing the solutions found with those obtained from a MILP solver on small-sized instances.

Our algorithm is implemented as single-threaded code in Java (OpenJDK 13) and for solving the SPP, Gurobi 9.1.1 is used as the MILP solver. The parameter tuning and all experiments were conducted on an Intel Core i7-6820HK CPU running at 2.7 GHz with 32 GB RAM under a Windows 10 operating system.

5.5.1 Parameter Settings

Regarding the selection of parameter values for our ALNS, we use the automatic algorithm configuration tool irace by López-Ibáñez et al. (2016), which is frequently used in the context of vehicle routing problems (see e.g., François et al., 2019; Friedrich and Elbert, 2022). To determinate the parameters with irace, we take, where applicable, the parameter values from Friedrich and Elbert (2022) as the default values. The parameter tuning procedure is run on a randomized subset of instances. This subset of instances is composed of 10 instances from each of the three regions from our real-world study that is presented in Section 5.6. The tuning budget of irace is set to 5000 runs, with 30 000 iterations each and a maximum runtime of 150 seconds. Table 5.4 gives an overview of the selected parameter values and their tested ranges in irace. The remaining parameters p_{worst}, p_{trip}, α_{string}, and β_{string} have been taken from Friedrich and Elbert (2022) and are set to $3, 3, 0.45$, and 0.03 respectively.

Table 5.4: Overview of the parameter configuration of the ALNS.

Category	Parameter	Type	Authorized range	Value
General ALNS	$\alpha^{\text{p}}_{\text{min}}$	Integer	$[1, 50]$	3
	$\alpha^{\text{p}}_{\text{max}}$	Integer, step 50	$[50, 1000]$	400
	ζ_0	Real	$[0.01, 0.15]$	0.02
	η^{reset}	Integer, step 10	$[10, 1000]$	30
	η^{SPP}	Integer, step 5000	$[5000, 20\,000]$	15 000
	η^{update}	Integer, step 500	$[500, 5000]$	2500
	ν_1	Real, step 0.01	$[0, 1]$	0.68
	ν_2	Real, step 0.01	$[0, 1]$	0.22
	ν_3	Real, step 0.01	$[0, 1]$	0.10
	ρ	Real, step 0.1	$[1, 2]$	1.4
	υ	Real, step 0.1	$[0.1, 1]$	0.8
	$p_{\text{localSearch}}$	Real	$[0, 0.2]$	0.08
Removal	ω_{min}	Real	$[0.05, 0.25]$	0.06
	ω_{max}	Real	$[0.25, 0.45]$	0.35
	$p_{\text{blinksRemoval}}$	Real	$[0, 0.3]$	0.13
	L_{max}	Integer	$[5, 20]$	13
	p_{merge}	Real	$[0.1, 1]$	0.76
	$p_{\text{trySmallerVehicle}}$	Real	$[0, 0.3]$	0.06
Insertion	$p_{\text{blinksDirect}}$	Real	$[0, 0.2]$	0.03
	p_{blinksTF}	Real	$[0, 0.3]$	0.03
	$p_{\text{blinksVehicle}}$	Real	$[0, 0.3]$	0.07
	$p_{\text{insertSwitch}}$	Real	$[0, 0.25]$	0.08

5.5.2 Comparison with Optimal Solutions on Small Instances

In this section, we compare the results of our ALNS with the optimal solutions or lower bounds found for our MILP from Subsection 5.3.2. Due to the high computational complexity, we propose small instances with 10, 15, and 20 customers each. All of the instances feature two vehicle types and are created analogously to the instances of our real-world study, the creation of which is described in Subsection 5.6.1. Each of the instances is labeled by an instance name. The instance name is represented by a string *region-a-b-c*, where *region* represents the region on which the instance is based, and *a* represents the number of customer requests that can be transshipped. Next, *b* is the number of customer requests that cannot be transshipped, and *c* is an identifier to distinguish random instances for each region.

To solve the MILP, we first generate an initial solution with our ALNS. Then, to reduce computational complexity, we limit the number of vehicles per type for our solver to the number in the solution of our ALNS, increased by one. These start solutions are then used to set upper-cost bounds as well as a warm start in the commercial solver Gurobi 9.1.1. For each of the instances, we limit the computation time in Gurobi to a maximum of 12 hours. Table 5.5 reports the result of the comparison between the ALNS and the solver. The first five columns from the left in Table 5.5 contain the instance name, average customer request size, the city toll type, the toll cost factor, and the cost per demand unit transshipment. Therein, PD represents a per-day toll scheme and PE represents a per-entrance toll scheme. Entries with '–' indicate instances without a toll scheme. For each instance, the average customer request size, city toll type, toll cost factor, and transshipment cost were randomly selected. The next three columns list the best solution value out of 5 runs, the average solution value, and the average computation time in seconds for our ALNS. The remaining five columns list the results from Gurobi. Column UB shows the upper bounds found and column LB the lower bounds. Columns Gap, T, and Nodes indicate the optimality gap, the computation time in seconds, and the number of nodes explored, respectively. If the solver did not finish before the time limit, we indicate the time as '–'. The number of nodes explored is presented rounded in thousands (K) and millions (M), respectively.

As Table 5.5 indicates, only instances with up to 15 customer requests can be optimally solved with the solver. For instances with 20 customers, the gaps to the lower bound are still high after 12 hours. This is especially true for the ruhr-5-15 instances, which are more complex because they consist of three cities, each with a UCC and a toll zone. Consequently, no meaningful lower bounds were found for the ruhr-5-15 instances. However, as for the quality of the solutions of our ALNS, it can be seen that our ALNS found all solutions that were later confirmed to be optimal by the solver. Furthermore, it is worth noting that all upper bounds reported by the solver are identical to the initial solution values provided by our ALNS. This shows that the solver could not improve any of the initial solutions from the ALNS.

5.6 Real-World Study

In this section, we present a real-world study based on three urban regions to gain insights into how city toll schemes affect the cost attractiveness of UCCs and fleet composition of LSPs.

5.6.1 Data Collection and Network Design

Our real-world instances are based on spatial and road network data obtained from OpenStreetMap (OSM). In generating the instances, we differentiate between customer locations that are within the toll zones and those that are located outside in the remaining study region. For each of the three regions, we create instances with 50 customers, of which either 20 % or 40 % are located in the toll zones. Regarding the UCCs of the urban areas, we assume that the service areas are equivalent to the toll zones of the urban area. Thus, customer requests whose customers are

Table 5.5: Solution of small instances with Gurobi and comparison with the proposed ALNS.

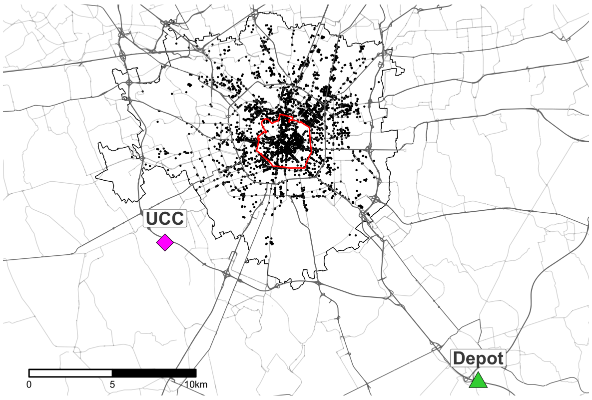
Instance	$\bar{q}_i$	Toll type	$c_\mathcal{T}$	c_{UCC}	ALNS			Gurobi				
					Best of 5	Avg. of 5	$\overline{\mathrm{T}}$	UB	LB	Gap (%)	T	Nodes
london-5-5-0	3.0	PD	10	6	447.98	447.98	8	447.98	447.98	0.00	85	67 K
london-5-5-1	1.0	PE	15	8	290.43	290.43	9	290.43	290.43	0.00	9	13 K
london-5-5-2	2.0	–	0	2	370.64	370.67	8	370.64	370.64	0.00	258	304 K
milan-5-5-0	3.0	PD	15	2	389.92	389.92	7	389.92	389.92	0.00	98	110 K
milan-5-5-1	3.0	PE	10	6	420.41	420.41	8	420.41	420.41	0.00	161	202 K
milan-5-5-2	2.0	–	0	4	260.46	260.46	6	260.46	260.46	0.00	5	6 K
ruhr-5-5-0	3.0	PD	5	4	318.71	318.71	16	318.71	318.71	0.00	45	29 K
ruhr-5-5-1	2.0	–	0	6	327.24	327.24	9	327.24	327.24	0.00	30	21 K
ruhr-5-5-2	1.5	PE	20	10	360.79	360.79	8	360.79	360.79	0.00	12	7 K
london-5-10-0	3.0	PD	5	8	606.27	606.27	16	606.27	606.27	0.00	10 372	4 M
london-5-10-1	2.0	PE	10	6	539.29	539.29	16	539.29	539.29	0.00	1130	485 K
london-5-10-2	1.0	PE	20	10	502.65	502.65	16	502.65	502.65	0.00	5384	3 M
milan-5-10-0	3.0	PE	5	2	402.32	402.32	16	402.32	402.32	0.00	12 686	6 M
milan-5-10-1	2.0	PD	5	4	406.56	406.56	15	406.56	406.56	0.00	247	144 K
milan-5-10-2	3.0	PE	20	4	515.46	515.46	13	515.46	515.46	0.00	13 744	6 M
ruhr-5-10-0	3.0	PD	15	2	486.15	486.15	27	486.15	486.15	0.00	29 770	5 M
ruhr-5-10-1	1.5	PE	10	6	463.52	463.52	25	463.52	463.52	0.00	29 634	8 M
ruhr-5-10-2	2.0	–	0	4	463.85	463.85	16	463.85	463.85	0.00	6483	2 M
london-5-15-0	2.0	–	0	4	704.18	704.18	25	704.18	527.26	25.12	–	3 M
london-5-15-1	2.0	PE	5	6	651.51	651.51	32	651.51	486.39	25.34	–	2 M
london-5-15-2	3.0	PE	10	2	738.51	738.51	28	738.51	428.16	42.02	–	1 M
milan-5-15-0	2.0	PD	10	6	508.96	508.96	26	508.96	408.35	19.77	–	2 M
milan-5-15-1	1.0	–	0	8	436.23	436.23	26	436.23	389.75	10.65	–	3 M
milan-5-15-2	2.0	PE	15	2	601.38	601.38	25	601.38	558.26	7.17	–	3 M
ruhr-5-15-0	3.0	PD	10	10	678.79	678.79	28	678.79	290.02	57.27	–	309 K
ruhr-5-15-1	1.0	PE	5	8	568.50	568.50	26	568.50	224.08	60.58	–	790 K
ruhr-5-15-2	2.0	PE	15	2	627.81	627.81	30	627.81	184.05	70.68	–	859 K

located in a toll zone can be transshipped at a UCC that serves that zone. To create an instance, we randomly select the required number of customer locations within and outside of each toll zone using the OSM key "*shop=**". The locations of the LSP depot and the UCCs, on the other hand, are based on the geographic coordinates of real logistics companies in the respective region.

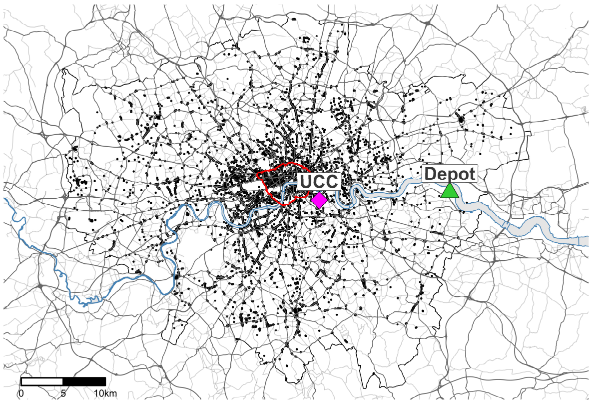
Study Regions

To mitigate the risk of structural bias that potentially results from focusing our experiments on a single city, we consider three regions with different sizes. We study Milan (Italy), London (UK), and the Ruhr region (Germany) (see Figure 5.3). For each region, we create multiple instances by varying the percentage of customers within the toll zones and selecting random customer locations.

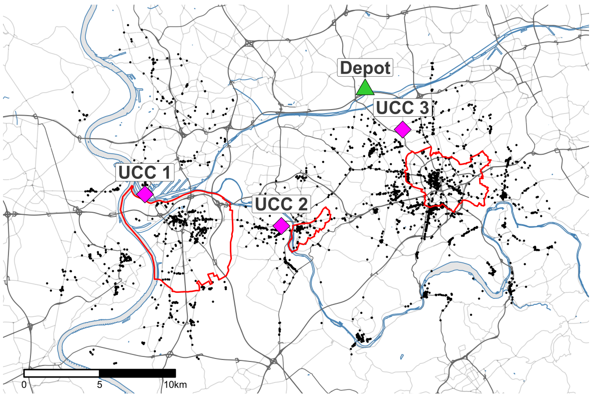
In the following, we briefly describe the three study regions. Table 5.6 summarizes the characteristics of each of the three regions. The municipality of Milan covers about 181 km^2 with about 1.4 million inhabitants. Since January 2012 the municipality charges vehicles a daily toll fee of 5 € to enter its historical center. This historical center, represented by the *Milan Area C*, spans about 8 km^2 and can be accessed through 43 camera gates (Comune di Milano, 2021). To create



(a) Milan



(b) London



(c) Ruhr region

Figure 5.3: Overview of the three study regions with the toll zones marked by red borders. The set of possible customer locations is marked by black dots, the UCC locations by magenta diamonds, and the depots by green triangles (Map data copyrighted OpenStreetMap Contributors).

the instances, we consider customer locations throughout the entire municipality of Milan and model its *Area C* as a toll zone and UCC area.

The second region considered is the London low emission zone (LEZ), which covers most of the Greater London region. Greater London has an approximate population of 8.9 million people and its LEZ has a size of roughly 1526 km^2. To drive within the LEZ, all vehicles with a gross vehicle weight of more than 3.5 tons need to fulfill the Euro IV emission standard or else pay a daily charge of up to £ 300 (Transport for London, 2021b). In addition to the LEZ, central London has also a congestion charge zone of approximately 21 km^2, for which a £ 15 daily charge applies (Transport for London, 2021a). In case a vehicle does not meet the emissions standards required to enter the ultra-low emission zone (ULEZ) which currently encompasses the same area as the congestion charge zone, additional penalty fees are charged. To create the instances, we consider customers within the entire London LEZ. However, we only consider the congestion zone as a toll zone, since we assume that all vehicles of the studied LSP comply with the LEZ and ULEZ vehicle requirements.

As Verlinde et al. (2012) point out, a truck might visit several cities within a tour. Hence, our third studied region is a polycentric region where several cities are located close to each other. The Ruhr region studied is a polycentric industrial region in western Germany. In contrast to the two other regions studied, the Ruhr region is characterized by several cities that have grown together to form an urban region. Due to the large size of the Ruhr region (4435 km^2), we limit our focus only to the western part of the Ruhr region, which encompasses the cities of Duisburg, Mühlheim an der Ruhr, and Essen. Together, the three cities have an area of about 533 km^2 and a population of 1.2 million people. None of the three cities currently has a city toll scheme in place, but each city has a low-emission zone. Since the three low-emission zones cover almost the entire area of the three cities, we instead consider one UCC per city and model the municipal district of each of the cities as a separate toll zone that must be paid for separately.

Table 5.6: Summary of the attributes of the three real-world instances.

Instance attribute	Milan (Italy)	London (UK)	Ruhr region (Germany)
Instance area [km^2]	181.87	1526.50	533.64
Toll zone/UCC area [km^2]	7.95	21.36	(3.08, 15.56, 34.97)
Number of toll zones $\|T\|$	1	1	3
Number of UCCs	1	1	3

Customer and UCC Properties

Each of the three regions is analyzed for two levels of total demand to be delivered from the depot. The first level assumes a total demand of 75 units whereas the second level assumes a total demand of 150 units. When allocating the demand to customers, we split the total demand based on the percentage of customers in each toll zone and the percentage of customers in the outside area, and then randomly allocate it to customers. This ensures that the demand per instance and toll zone remains constant to facilitate the comparison between instances. Depending on the total units to be delivered, this results in an average demand $\bar{q}$ of 1.5 or 3 units per customer. This resembles the demand of small to medium retailers, whose deliveries are usually the target of UCC initiatives (Browne et al., 2005).

For every toll zone, we model one UCC. Each customer request destined for a toll zone can be transshipped to the corresponding UCC of that zone. Regarding the time windows of the customer and UCC locations, we assume that UCCs must be visited early in the morning, so that $a_i = 0$ and $b_i = 120$ minutes. Note, that due to these time window constraints, each UCC can be visited only once per vehicle in every instance. In line with urban delivery surveys summarized by Cherrett et al. (2012), we assume that customers within a toll zone should be visited during the morning, with $a_i \in [120, 240]$ and $b_i = a_i + 60$ minutes. This can also be explained by the fact that many urban areas have time window restrictions for delivery vehicles (e.g., in pedestrian zones). Customers that are not located in a toll zone can be visited during time windows where $a_i \in [60, 540]$ and $b_i = a_i + 60$ minutes. Lastly, the maximum tour duration is set to $D_{\text{max}} = 480$ minutes and the latest arrival at the depot is set to $a_{0'} = 660$ minutes.

The appropriate determination of the demand-independent preparation time and the service time for unloading the load units is rather difficult, as a large number of influencing factors affect these times (see e.g., Allen et al., 2000). It is known from studies that the time spent per urban delivery stop does not necessarily correlate with the quantity unloaded. For example, Schoemaker et al. (2006) and Allen et al. (2008) report dwell times between 7 and 31 minutes from observations in Amsterdam and several British cities. Without consideration of the actual volumes unloaded, they show that larger vehicles tend to spend a longer time unloading. Quak and de Koster (2009), in turn, report a demand-independent preparation time of 12 minutes and a variable service time of 2 minutes per unloaded roll container in their case study on a fashion retailer. Alcaraz et al. (2019), on the other hand, who also validated their data with a real company, assume 30 minutes of fixed time and 3 minutes per pallet to be unloaded. Lastly, using GPS data obtained from an LSP, Hughes et al. (2019) report an average dwell time of 37.4 minutes for an average quantity of 21.09 pallets per delivery stop. They further show that besides the demand, the position of the stop within the tour, as well as the time of day, and type of street influence the unloading times. Since assumptions and field data vary widely in the literature, we make assumptions regarding the fixed and variable unloading times. For all locations, including replenishment visits at the depot, we assume a fixed demand-independent preparation time of $t_l^{\text{prep}} = 15$ minutes. For the service time s_n of each customer request $n \in N$, we assume a fixed ratio of one minute per unit of demand q_n. Lastly, for the service-dependent loading time, we assume that $\beta = 1$, so that loading and unloading require the same amount of time.

LSP and Vehicle Properties

Similar to the survey and interview results presented in Cherrett et al. (2012) which showed that LSPs operate between two to three vehicle types of different sizes, we assume that the LSP in each of the three regions has two vehicle types of different size. Table 5.7 provides an overview of the two vehicle types. The first vehicle type represents a typical distribution truck with a gross vehicle weight of 7.5 t (e.g., Mercedes-Benz Atego 818 L). The second vehicle type represents a large articulated truck with a trailer with a gross vehicle weight of up to 40 t (e.g., Mercedes-Benz Actros). Note that since we also want to study fleet composition, the number of vehicles per vehicle type is unlimited. To determine the cost factors of the two vehicle types, we assume an hourly wage of 21€/h, identical to van Heeswijk et al. (2020). The costs per kilometer and per day are based on the vehicle data and total cost of ownership calculations from (EuroTransportMedia Verlags- und Veranstaltungs-GmbH, 2017). Thereby, the fixed costs include taxes, insurance, depreciation, and capital cost. The distance-based costs, in turn, are comprised of fuel, lubricant, AdBlue, tire wear, and maintenance costs.

Table 5.7: Vehicle properties for the real-world MTMP-FSMTWTF instances.

Vehicle property	Medium truck	Large truck
Distance-based costs c_d^h [€/km]	0.32	0.58
Time-based costs c_t^h [€/h]	21	21
Fixed costs c_f^h [€/day]	72.89	157.71
Capacity Q_h	15	38

Time-distance Matrix Creation

To account for multiple efficient paths in the presence of toll zones with daily fees and to find out which toll zones are visited on each path, we perform modifications on the underlying road networks based on the number of toll zones $|T|$. Using the obtained route network from OSM, we copy the road network for all $2^{|T|}$ toll zone subsets $T_i \subseteq T$ and modify the copied network to block access to the complement of the toll zone subset ($T \setminus T_i$). For example, for an instance with two toll zones τ_1 and τ_2, we create four different road networks RN ($RN_\emptyset$, RN_{τ_1}, RN_{τ_2}, $RN_{\{\tau_1,\tau_2\}}$), where the index of RN corresponds to the subset of toll zones that can be visited in the road network. After creating the road networks, we determine the minimum time paths along with their distance between every accessible pair of locations for each road network. To calculate the distances and travel times, we use the Open Source Routing Machine (Luxen and Vetter, 2011) with a customized truck routing profile. By removing all duplicate paths, we obtain a vehicle-independent, location-based graph with up to $2^{|T|}$ different paths between any two locations. Using the arc-based and duration-based cost-factors of each vehicle type, we transform this vehicle-independent graph into a vehicle-dependent graph for each vehicle type by removing the dominated arcs.

5.6.2 Design of Experiments

Through our experiments, we aim to investigate the factors impacting the usage of UCCs. To do so, we create 10 instances with random customer locations, demand assignments, and time windows for each of the three regions, toll zone customer shares, and demand levels. For each of the resulting 120 instances, we systematically vary the UCC usage cost factor per demand unit (c_{UCC}) and toll factor (c_τ). For the latter, we differentiate between a per-day toll scheme and a per-entry toll scheme, as well as an unrestricted case with no toll scheme in place. Regarding the levels of the studied factors, we consider $c_{\text{UCC}} \in \{2, 4, 6, 8, 10\}$ and $c_\tau \in \{0, 5, 10, 15, 20\}$, so that we can study a wide range of UCC usage costs and tolls without increasing the number of experiments too much. For simplicity, we assume that for instances with multiple UCCs and toll zones, all UCCs and toll zones have the same cost factors. Table 5.8 summarizes the factor levels studied in our experiments. Overall, we study 45 factor level combinations for each of the 120 instances, resulting in a total of 5400 experiments. All instance files, including those used in Subsection 5.5.2, are publicly available in Friedrich (2022).

Table 5.8: Overview of the studied factors and factor levels in the real-world study

Factor	Levels
Study region	{Milan, London, Ruhr}
% Customers in toll zones	$\{20, 40\}$
Avg. demand	$\{1.5, 3\}$
UCC usage cost factor c_{UCC}	$\{2, 4, 6, 8, 10\}$
Toll types	{per day, per entrance}
Toll factor c_τ	$\{0, 5, 10, 15, 20\}$

5.6.3 Results

In this section, we report the results of our experiments. All reported data is based on the best solution out of five runs for each of the factor level combinations. The reported mean values and error bars correspond to the subset of experiments with the respective factor level combination presented.

Impact of UCC Usage Cost and Customer Demand

Figure 5.4 shows how the average demand per customer and the UCC usage cost factor c_{UCC} impact the percentage of viable customer requests transshipped. Each data point corresponds to the mean solution cost per city and factor level combination. First, the graph shows, that similar to what is reported in Friedrich and Elbert (2022) and Janjevic and Ndiaye (2017b), UCC usage is highly dependent on UCC pricing and decreases rapidly as the cost factor c_{UCC} for using the UCC increases. Second, because of the quantity-based transshipment costs, it can be seen that with higher average demand per customer, the UCC usage decreases. Thus, UCCs appear to be more attractive for LSPs with low demand per stop. This finding is in line with earlier studies, such as Browne et al. (2005), who suggested that especially LSPs with small deliveries could benefit from UCCs. Similarly, Janjevic and Ndiaye (2017b) showed that the cost attractiveness of UCCs strongly depends on the number of pallets delivered per stop. One rationale for this is that for low delivery quantities, the duration-based costs associated with unloading and preparations at each stop exceed the cost of using the UCC (Browne et al., 2005). The use of UCCs is therefore cost-effective for LSPs with low demand per stop. Third, only minor differences between the three study regions can be observed in terms of the relationship between the UCC usage and the UCC usage cost factor. This suggests that the impact of UCC usage costs is only slightly influenced by the spatial structure of the study region. However, it is noticeable that the UCC usage is considerably higher in London for the average customer demand of 1.5 units than in the other two cities. This could be attributed to the larger instance area of the London region, which means that the delivery locations are more widely scattered.

While Figure 5.4 shows the impact of the UCC usage cost factor on the UCC usage, Figure 5.5 shows how the total delivery costs increase as UCC usage costs increase. Since the order of magnitude of the costs per region varies largely, we transformed the costs so that for each studied region and demand level the mean total cost at $c_{\text{UCC}} = 2$ are equal to 1.0. Here, it can be observed that the cost increase from $c_{\text{UCC}} = 6$ becomes significantly smaller for the higher demand compared to the lower demand due to the lower UCC usage.

Concerning the impact of UCC usage costs on fleet composition, our data, presented in Figure 5.6, shows that with higher UCC usage costs and thus lower UCC usage, the use of the larger truck type generally decreases. Moreover, the results indicate that the large truck type is used proportionally more for the larger demand ($\bar{q} = 3$) and higher shares of city customers. Furthermore, it can be observed that the large truck type is hardly used in the Ruhr instances. The dependence on the average customer request demand and the number of urban customers can probably be explained by the fact that for higher quantities to be delivered to a UCC or a dense urban area, the large trucks can be used more efficiently. For the Ruhr instances, however, fewer requests can be consolidated per city and UCC due to the division of customer requests into three cities and UCCs. Overall, the fleet size ranges between 3 to 6 vehicles for $\bar{q} = 1.5$ and 4 to 7 vehicles for $\bar{q} = 3$.

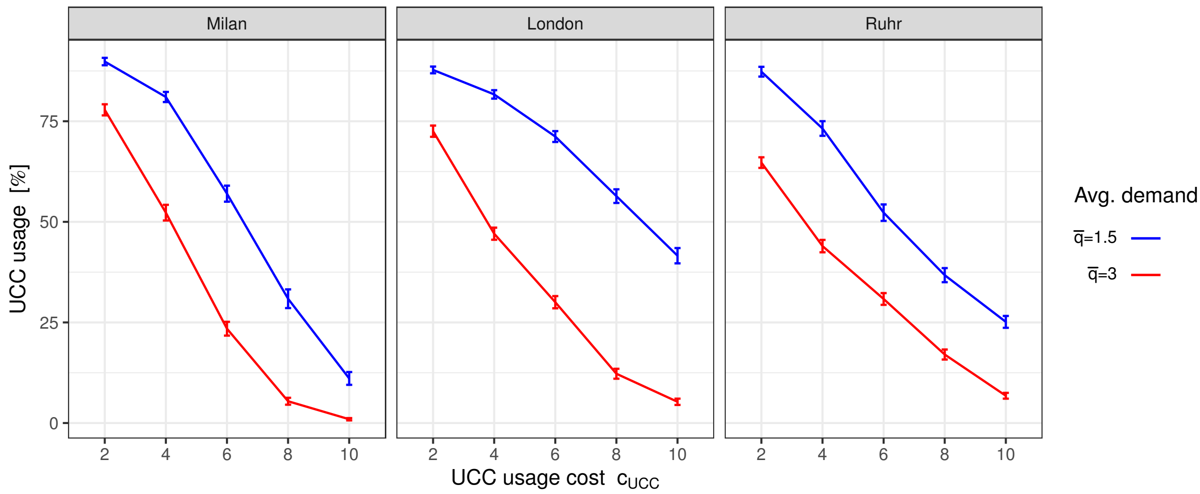


Figure 5.4: Mean proportion of viable customer requests transshipped at a UCC depending on the UCC usage cost c_{UCC}, and average customer demand.

Impact of City Toll Schemes

In order to analyze the impact of the per-day city toll scheme and the per-entrance city toll scheme with varying cost factors, we compare in Figure 5.7 the increase in UCC usage relative to the unconstrained case without city toll scheme for each studied region. As expected, for all three regions and both toll schemes, the UCC usage increases with the toll factor $c_{\mathcal{T}}$. Depending on the city and the toll scheme, the mean increase in UCC usage varies from 4.4 % (London, 5 per day) to 105.7 % (Ruhr, 20 per entrance). Moreover, it can be observed that for equal values of $c_{\mathcal{T}}$, the per-entrance scheme always leads to a higher mean UCC usage compared to the per-day scheme. The per-entrance scheme results in higher mean usage for all three study regions, even if the toll cost factor $c_{\mathcal{T}}$ is 5 € less than in the per-day scheme. This could be explained by the fact that vehicles visiting a toll zone tend to do so multiple times if no per-entrance scheme is selected. For example, in the absence of a toll scheme trucks that visit a toll zone, enter it on average 2.07 to 2.38 times, depending on the instance. In contrast, a per-entrance scheme with $c_{\mathcal{T}} = 20$ reduces the number of entries per truck visiting the zone to an average of 1.04 to 1.22 entries. Similarly, a decline in the total toll zone entrances per instance can be seen in Figure 5.8. Whereas the number of entries per truck is only roughly halved for the most restrictive toll scheme, as described above, the total number of entries falls more sharply, since the overall number of trucks entering the toll zone also reduces. For example, for the Ruhr instances, the mean number of trucks entering any of the three toll zones is reduced by 88.4 % for the per-entrance scheme with $c_{\mathcal{T}} = 20$.

Impact of the Share of Customers in Toll Zones

Finally, we address the question of whether and how the share of customers located in a city toll zone, i.e., the customers whose requests can be transshipped at a UCC, affect the percentage of UCC usage. Figure 5.9 shows the differences in UCC usage for both customer share levels. With the exception of the demand factor level $\bar{q} = 1.5$ in London, it appears that as the number of customers

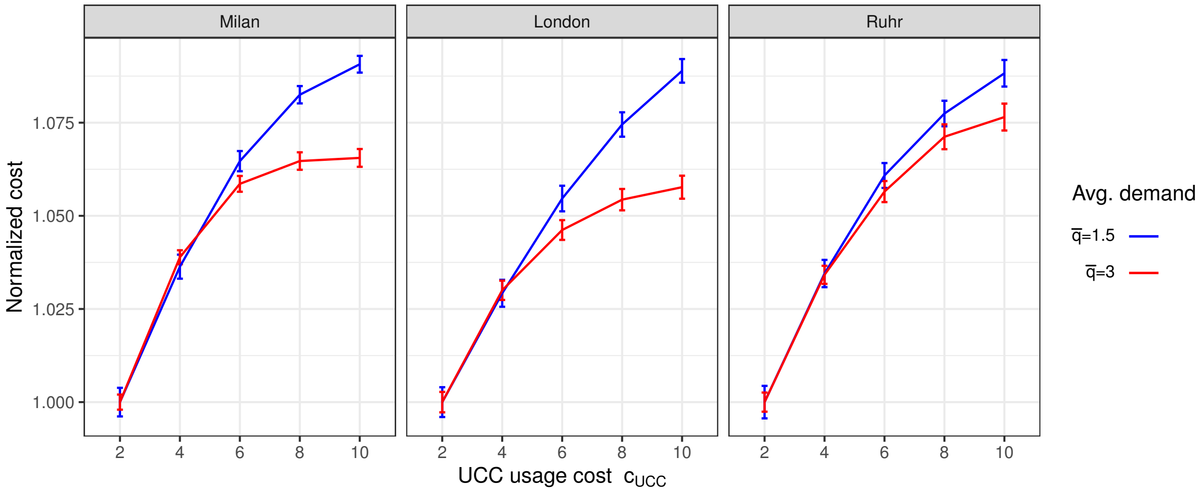


Figure 5.5: Mean change in total delivery cost as a function of UCC usage cost c_{UCC} and average customer demand. Costs are normalized by dividing each data point by the group mean per city and demand at $c_{\text{UCC}} = 2$.

within the toll zones increases, the proportion of customer requests that are transshipped at the UCCs also increases. This overall trend could be partially explained by the increasing number of customer requests whose time windows overlap. When the number of customer requests within a city increases, some deliveries have to be made at the same time. Consequently, these requests cannot be served by the same vehicle, even if they are geographically close. This increases the number of vehicles needed and therefore the delivery costs if no UCC is used.

Managerial Insights

Consistent with previous research (e.g., van Heeswijk et al., 2020; Janjevic and Ndiaye, 2017b), our results show a strong price sensitivity regarding the use of UCCs. As a result, UCC usage pricing must be set at competitive levels to encourage LSPs to use their service. However, a low UCC usage fee that attracts many LSPs may not be profitable for UCC operators, so local administrations may need to subsidize UCC operations to enable attractive pricing.

According to the literature, UCCs mostly follow a quantity-based pricing system in practice (Janjevic and Ndiaye, 2017b). As our results and previous studies show, this especially favors LSPs with low delivery quantities per stop, due to the higher potential savings related to demand-independent preparation times. If, in turn, the UCC charges a fixed fee per customer request (or delivery stop), as in van Heeswijk et al. (2020), then the request size is likely to have a smaller impact on the UCC usage. To extend the business model of UCCs to also attract LSPs with both small and high volumes per stop, different pricing models might be needed. For example, to account for both the number of requests transshipped and their volume, a pricing model with a fixed fee per request and a variable fee per pallet could be considered.

Both the per-day and the per-entrance city toll schemes have shown that local administrations could use city toll schemes to increase the cost attractiveness of UCCs. Moreover, the revenues

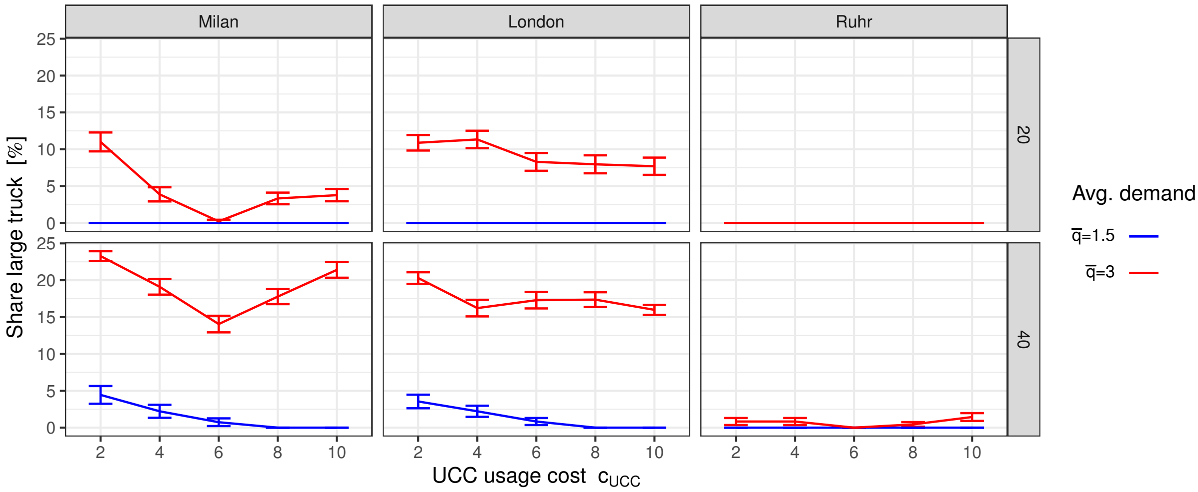


Figure 5.6: Mean percentage of large truck usage in total fleets as a function of UCC usage costs, percentage of customers in toll zones, customer demands, and study region.

generated by the city toll schemes could be used to subsidize the UCC operations and usage fees. When comparing the two toll schemes, it can be seen that a per-entrance city toll scheme provides greater support for UCC usage than a per-day city toll scheme. On the one hand, this is because vehicles in city logistics often make more than one trip per day. On the other hand, the presence of customers in the area surrounding the toll zone might lead to multiple entries and exits to reduce routing costs.

Concerning the impact of the number of customers in the toll zone on the proportion of UCC usage, it can be concluded that for most cases the share of viable customers transshipped slightly increases with an increasing number of customers in the toll zones. This result is in contrast to van Heeswijk et al. (2020) and Janjevic and Ndiaye (2017b) who both state that the benefits of using a UCC decrease as the number of customers (stops) per city increases. However, in Janjevic and Ndiaye (2017b) no time windows and route duration constraints are considered so that a higher density of customers directly relates to more efficient routes. With overlapping customer time windows, however, the potential efficiency gains are reduced, as customers may not be visited by the same vehicle despite their geographical proximity. Our results indicate that the relationship between the proportion of viable customers transshipped and the number of customers is not as straightforward as it seems. The results seem to depend on the city and demand, on the one hand, and possibly on the time windows, on the other.

Although the level of UCC usage varies among the regions examined, our results indicate that the impact of UCC usage costs and city toll schemes are fairly similar across the three regions. However, when we compare the proportion of UCC usage in London and Milan, both of which have only one toll zone, we notice that UCC usage is higher on average in London than in Milan (London: 50.57 %, Milan 42.97 %), but lower or close to equal for runs with low UCC usage costs ($c_{\text{UCC}} \in \{2, 4\}$). Furthermore, the smaller-sized Milan instances seem to be more sensitive to an increase in UCC usage costs than the larger-sized London instances. Similar results that the use of UCCs is more attractive for larger areas are also reported by van Heeswijk et al. (2020) and

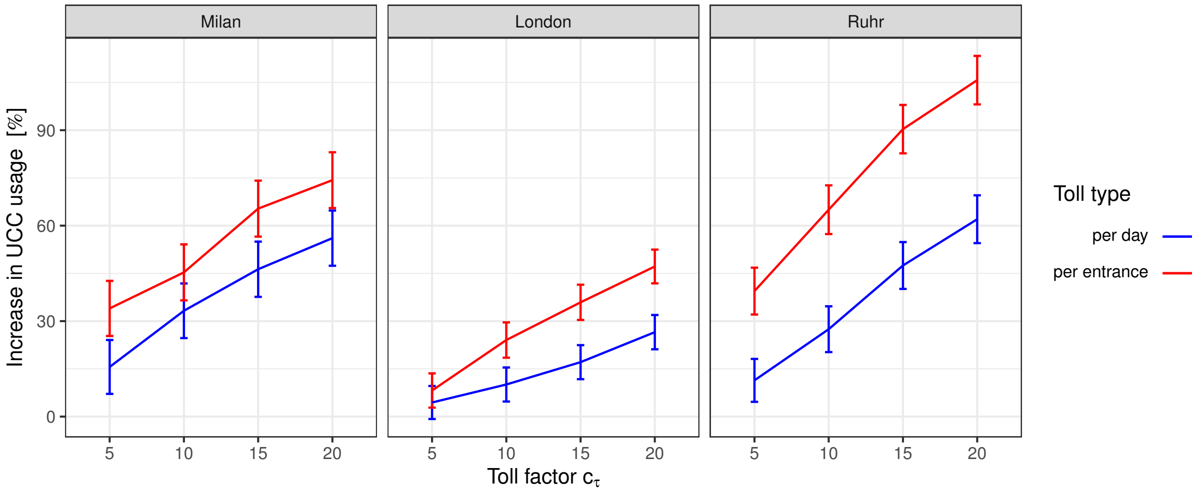


Figure 5.7: Mean increase in UCC usage per city, toll type, and toll factor compared to the unrestricted case without city toll.

Roca-Riu and Estrada (2012).

5.7 Conclusion and Further Research

In this paper, we propose a rich fleet size and mix vehicle routing problem with time windows, transshipment facilities, multiple paths, and multiple trips per vehicle. The proposed problem jointly optimizes the fleet size and composition, customer-to-vehicle-assignments, delivery-transshipment decisions, location-visit-sequence, and path choices between successive visits considering per-day and per-entrance city toll schemes. The complexity of the considered problem lies, on the one hand, in the presence of multiple delivery options per request. On the other hand, the path selection is non-trivial due to the non-dominated trade-offs between distance, time and toll costs. Moreover, multiple trips per vehicle, time window and maximum tour duration constraints, as well as the heterogeneous fleets add to the complexity of the problem.

We present a mathematical formulation that addresses the interdependent aspects of our rich vehicle routing problem. Due to the high complexity of the problem, only small instances can be solved optimally using standard solvers. For this reason, we present an ALNS heuristic with an embedded local search and route recombination mechanism to solve large-size instances efficiently. In this context, we extend and combine recent developments for different problem aspects into a unified heuristic which focuses particularly on heterogeneous vehicle fleets.

With our proposed heuristic, we study from the point of view of a LSP how per-day and per-entrance city toll scheme with different rates influence the cost attractiveness of UCCs under various conditions. To this end, we consider different UCC usage fees, customer demands, and percentages of customers located in toll zones as additional factors to be varied. Using these factors and their respective factor levels, we conduct full factorial experiments for three urban regions, totaling 5400 experiments. Analyzing the results of the experiments, we provide decision-making support for UCC operators and local administrations on how to set UCC fees and city tolls to encourage the

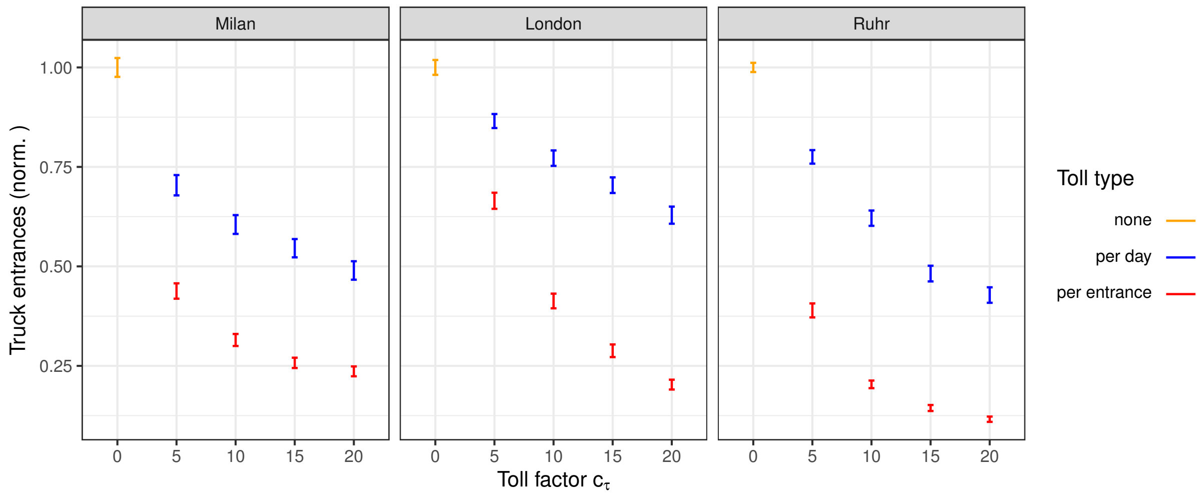


Figure 5.8: Mean relative change in toll zone entrances depending on the toll scheme and toll cost factor c_τ. Note that for every data point the number of entrances is divided by the mean number of entrances at $c_\tau = 0$, grouped by the city, demand level, and percentage of customers in toll zones.

use of UCCs.

Finally, for future research, we recommend the development and analysis of different UCC pricing schemes to attract a wider range of LSPs while ensuring the profitability of UCCs. Furthermore, the studied problem could be extended to include congestion in the form of time-dependent stochastic travel times to further bridge the gap to real-world operations

CRediT authorship contribution statement

Christian Friedrich: Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Ralf Elbert:** Conceptualization, Supervision, Project Administration, Writing – Review & Editing.

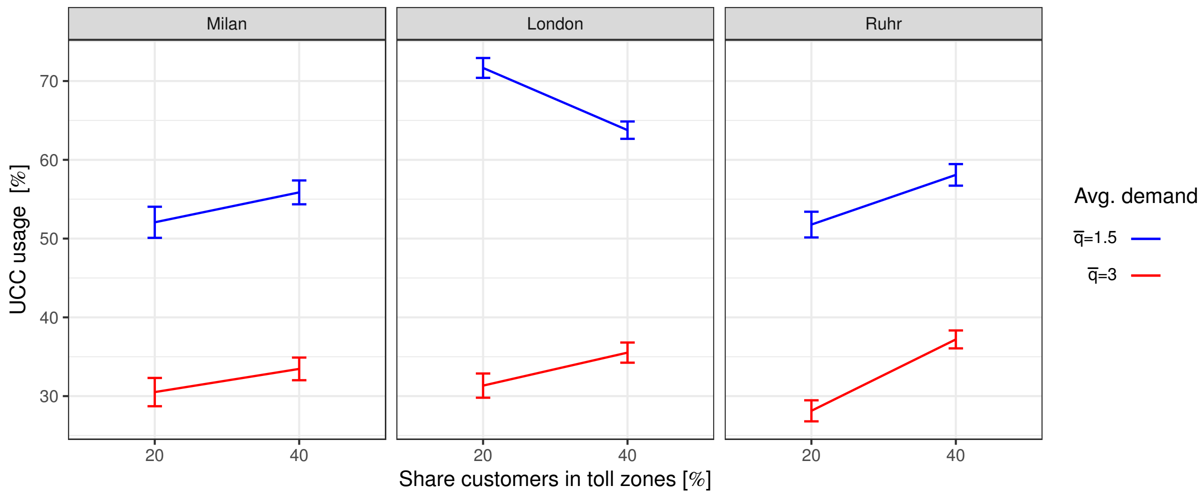


Figure 5.9: Comparison of mean UCC usage for all three regions and demand factor levels as a function of the proportion of customers in toll zones.

5 Appendix

Appendix 5.A Lists of Notations

Table 5.9: Overview of notations used for the ALNS.

Notation	Description	Numerical values considered
General		
B	Set of unassigned customer requests	–
D^k_{max}	Maximum allowable shift duration of vehicle $k \in K$	480 min
$f(S')$	Objective value of solution S'	–
$f_{\text{mod}}(S')$	Augmented objective value of solution S'	–
L_{max}	Maximum sequence length for adjacent string removal	13
OT_k	Violation of the maximum allowable shift duration D^k_{max} of vehicle k (overtime)	–
$OT(S')$	Sum of the maximum allowable shift duration violation (overtime) of solution S'	–
RN_{T_i}	Road network that can access the toll zones of $T_i \subseteq T$	–
$p_{\text{localSearch}}$	Probability to conduct a local search during an ALNS iteration	0.08
S_t	Incumbent solution	–
S'	Current solution	–
S_{best}	Best found solution	–
$TW(S')$	Sum of time window violation of solution S'	–
α^{p}	Adaptive parameter to control the penalization of overtime and time window violations	–
$\alpha^{\text{p}}_{\text{min}}$	Initial value of α^{p}	3
$\alpha^{\text{p}}_{\text{max}}$	Maximum value of α^{p}	400
β	Loading time factor	1
ζ_η	Threshold parameter at iteration η	–
ζ_0	Start threshold parameter at iteration 0	0.02
η^{SPP}	Number of iterations after which the SPP procedure is called	15 000
η^{reset}	Number of iterations after which α^{p} is reset to $\alpha^{\text{p}}_{\text{min}}$	30
η^{update}	Number of iterations after which the selection probabilities of the removal and insertion operators are updated	2500
η^{max}	Maximum number of iterations after which the algorithm terminates	30 000
ρ	Parameter to control the adjustment of α^{p}	1.4
Removal and Insertion		
p_{merge}	Probability to try merging the trips of a tour after a customer request is removed	0.76
$p_{\text{trySmallerVehicle}}$	Probability to try switching the vehicle type of a route during insertion	0.06
$p_{\text{insertSwitch}}$	Probability to try assigning a smaller vehicle to a tour after a customer request is removed	0.08
p_{worst}	Randomization parameter for the worst removal operator	3

continued on next page

Table 5.9: (Continued)

Notation	Description	Numerical values considered
p_{trip}	Randomization parameter for the trip removal operator	3
$p_{\text{blinksRemoval}}$	Probability to blink on a customer request during removal	0.13
p_{blinksTF}	Probability to blink on an insertion position for a transshipment facility	0.03
$p_{\text{blinksDirect}}$	Probability to blink on an insertion position for a direct delivery option	0.03
$p_{\text{blinksVehicle}}$	Probability to skip the evaluation of insertion positions for the current vehicle of a route	0.07
$R(ij)$	Relatedness of customer requests i and j	–
w_i	Weight of removal or insertion operator i	–
α_{string}	Probability for preserving a subsequence of customer requests during the adjacent string removal	0.45
β_{string}	Controls the length of the subsequence of customer requests to be preserved during the adjacent string removal	0.03
δ	Random number of customer requests to be removed during an iteration	–
θ_i	Number of times removal or insertion operator i was selected during the last segment	–
ν_1	Coefficient added to the score of removal and insertion operators when a new best solution S_{best} is found	0.68
ν_2	Coefficient added to the score of removal and insertion operator when the incumbent solution S_t is improved	0.22
ν_3	Coefficient added to the score of removal and insertion operator when the current solution S' is accepted	0.10
π_i	Score of removal or insertion operator i	–
υ	Parameter to control how strong the previous operator weight w_i impacts the new weight of a removal or insertion operator i	0.8
ω_{min}	Minimum percentage of customer requests to be removed	0.06
ω_{max}	Maximum percentage of customer requests to be removed	0.35
Set Partitioning Problem		
c_r	Cost of route r	–
μ_r	Binary variable for the SPP to indicate whether a route r is included in the solution	–
r	Vehicle route originating from the depot 0 and ending at the depot $0'$	–
R^{pool}	Pool to store feasible routes for the set partitioning problem	–
Labels and Resources		
$\mathcal{D}_i$	Origin depot of the trip containing vertex i	
$\mathcal{D}'_i$	Destination depot of the trip containing vertex i	
$L^h_{[i,j]}$	Label of a sequence of vertices visited by a vehicle of type h, starting from vertex i and ending at vertex j	–
$R(L^h_{[i,j]})$	Resources of label $L^h_{[i,j]}$	–
$T^{\text{AC}}(L^h_{[i,j]})$	Arc-based cost of label $L^h_{[i,j]}$	–
$T^{\text{Cost}}(L^h_{[i,j]})$	Total cost of label $L^h_{[i,j]}$	–
$T^{\text{DUR}}(L^h_{[i,j]})$	Duration of label $L^h_{[i,j]}$	–
$T^{\text{E}}(L^h_{[i,j]})$	Earliest start time of label $L^h_{[i,j]}$ that leads to a schedule with minimum duration and time warp	–
$T^{\text{L}}(L^h_{[i,j]})$	Latest start time of label $L^h_{[i,j]}$ that leads to a schedule with minimum duration and time warp	–
$T^{\text{OT}}(L^h_{[i,j]})$	Over time of label $L^h_{[i,j]}$	–

continued on next page

Table 5.9: (Continued)

Notation	Description	Numerical values considered
$T^{\mathrm{Q}}(L^h_{[i,j]})$	Demand of label $L^h_{[i,j]}$	–
$T^{\mathrm{S}}(L^h_{[i,j]})$	Cumulative service time of label $L^h_{[i,j]}$	–
$T^{\mathrm{T}}(L^h_{[i,j]})$	Set of toll zones visited by label $L^h_{[i,j]}$	–
$T^{\mathrm{TW}}(L^h_{[i,j]})$	Time window violation of label $L^h_{[i,j]}$	–

Appendix 5.B Arc Reduction for Replenishment Arcs

Analogously to the set of arcs A_k, described in Subsection 5.3.2, the set of replenishment arcs A'_k can be denoted as:

$$\begin{aligned} A'_k \subseteq &\{(i,j)^p_{'k} \in O \times O : l_i, l_j \notin L^{\mathrm{TF}}, p = 1, \ldots, m^{'k}_{ij}\} \\ &\cup \{(f_l, j)^p_{'k} \in F \times O : l_j \notin L^{\mathrm{TF}}, j \neq 0, p = 1, \ldots, m^{'k}_{f_l j}\} \\ &\cup \{(i, e_l)^p_{'k} \in O \times E : i \neq 0', l_i \notin L^{\mathrm{TF}}, p = 1, \ldots, m^{'k}_{i e_l}\} \\ &\cup \{(f_l, e'_l)^p_{'k} \in F \times E : l \neq l', p = 1, \ldots, m^{'k}_{f_l e'_l}\}. \end{aligned}$$

6 Conclusion

Urban freight transport is an important and inevitable aspect of the economic and social life in urban areas. However, it is also associated with negative externalities, such as noise, pollutant emissions, and traffic accidents. A common measure, that is often pursued by local administrations to increase the efficiency of urban freight transport is the urban consolidation center (UCC) concept. In this concept, freight shipments from several logistics service providers (LSPs) destined for an urban area are consolidated in a logistics facility located in the proximity of the urban area. As highlighted in Chapters 1 and 2, many UCCs in practice faced financial problems and a lack of participation from actors. Subsequently, numerous UCCs initiatives have failed over time.

Despite its long history and the abundance of case studies and reports from practice, the literature on evaluating the cost attractiveness of UCCs and modeling the decision of LSPs to use UCCs is still rather limited and subject to a number of simplifications. In particular, quantitative model-based research on regulatory impacts is limited. This dissertation seeks to methodologically extend research on UCCs by presenting models and algorithms that provide decision support for the quantitative evaluation of the cost attractiveness of jointly-operated and third-party UCCs. Additionally, the research in this dissertation aims to expand the understanding of the impact of urban freight transport regulations and operational characteristics on the cost attractiveness of UCCs.

In the remainder of this chapter, Section 6.1 reflects on the research objective and research questions (RQs). Section 6.2 summarizes the managerial insights that can be derived from the research in this dissertation. Then, Section 6.3 discusses the limitations of the research. Finally, in Section 6.4, opportunities for future research are derived from the limitations and briefly discussed.

6.1 Reflection of Research Objective and Research Questions

The research in this dissertation addresses the topic of UCCs from the perspective of LSPs and is motivated by the scarcity of quantitative model-based research to evaluate the cost attractiveness of UCCs for LSPs under different operational and regulatory settings. The overall objective of the dissertation is to close this research gap by presenting models and algorithms to evaluate the cost attractiveness of UCCs. A distinction is made between jointly-operated UCCs, where the decision to use UCCs is assumed to be strategic, and third-party UCCs, where the decision to use UCCs is operational. For third-party UCCs, special attention is paid to integrating the transshipment decision into the vehicle routing of LSPs and to solve this problem heuristically. In addition to providing models and algorithms for evaluating the cost attractiveness of UCCs, the research presented in this dissertation also aims to provide insights into the impact of urban freight transport regulations and operational characteristics on the cost attractiveness of UCCs. This objective gave rise to the four RQs, which are repeated along with their research propositions

(RPs) in the following for individual reflection.

RQ 1: *How can the cost attractiveness of UCCs be evaluated for LSPs, taking into account urban freight transport regulations?*

RP 1.1: *To strategically evaluate the cost attractiveness of jointly-operated UCCs for LSPs considering urban freight transport regulations and LSP-specific operational characteristics, scenario-based simulation modeling is an appropriate method.*

RP 1.2: *To operationally evaluate the cost attractiveness of third-party UCCs from the perspective of a LSP, an appropriate method is to integrate the decision to use UCCs into the vehicle route planning and thereby consider each customer request individually.*

The first question RQ 1 focuses on the topic of how to evaluate the cost attractiveness of jointly-operated and third-party UCCs for LSPs, taking into account urban freight transport regulations. By analyzing the quantitative approaches used in the literature to evaluate UCCs in Subsection 2.2.6, it has been shown that the methods applied can be broadly categorized into simulation modeling, cost modeling, and optimization. Overall, RQ 1 spans Chapters 3 to 5. Chapter 3 addresses RQ 1.1 and focuses on the evaluation of jointly-operated UCCs. Here, as previously described, it is assumed that the decision of LSPs to use UCCs is strategic since the implementation of a UCC also incurs fixed costs that must be split among the participating LSPs and amortized over its lifetime. Furthermore, the usage costs for each participating LSP depend directly on the operating costs of the jointly-operated UCC. In order to evaluate the cost attractiveness of this type of UCC, a simulation framework, its implementation, and its application to a case study are presented. The proposed framework considers the interactions of a UCC operator, receivers, and a group of LSPs that cooperate to use the UCC. To quantify the effects of the urban freight transport regulations on the UCC and its participating LSPs, the cost relationships between the actors are modeled. Unlike previous models, the framework takes into account the presence of receivers outside the UCC service area. This allows a more comprehensive assessment of the impact of urban freight transport regulations on the transport costs of LSPs. In addition, it is also possible to analyze which cost and operational changes result for LSPs overall as they join to operate a UCC. In consequence, the presented real-world case study validates the applicability of the framework and thus confirms RP 1.1. Chapters 4 and 5 address RQ 1.2 and deal with UCCs operated by third parties. In this case, UCCs offer their services, i.e., transport to receivers in cities, for a fee to LSPs. Therefore, it is assumed that LSPs can decide individually for each customer request whether and to which UCC to transship it to. To evaluate the cost attractiveness of this type of UCC, an approach based on an integrated vehicle routing problem (VRP) is proposed. Similar, to existing approaches that use continuous approximations for transport costs, a single operative decision epoch (e.g., a day) is considered. However, contrary to the existing approaches, in the presented approach the cost attractiveness of UCCs is evaluated based on the results of an integrated VRP. Thereby, operational and regulatory factors can be varied to provide further insights. Using multiple case studies, both chapters confirm RP 1.2 by demonstrating the advantages of the integrated decision approach.

RQ 2: *How can the integrated routing problem of LSPs, which features the decision of whether and which customer requests to transship to which third-party UCC, be solved heuristically?*

RP 2.1: *The heuristic solution procedures provide solutions with low optimality gaps (compared to results from the literature and commercial solvers).*

RP 2.2: *The heuristic solution procedures provide solutions with significantly lower runtimes than exact solution methods.*

RQ 2 revolves around the heuristic solution and extension of the integrated routing problem of LSPs, which features the decision of whether and which customer requests to transship to which third-party UCC. In this context, particular importance is attached to the consideration of urban freight transport regulations and operational characteristics. RQ 2 is addressed in Chapters 4 and 5. Chapter 4 presents an adaptive large neighborhood search (ALNS) heuristic with an embedded randomized variable neighborhood descent (RVND) as a local search component and a set partitioning problem (SPP) for the recombination of routes for the vehicle routing problem with transshipment facilities (VRPTF). To address the transshipment possibilities in the proposed heuristic, newly adapted operators and diversification mechanisms are proposed to be used within the heuristic. In addition, the VRPTF and the presented ALNS heuristic are extended with respect to RQ 2.1 by including time window constraints and heterogeneous fleets with fleet size and mix decisions. Moreover, in order to more realistically represent the actual transport costs of LSPs an objective function including total durations and fixed vehicle costs is presented for the VRPTF. Chapter 5 covers RQ 2.2 and extends the heuristic from Chapter 4. Apart from enabling the planning of multiple trips per vehicle and day, the extended heuristic also integrates per-day and per-entry city toll schemes into the route planning. The resulting novel optimization problem is formalized into a mixed-integer linear programming (MILP) model.

To analyze and validate the solution quality and performance of both heuristics for different problem variants and thus answer RQ 2.3, both chapters include numerical experiments. In Chapter 4, benchmarks for multiple problem variants are presented. For one, the proposed ALNS is compared with an exact solution approach for the VRPTF from the literature. The results of this comparison show that the proposed heuristic yields solution improvements of 0.68 % for the VRPTF on average while only requiring a fraction of the computation time of the exact method. For another, the ALNS is compared with three other approaches from the literature on instances of the related vehicle routing problem with roaming delivery locations (VRPRDL) and the vehicle routing problem with home and roaming delivery locations (VRPHRDL). Furthermore, to evaluate the fleet size and mix component of the presented heuristic, a comparison with three heuristics for the fleet size and mix vehicle routing problem with time windows (FSMTW) from the literature is carried out. The comparisons show that the proposed heuristic is competitive in terms of both solution quality and computation time. In Chapter 5 the results of the proposed heuristic are compared to those obtained by the commercial solver Gurobi 9.1.1. Only small-sized problem instances can be solved to optimality within twelve hours using the commercial solver, while the proposed heuristic requires a much lower computational effort. The results show that all solutions confirmed to be optimal by the solver were also found by the proposed heuristic, and no improvements were found using the solver over the solutions obtained by the ALNS. Through the aforementioned benchmarks, both heuristics were shown to produce solutions of high quality, allowing RP 2.1 to be confirmed. Furthermore, by comparing the runtimes of the heuristic from Chapter 4 to those of the exact solution procedure for the VRPTF and by comparing the runtime of the heuristic for the multi-trip multi-path fleet size and mix vehicle routing problem with time windows and transshipment facilities (MTMP-FSMTWTF) from Chapter 5 to the commercial solver, the computational time savings of both heuristics were demonstrated, thus confirming RP 2.2.

RQ 3: *How does the integration of UCC transshipment decisions into vehicle routing affect the transport plans of LSPs compared to a blanket decision approach?*

RP 3.1: *The cost attractiveness and thus usage of UCCs differ between the integrated routing approach and the blanket decision approach.*

RP 3.2: *By taking transshipment decisions for each customer request individually, the integrated routing approach provides solutions with lower or equal costs compared to the blanket decision approach.*

RQ 3 addresses the question of how the integration of transshipment decisions into vehicle routing affects the cost attractiveness of UCCs and therefore the routing plans of LSPs. In addition, it raises the question of which potential cost savings LSPs could achieve by using this integrated decision approach. As stated in RP 3.1 and RP 3.2, it is expected that the solutions of the two approaches differ, i.e., only a subset of the possible customer requests is transshipped to a UCC in the integrated approach. Subsequently, it is expected that the costs of the integrated approach will be lower or equal to those of the blanket approach. To answer this RQ, the experiments of the real-world study of Chapter 4 are repeated using a blanket approach where either all or no customer requests are transshipped to a UCC. In this comparison, numerical experiments are performed for all possible combinations of two instance sizes, three time window lengths, five customer demand sizes, and ten levels of UCC usage costs for both homogeneous and heterogeneous fleets. The comparison between the results of both approaches shows that UCC usage, and thus the cost attractiveness of UCCs, varies between the two approaches and depends on the fleet, the size of the customer request, and the UCC usage fee. Overall, however, the integrated approach results in slightly lower use of the UCCs ($-1.78\,\%$ for heterogeneous fleet, $-3.20\,\%$ for homogeneous fleet). Thus, RP 3.1 can be confirmed. Similar to the analysis of the UCC usage, the analysis of the costs shows that the transport cost differences between both approaches also vary strongly depending on the factor level combination. Lower costs when using the integrated approach are observed especially for low delivery quantities per customer request since requests with low delivery quantities are particularly suitable for transshipment to a UCC due to the quantity-based usage fee. In contrast, for higher delivery quantities per customer request, both approaches yield the same costs, as both approaches provide solutions in which no customers requests are transshipped. Overall, however, RP 3.2 can be confirmed, as the costs for LSP can be reduced on average by 0.55 % for heterogeneous fleets and 0.82 % for homogeneous fleets in the case study. Depending on the factor level combinations cost savings of up to 7.7 % can be observed compared to the simplified blanket approach.

RQ 4: *How do urban freight transport regulations and operational characteristics affect the cost attractiveness of UCCs for LSPs?*

RP 4.1: *Urban freight transport regulations increase the cost attractiveness of jointly-operated UCCs for LSPs. The extent, however, differs among participating LSPs.*

RP 4.2: *Time windows and city toll regulations increase the cost attractiveness of UCCs for LSPs.*

RP 4.3: *Increases in UCC usage fees, as well as in the average demand volume of customer requests, strongly reduce the cost attractiveness of UCCs for LSPs.*

RQ 4 addresses the impact of urban freight transport regulations and operational characteristics on the cost attractiveness of UCCs and spans over Chapters 3, 4, and 5. Chapter 3 addresses subquestion RQ 4.1 and places its focus on jointly-operated UCCs and examines three scenarios featuring a mix of urban freight transport regulations compared to one unrestricted scenario. Time window restrictions, per-day city tolls (zone-based access charges), and vehicle-based access restrictions are considered. The results of the comparison of the four scenarios show that regulations increase the cost attractiveness of the jointly-operated UCCs. Especially narrow delivery time windows in combination with vehicle-based access restrictions seem to strongly increase the cost attractiveness. As the observations show, the overall cost attractiveness of the UCC, as well as its change depending on the urban freight transport regulations in place, differ between the LSPs. From this, it can be concluded, that it is crucial to account for individual operative characteristics of LSPs, such as their location or customer request structure, when evaluating UCCs. Chapter 4 and Chapter 5 study the effects of regulations and operational characteristics on third-party UCCs. Chapter 4 addresses RQ 4.2 which raises the question of how time windows, UCC usage fees, customer request sizes, and the employed fleet affect the cost attractiveness of third-party UCCs for LSPs. The results confirm RP 4.3 by showing that the cost attractiveness of UCCs is strongly affected by UCC usage fees and customer request size, as the fees are proportional to the latter. From this, it can be concluded that UCCs are particularly cost-attractive for LSPs with low delivery volumes per customer request. Aiding the confirmation of RP 4.2, the analysis demonstrates by comparing the solutions obtained for three time window widths that shorter time windows increase the cost attractiveness of UCCs. Finally, the analysis also reveals differences regarding the cost attractiveness of UCCs between homogeneous and heterogeneous fleets. However, these differences are not the same across different factor level combinations and depend, among other things, on the length of the time windows and the volume of customer requests. Chapter 5 addresses RQ 4.3 and thus shifts the focus on the impact of city toll schemes. A per-day and a per-entry toll are studied for four toll levels and compared to experiments without a city toll. Furthermore, two average customer request sizes, two values for the share of customers in toll areas, and five UCC usage fees are considered. To reduce the geographic bias of the analysis, experiments are conducted for three European cities, each with ten randomly generated customer distributions per assumed percentage of customers in toll areas. The analysis of the results shows that city toll schemes, especially per entry schemes, increase the transport costs of LSPs in urban areas and thus positively influence the cost attractiveness of UCCs. Depending on the factor level combinations between 4.4 % to 105.7 % increase in UCC usage can be observed in the experiments. In consequence, it can be confirmed that city tolls increase the cost attractiveness of UCCs, as proposed in RP 4.2. In addition, the impact of UCC usage fees and the size of customer requests is further confirmed by the experiments provided in Chapter 5.

6.2 Managerial Insights

The research in this dissertation provides managerial insights to LSPs as well as local administrations and UCC operators. The insights include both holistic, cross-actor aspects as well as actor-specific considerations.

From the overall perspective, it became clear that although UCCs can increase the sustainability of urban freight transport, establishing a cost-effective UCC and attracting LSPs to use its service is a challenging task. For example, it became evident in Chapter 3 that the location of the users of a UCC, the LSPs, relative to the UCC can play a major role in the cost benefits of a jointly-operated UCC. LSPs that plan to operate a UCC jointly must therefore consider and evaluate the location of the UCC relative to the potential participants. With regard to the influence of regulations, it is also evident that certain differences exist depending on the location and operational characteristics. The comparison of three European urban regions presented in Chapter 5 shows, however, that the general influence of regulations and operational characteristics on the cost attractiveness of UCCs is comparable.

Another aspect that concerns both the potential users of UCCs, their operators, and local administrations are regulations of urban freight transport. The simulation study presented in Chapter 3 gives a brief insight that time windows, city toll, and vehicle-based restrictions, can contribute to the cost attractiveness of UCCs for LSPs. In Chapter 4, the impact of time window restrictions for LSPs serving multiple cities is investigated using a real-world study. Three time window lengths are considered. The results indicate that time windows, especially when narrow (e.g., 60 minutes), can have a significant impact on the cost attractiveness of UCCs. Chapter 5 focuses on city tolls. It demonstrates how per-day and entry-based tolls increase the cost attractiveness of UCCs. These results illustrate for local administration that regulations can be an effective way to incentivize LSPs to use UCCs and thus reduce the number of trucks in urban areas, thereby reducing the negative impacts of freight transport. In addition, if city tolls are in place, local administrations could use the revenues from it to subsidize UCCs to ensure attractive pricing of UCC services. For LSPs, on the other hand, it shows that UCCs can be a way to make their transport operations more efficient in the context of urban freight transport regulations. Overall, the results of this dissertation indicate that urban freight transport regulations can increase the cost attractiveness of UCCs to LSPs. As a result of an increased cost attractiveness, an increase in LSPs participation in UCCs schemes can be expected, reducing the negative impact of urban freight transport. In addition, with increased LSPs participation, UCCs can increase their economies of scale and ensure their financial viability.

From an operations perspective, the results from Chapters 4 and 5 provide insights into how UCC usage fees and delivery quantities per stop affect the cost attractiveness of UCCs. For both factors, it can be shown that LSPs are very sensitive to their levels, as increases in UCC usage fees and delivery quantities per stop reduce the cost attractiveness of UCCs. Therefore, the commonly cited quantity- or volume-based pricing schemes make small shipments particularly attractive for the use of UCCs. Consequently, UCC operators could particularly target LSPs that deliver small quantities per delivery stop. On the other hand, this shows that other pricing mechanisms are needed to attract LSPs with higher quantities per delivery stop.

For LSPs, it was shown in Chapter 4 that integrating the decision to use UCCs into the vehicle routing is superior to the usual approach in the literature of either transshipping all or nothing. The results of the real-world study in Appendix 4.B of Chapter 4 illustrate that in many cases it is advantageous to make the decision to use UCCs individually for each customer request. LSPs could thus reduce their transport costs by evaluating for which customer requests it is cost-effective to use a UCC. Another aspect, which is made clear in Chapter 4, is the potential cost advantages of employing a heterogeneous fleet. This does not necessarily apply only to the context of UCCs, but to urban freight transport in general. Related to this, local administrations could also use the results and proposed methodology to evaluate how different regulations affect the fleet composition of

LSPs in urban freight transport in order to promote the adoption of more environmentally friendly vehicles. Lastly, multiple trips per vehicle per day also seems to be a promising approach for LSPs to better utilize vehicles and drivers and to reduce transport cost.

6.3 Research Limitations

The research presented in this dissertation is subject to a number of limitations, which are discussed hereafter in this section. The first limitation stems from the considered type of UCC and industry. The overview of the categorization options of UCCs in Subsection 2.2.3 of Chapter 2 illustrates that there is a fair amount of heterogeneity in terms of the type and design of UCCs. In this dissertation, the focus is limited to urban freight transport serving the retail sector and UCCs serving a city or urban area. Furthermore, only LSPs are considered as customers of UCCs. Thus, the research represents only a part of urban freight transport and the practice of UCCs. Specifics from other industries (e.g., hotels, restaurants, and cafés (HoReCa)) and other UCC business models (e.g., single-site UCCs or UCCs that focus on receivers as customers) are thus not covered.

Another limitation concerns the ability to generalize the research findings. Whereas the conceptual simulation model presented in Chapter 3, and the problem formulation and solution approaches of Chapters 4 and 5 are not bound to a specific city or context, the findings regarding RQ 4, i.e., the influencing factors, are. Despite the use of real-world data and the analysis of real cities from three countries, the findings may not be valid for any UCC and city. To begin with, the real-world studies presented in this dissertation are limited to European cities. One reason for this is that UCCs have so far been implemented almost exclusively in Europe. Moreover, countries in Europe share certain similarities in terms of their legislation, economy, and infrastructure. For other regions, as for example emerging economies, the circumstances related to urban freight transport may be very different. This includes, for example, the infrastructure of urban regions, the type and operations of freight transport, and the supply of retailers. In addition, cost factors, which refer to the situation in Europe in this dissertation, might play an important role. In Europe, for example, driver salaries in urban freight transport, in particular, account for a high proportion of transport costs and consequently also influence the cost attractiveness of UCCs. In emerging economies, lower levels of driver salaries might affect the cost attractiveness of UCCs differently. Next, it is important to note that even among cities in Europe, there can be significant differences in terms of size, transport structure, and geography. For example, the transport infrastructure of cities with historic old towns can differ greatly from those without. Chapter 5 attempts to address this issue by examining three cities with random selections of retail locations. However, as the number of study areas increases, so does the complexity and the required computational effort.

Another limitation stems from the consideration of the cost attractiveness of UCCs itself. Following the literature on evaluating UCCs, the research in this dissertation places its focus on the cost savings that LSPs can achieve by using UCCs as an indicator to estimate the use of UCCs. In this, LSPs are assumed to be rational decision-makers that if the UCC offers cost reductions and matches their desired service level would choose to use it. However, in reality, perfect rationality of decisions might not be given and other factors might influence the decision to use UCCs, as well. The psychological barriers concerning the use of UCCs, briefly reviewed in Subsection 2.2.4, indicate that indeed other factors also influence the decision of LSPs to use UCCs. However, these psychological factors are not easily quantifiable and modeled in decision support models. The focus in this dissertation is therefore only on the cost attractiveness of UCCs.

6.4 Future Research

Closely related to the limitations, are the possibilities for future research. An area for future research pertains to the different types of UCCs and sectors of urban freight transport. Research on specialized UCCs, such as construction UCCs or UCCs for perishable goods is still comparatively scarce. However, considering the requirements of these sectors and their goods in the analysis of UCCs could provide guidance for future UCC business models.

Based on the fact that the focus of UCC studies is mostly on Europe and developed countries, another aspect for future research could be to expand the focus to emerging countries, taking into account their specifics regarding urban freight transport. Initial work on this has already been done by Kin et al. (2018), for example.

Another aspect for future research pertains to the inclusion of non-monetary aspects, such as psychological barriers or emissions, into the evaluation of UCCs. As described in the previous subsection, the prevailing focus of quantitative models is on the cost attractiveness of UCCs. In future evaluation approaches, multi-criteria approaches could be devised to broaden the focus to include these non-monetary factors.

Looking at the integrated VRPs from Chapters 4 and 5, further extensions and problem refinements are another promising research direction. The problems and algorithms could consider, for example, congestion and time-dependent travel times that were discussed in Subsection 2.3.3. Furthermore, the objective functions could be extended to include the externalities of urban freight transport as reviewed in Subsection 2.3.1. Finally, another aspect concerns the consideration of uncertainties. To this end, planning procedures could be developed to take into account uncertainties regarding travel and unloading times or available capacities at the UCCs.

Bibliography

Agence de l'Environnement et de la Maîtrise de l'Énergie (2004). *Espaces Logistiques Urbains de Monaco et La Rochelle. Analyse comparative des systèmes logistiques rochelais et monégasques*. URL: https://www.ademe.fr/sites/default/files/assets/documents/29229_analyse_comparative_elu_tome2.pdf.

Akca, Z., R. T. Berger, and T. K. Ralphs (2009). "A Branch-and-Price Algorithm for Combined Location and Routing Problems Under Capacity Restrictions". In: *Operations Research and Cyber-Infrastructure*. Ed. by J. W. Chinneck, B. Kristjansson, and M. J. Saltzman. Boston, MA: Springer US, pp. 309–330. ISBN: 978-0-387-88843-9.

Akgün, E. Z., J. Monios, and A. Fonzone (2020). "Supporting urban consolidation centres with urban freight transport policies: a comparative study of Scotland and Sweden". In: *International Journal of Logistics Research and Applications* 23.3, pp. 291–310. DOI: 10.1080/13675567.2019.1679743.

Alcaraz, J. J., L. Caballero-Arnaldos, and J. Vales-Alonso (2019). "Rich vehicle routing problem with last-mile outsourcing decisions". In: *Transportation Research Part E: Logistics and Transportation Review* 129, pp. 263–286. DOI: 10.1016/j.tre.2019.08.004.

Aljohani, K. and R. G. Thompson (2020a). "An Examination of Last Mile Delivery Practices of Freight Carriers Servicing Business Receivers in Inner-City Areas". In: *Sustainability* 12.7, p. 2837. DOI: 10.3390/su12072837.

– (2020b). "Receivers-led delivery consolidation policy: Estimating the characteristics of the most interested businesses to participate". In: *Research in Transportation Economics* 80, p. 100808. DOI: 10.1016/j.retrec.2019.100808.

Allen, J., G. Thorne, and M. Browne (2007). *BESTUFS Good Practice Guide on Urban Freight Transport*. BESTUFS.net. URL: http://www.bestufs.net/download/BESTUFS_II/good_practice/English_BESTUFS_Guide.pdf.

Allen, J., M. Browne, T. Cherrett, and F. McLeod (2008). *Review of UK urban freight studies. Green Logistics Report*. University of Westminster and University of Southampton. URL: https://westminsterresearch.westminster.ac.uk/item/91114/review-of-uk-urban-freight-studies (visited on 01/21/2021).

Allen, J., G. Tanner, M. Browne, and P. Jones (2000). *A Framework for Considering Policies to Encourage Sustainable Urban Freight Traffic and Goods/Service Flows – Summary Report*. London: University of Westminster. URL: http://home.wmin.ac.uk/transport/projects/u-d-summ.htm (visited on 01/21/2021).

Allen, J., M. Browne, A. Woodburn, and J. Leonardi (2012). "The Role of Urban Consolidation Centres in Sustainable Freight Transport". In: *Transport Reviews* 32.4, pp. 473–490. DOI: 10.1080/01441647.2012.688074.

– (2014). "A Review of Urban Consolidation Centres in the Supply Chain Based on a Case Study Approach". In: *Supply Chain Forum: An International Journal* 15.4, pp. 100–112. DOI: 10.1080/16258312.2014.11517361.

Ambrosini, C. and J.-L. Routhier (2004). “Objectives, Methods and Results of Surveys Carried out in the Field of Urban Freight Transport: An International Comparison”. In: *Transport Reviews* 24.1, pp. 57–77. DOI: 10.1080/0144164032000122343.

Anand, N., J. R. van Duin, and L. Tavasszy (2016). “Framework for Modelling Multi-stakeholder City Logistics Domain Using the Agent based Modelling Approach”. In: *Transportation Research Procedia* 16, pp. 4–15. DOI: 10.1016/j.trpro.2016.11.002.

Anand, N., R. van Duin, and L. Tavasszy (2021). “Carbon credits and urban freight consolidation: An experiment using agent based simulation”. In: *Research in Transportation Economics* 85, p. 100797. DOI: 10.1016/j.retrec.2019.100797.

Anand, N., M. Yang, J. van Duin, and L. Tavasszy (2012). “GenCLOn: An ontology for city logistics”. In: *Expert Systems with Applications* 39.15, pp. 11944–11960. DOI: 10.1016/j.eswa.2012.03.068.

Anderluh, A., P. C. Nolz, V. C. Hemmelmayr, and T. G. Crainic (2021). “Multi-objective optimization of a two-echelon vehicle routing problem with vehicle synchronization and ‘grey zone’ customers arising in urban logistics”. In: *European Journal of Operational Research* 289.3, pp. 940–958. DOI: 10.1016/j.ejor.2019.07.049.

Anderson, S., J. Allen, and M. Browne (2005). “Urban logistics—–how can it meet policy makers’ sustainability objectives?” In: *Journal of Transport Geography* 13.1, pp. 71–81. DOI: 10.1016/j.jtrangeo.2004.11.002.

Archetti, C. and M. Speranza (2014). “A survey on matheuristics for routing problems”. In: *EURO Journal on Computational Optimization* 2.4, pp. 223–246. DOI: 10.1007/s13675-014-0030-7.

Asefi, H., S. Shahparvari, and P. Chhetri (2019). “Integrated Municipal Solid Waste Management under uncertainty: A tri-echelon city logistics and transportation context”. In: *Sustainable Cities and Society* 50, p. 101606. DOI: 10.1016/j.scs.2019.101606.

Azi, N., M. Gendreau, and J.-Y. Potvin (2014). “An adaptive large neighborhood search for a vehicle routing problem with multiple routes”. In: *Computers & Operations Research* 41, pp. 167–173. DOI: 10.1016/j.cor.2013.08.016.

Baldacci, R., A. Mingozzi, and R. Roberti (2012). “Recent exact algorithms for solving the vehicle routing problem under capacity and time window constraints”. In: *European Journal of Operational Research* 218.1, pp. 1–6. DOI: 10.1016/j.ejor.2011.07.037.

Baldacci, R., S. U. Ngueveu, and R. W. Calvo (2017). “The Vehicle Routing Problem with Transhipment Facilities”. In: *Transportation Science* 51.2, pp. 592–606. DOI: 10.1287/trsc.2016.0711.

Ballantyne, E. E., M. Lindholm, and A. Whiteing (2013). “A comparative study of urban freight transport planning: addressing stakeholder needs”. In: *Journal of Transport Geography* 32.1, pp. 93–101. DOI: 10.1016/j.jtrangeo.2013.08.013.

Balm, S., M. Browne, J. Leonardi, and H. J. Quak (2014). “Developing an Evaluation Framework for Innovative Urban and Interurban Freight Transport Solutions”. In: *Procedia - Social and Behavioral Sciences* 125, pp. 386–397. DOI: 10.1016/j.sbspro.2014.01.1482.

Battaia, G., L. Faure, G. Marqués, R. Guillaume, and J. R. Montoya-Torres (2014). “A Methodology to Anticipate the Activity Level of Collaborative Networks: The Case of Urban Consolidation”. In: *Supply Chain Forum: An International Journal* 15.4, pp. 70–82.

Battarra, M., M. Monaci, and D. Vigo (2009). “An adaptive guidance approach for the heuristic solution of a minimum multiple trip vehicle routing problem”. In: *Computers & Operations Research* 36.11, pp. 3041–3050. DOI: 10.1016/j.cor.2009.02.008.

Behnke, M., T. Kirschstein, and C. Bierwirth (2021). “A column generation approach for an emission-oriented vehicle routing problem on a multigraph”. In: *European Journal of Operational Research* 288.3, pp. 794–809. doi: 10.1016/j.ejor.2020.06.035.

Bektaş, T. and G. Laporte (2011). “The Pollution-Routing Problem”. In: *Transportation Research Part B: Methodological* 45.8, pp. 1232–1250. doi: 10.1016/j.trb.2011.02.004.

Bell, W. J., L. M. Dalberto, M. L. Fisher, A. J. Greenfield, R. Jaikumar, P. Kedia, R. G. Mack, and P. J. Prutzman (1983). “Improving the Distribution of Industrial Gases with an On-Line Computerized Routing and Scheduling Optimizer”. In: *Interfaces* 13.6, pp. 4–23. doi: 10.1287/inte.13.6.4.

Ben Ticha, H., N. Absi, D. Feillet, and A. Quilliot (2017). “Empirical analysis for the VRPTW with a multigraph representation for the road network”. In: *Computers & Operations Research* 88, pp. 103–116. doi: 10.1016/j.cor.2017.06.024.

– (2018). “Vehicle routing problems with road-network information: State of the art”. In: *Networks* 72.3, pp. 393–406. doi: 10.1002/net.21808.

– (2019a). “Multigraph modeling and adaptive large neighborhood search for the vehicle routing problem with time windows”. In: *Computers & Operations Research* 104, pp. 113–126. doi: 10.1016/j.cor.2018.11.001.

Ben Ticha, H., N. Absi, D. Feillet, A. Quilliot, and T. van Woensel (2019b). “A branch–and–price algorithm for the vehicle routing problem with time windows on a road network”. In: *Networks* 73.4, pp. 401–417. doi: 10.1002/net.21852.

Bertrand, J. W. M. and J. C. Fransoo (2002). “Operations management research methodologies using quantitative modeling”. In: *International Journal of Operations & Production Management* 22.2, pp. 241–264. doi: 10.1108/01443570210414338.

Björklund, M., M. Abrahamsson, and H. Johansson (2017). “Critical factors for viable business models for urban consolidation centres”. In: *Research in Transportation Economics* 64, pp. 36–47. doi: 10.1016/j.retrec.2017.09.009.

Björklund, M. and H. Johansson (2018). “Urban consolidation centre – a literature review, categorisation, and a future research agenda”. In: *International Journal of Physical Distribution & Logistics Management* 48.8, pp. 745–764. doi: 10.1108/IJPDLM-01-2017-0050.

Blanco, E. E. and J. C. Fransoo (2013). *Reaching 50 million nanostores: retail distribution in emerging megacities*. Technische Universiteit Eindhoven.

Blum, C. and A. Roli (2003). “Metaheuristics in combinatorial optimization”. In: *ACM Computing Surveys* 35.3, pp. 268–308. doi: 10.1145/937503.937505.

Boschetti, M. A., V. Maniezzo, M. Roffilli, and A. Bolufé Röhler (2009). “Matheuristics: Optimization, Simulation and Control”. In: *Hybrid metaheuristics. 6th international workshop, HM 2009, Udine, Italy, October 16 - 17, 2009 ; proceedings*. Ed. by M. J. Blesa, C. Blum, L. Di Gaspero, A. Roli, M. Sampels, and A. Schaerf. Vol. 5818. Lecture Notes in Computer Science 5818. Berlin: Springer, pp. 171–177. isbn: 978-3-642-04918-7. doi: 10.1007/978-3-642-04918-7_13.

Braekers, K., K. Ramaekers, and I. van Nieuwenhuyse (2016). “The vehicle routing problem: State of the art classification and review”. In: *Computers & Industrial Engineering* 99, pp. 300–313. doi: 10.1016/j.cie.2015.12.007.

Bräysy, O., W. Dullaert, G. Hasle, D. Mester, and M. Gendreau (2008). “An Effective Multirestart Deterministic Annealing Metaheuristic for the Fleet Size and Mix Vehicle-Routing Problem with Time Windows”. In: *Transportation Science* 42.3, pp. 371–386. doi: 10.1287/trsc.1070.0217.

Bräysy, O. and M. Gendreau (2005a). "Vehicle Routing Problem with Time Windows, Part I: Route Construction and Local Search Algorithms". In: *Transportation Science* 39.1, pp. 104–118. DOI: 10.1287/trsc.1030.0056.

– (2005b). "Vehicle Routing Problem with Time Windows, Part II: Metaheuristics". In: *Transportation Science* 39.1, pp. 119–139. DOI: 10.1287/trsc.1030.0057.

Browne, M., J. Allen, and J. Leonardi (2011). "Evaluating the use of an urban consolidation centre and electric vehicles in central London". In: *IATSS Research* 35.1, pp. 1–6. DOI: 10.1016/j.iatssr.2011.06.002.

Browne, M., J. Allen, T. Nemoto, D. Patier, and J. Visser (2012). "Reducing Social and Environmental Impacts of Urban Freight Transport: A Review of Some Major Cities". In: *Procedia - Social and Behavioral Sciences* 39, pp. 19–33. DOI: 10.1016/j.sbspro.2012.03.088.

Browne, M., M. Sweet, A. Woodburn, and J. Allen (2005). *Urban Freight Consolidation Centres*. London: University of Westminster.

Burr, W. (2012). "Zur Geschichte der deutschsprachigen Betriebswirtschaftslehre". In: *Der Verband der Hochschullehrer für Betriebswirtschaft. Geschichte des VHB und Geschichten zum VHB*. Ed. by W. Burr and A. Wagenhofer. Wiesbaden: Gabler Verlag, pp. 121–161. ISBN: 978-3-8349-7132-6. DOI: 10.1007/978-3-8349-7132-6_6.

Cattaruzza, D., N. Absi, and D. Feillet (2016). "Vehicle routing problems with multiple trips". In: *4OR* 14.3, pp. 223–259. DOI: 10.1007/s10288-016-0306-2.

– (2018). "Vehicle routing problems with multiple trips". In: *Annals of Operations Research* 271.1, pp. 127–159. DOI: 10.1007/s10479-018-2988-7.

Cattaruzza, D., N. Absi, D. Feillet, and J. González-Feliu (2017). "Vehicle routing problems for city logistics". In: *EURO Journal on Transportation and Logistics* 6.1, pp. 51–79. DOI: 10.1007/s13676-014-0074-0.

Cattaruzza, D., N. Absi, D. Feillet, and T. Vidal (2014). "A memetic algorithm for the Multi Trip Vehicle Routing Problem". In: *European Journal of Operational Research* 236.3, pp. 833–848. DOI: 10.1016/j.ejor.2013.06.012.

Chandra, P. and M. L. Fisher (1994). "Coordination of production and distribution planning". In: *European Journal of Operational Research* 72.3, pp. 503–517. DOI: 10.1016/0377-2217(94)90419-7.

Cherrett, T., J. Allen, F. McLeod, S. Maynard, A. Hickford, and M. Browne (2012). "Understanding urban freight activity – key issues for freight planning". In: *Journal of Transport Geography* 24.1, pp. 22–32. DOI: 10.1016/j.jtrangeo.2012.05.008.

Christiaens, J. and G. Vanden Berghe (2020). "Slack Induction by String Removals for Vehicle Routing Problems". In: *Transportation Science* 54.2, pp. 417–433. DOI: 10.1287/trsc.2019.0914.

Churchill, K. (2014). *A Public Sector Perspective on Consolidation-London Boroughs Consolidation Centre*. URL: https://www.urbantransportgroup.org/system/files/general-docs/Kevin%20Churchill.pdf (visited on 10/02/2021).

Ciardiello, F., A. Genovese, S. Luo, and A. Sgalambro (2021). "A game-theoretic multi-stakeholder model for cost allocation in urban consolidation centres". In: *Annals of Operations Research* 75.4, p. 88. DOI: 10.1007/s10479-021-04013-3.

Città di Vicenza (2007). *Inaugurata la sede del V.E.L.O.C.E.* URL: https://www.comune.vicenza.it/albo/notizie.php/50171 (visited on 08/30/2021).

Clarke, G. and J. W. Wright (1964). “Scheduling of Vehicles from a Central Depot to a Number of Delivery Points”. In: *Operations Research* 12.4, pp. 568–581. DOI: 10.1287/opre.12.4.568.

Cleophas, C., C. Cottrill, J. F. Ehmke, and K. Tierney (2019). “Collaborative urban transportation: Recent advances in theory and practice”. In: *European Journal of Operational Research* 273.3, pp. 801–816. DOI: 10.1016/j.ejor.2018.04.037.

Comune di Milano (2021). *Area C*. URL: https://www.comune.milano.it/aree-tematiche/mobilita/area-c (visited on 01/13/2021).

Contardo, C., V. Hemmelmayr, and T. G. Crainic (2012). “Lower and upper bounds for the two-echelon capacitated location-routing problem”. In: *Computers & Operations Research* 39.12, pp. 3185–3199. DOI: 10.1016/j.cor.2012.04.003.

Cordeau, J.-F., G. Desaulniers, J. Desrosiers, M. M. Solomon, and F. Soumis (2002). “7. VRP with Time Windows”. In: *The vehicle routing problem*. Ed. by P. Toth and D. Vigo. SIAM monographs on discrete mathematics and applications. Philadelphia, Pa.: Society for Industrial and Applied Mathematics, pp. 157–193. ISBN: 978-0-89871-498-2. DOI: 10.1137/1.9780898718515.ch7.

Coulombel, N., L. Dablanc, M. Gardrat, and M. Koning (2018). “The environmental social cost of urban road freight: Evidence from the Paris region”. In: *Transportation Research Part D: Transport and Environment* 63.1, pp. 514–532. DOI: 10.1016/j.trd.2018.06.002.

Crainic, T. G., N. Ricciardi, and G. Storchi (2009). “Models for Evaluating and Planning City Logistics Systems”. In: *Transportation Science* 43.4, pp. 432–454.

Cuda, R., G. Guastaroba, and M. G. Speranza (2015). “A survey on two-echelon routing problems”. In: *Computers & Operations Research* 55, pp. 185–199. DOI: 10.1016/j.cor.2014.06.008.

Dablanc, L. (2008). “Urban Goods Movement and Air Quality Policy and Regulation Issues in European Cities”. In: *Journal of Environmental Law* 20.2, pp. 245–266. DOI: 10.1093/jel/eqn005.

Danielis, R., L. Rotaris, and E. Marcucci (2010). “Urban freight policies and distribution channels: a discussion based on evidence from Italian cities”. In: *European Transport \ Trasporti Europei* 46.XVI, pp. 114–146. URL: http://hdl.handle.net/10077/6169.

Dantzig, G. B. and J. H. Ramser (1959). “The Truck Dispatching Problem”. In: *Management Science* 6.1, pp. 80–91. DOI: 10.1287/mnsc.6.1.80.

De Carvalho, N. L. A., P. C. C. Ribeiro, C. García-Martos, C. G. Fernández, and J. G. V. Vieira (2019). “Urban distribution centres in historical cities from the perspective of residents, retailers and carriers”. In: *Research in Transportation Economics* 77, p. 100744. DOI: 10.1016/j.retrec.2019.100744.

Demir, E., T. Bektaş, and G. Laporte (2012). “An adaptive large neighborhood search heuristic for the Pollution-Routing Problem”. In: *European Journal of Operational Research* 223.2, pp. 346–359. DOI: 10.1016/j.ejor.2012.06.044.

– (2014). “A review of recent research on green road freight transportation”. In: *European Journal of Operational Research* 237.3, pp. 775–793. DOI: 10.1016/j.ejor.2013.12.033.

Department for Transport (2019). *Domestic Road Freight Statistics, United Kingdom 2018*. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815839/domestic-road-freight-statistics-2018.pdf (visited on 09/07/2021).

Desaulniers, G., O. B. Madsen, and S. Ropke (2014). “Chapter 5: The Vehicle Routing Problem with Time Windows”. In: *The vehicle routing problem. Problems, methods, and applications*. Ed. by P. Toth. 2. ed. MOS-SIAM series on optimization. Philadelphia, Pa.: SIAM, pp. 119–159. ISBN: 978-1-61197-359-4. DOI: 10.1137/1.9781611973594.ch5.

Dolati Neghabadi, P., K. Evrard Samuel, and M.-L. Espinouse (2019). “Systematic literature review on city logistics: overview, classification and analysis”. In: *International Journal of Production Research* 57.3, pp. 865–887. DOI: 10.1080/00207543.2018.1489153.

Domschke, W., A. Drexl, R. Klein, and A. Scholl (2015). *Einführung in Operations Research*. 9., überarbeitete und verbesserte Auflage. Berlin and Heidelberg: Springer Gabler. ISBN: 978-3-662-48216-2.

Domschke, W. and A. Scholl (2008). *Grundlagen der Betriebswirtschaftslehre. Eine Einführung aus entscheidungsorientierter Sicht*. Vierte, verbesserte und aktualisierte Auflage. Springer-Lehrbuch. Berlin: Springer. ISBN: 9783540850779.

Douglas, M., T. Schubert, and T. Schuhmacher (2020). *Urbane Logistik – Herausforderungen für Kommunen. Auswertung und Ergebnisbericht einer Online-Befragung*. Dessau-Roßlau: Umweltbundesamt. URL: https://www.umweltbundesamt.de/publikationen/urbane-logistik-herausforderungen-fuer-kommunen (visited on 09/07/2021).

Drexl, M. (2012). “Rich vehicle routing in theory and practice”. In: *Logistics Research* 5.1-2, pp. 47–63. DOI: 10.1007/s12159-012-0080-2.

Ducret, R. (2014). “Parcel Deliveries and Urban Logistics: Changes and Challenges in the Courier Express and Parcel Sector in Europe — The French Case”. In: *Research in Transportation Business & Management* 11, pp. 15–22.

Dueck, G. (1993). “New Optimization Heuristics”. In: *Journal of Computational Physics* 104.1, pp. 86–92. DOI: 10.1006/jcph.1993.1010.

Dueck, G. and T. Scheuer (1990). “Threshold accepting: A general purpose optimization algorithm appearing superior to simulated annealing”. In: *Journal of Computational Physics* 90.1, pp. 161–175. DOI: 10.1016/0021-9991(90)90201-B.

Dumez, D., F. Lehuédé, and O. Péton (2021a). “A large neighborhood search approach to the vehicle routing problem with delivery options”. In: *Transportation Research Part B: Methodological* 144.1, pp. 103–132. DOI: 10.1016/j.trb.2020.11.012.

Dumez, D., C. Tilk, S. Irnich, F. Lehuédé, and O. Péton (2021b). “Hybridizing Large Neighborhood Search and Exact Methods for Generalized Vehicle Routing Problems with Time Windows (Revision 2)”. In: *EURO Journal on Transportation and Logistics* 86.1, p. 100040. DOI: 10.1016/j.ejtl.2021.100040.

Durham County Council (2020). *Durham Road User Charge Zone (congestion charge)*. URL: https://www.durham.gov.uk/article/3437/Durham-Road-User-Charge-Zone-congestion-charge (visited on 10/14/2020).

Dye, T. R. (2017). *Understanding public policy*. Fifteenth edition. Boston et al.: Pearson. ISBN: 0134169972.

Egger, D. and M. Ruesch (2002). *BESTUFS Best Practice Handbook Year 3 (2002). Road pricing and urban freight transport Urban freight platforms*. Ed. by BESTUFS.net. URL: www.bestufs.net (visited on 09/07/2021).

Ehmke, J. F., A. M. Campbell, and B. W. Thomas (2018). “Optimizing for total costs in vehicle routing in urban areas”. In: *Transportation Research Part E: Logistics and Transportation Review* 116, pp. 242–265. DOI: 10.1016/j.tre.2018.06.008.

Ehmke, J. F., A. M. Campbell, and B. W. Thomas (2016). “Vehicle routing to minimize time-dependent emissions in urban areas”. In: *European Journal of Operational Research* 251.2, pp. 478–494. DOI: 10.1016/j.ejor.2015.11.034.

Elbert, R. and C. Friedrich (2018a). “Simulation-based Evaluation of Urban Consolidation Centers Considering Urban Access Regulations”. In: *2018 Winter Simulation Conference (WSC)*. Ed. by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson. [Piscataway, NJ]: IEEE, pp. 2827–2838. ISBN: 978-1-5386-6572-5. DOI: 10.1109/WSC.2018.8632356.

– (2018b). “Urban Consolidation Centres”. In: *WiSt - Wirtschaftswissenschaftliches Studium* 47.12, pp. 57–59. DOI: 10.15358/0340-1650-2018-12-57.

Elshaer, R. and H. Awad (2020). “A taxonomic review of metaheuristic algorithms for solving the vehicle routing problem and its variants”. In: *Computers & Industrial Engineering* 140, p. 106242. DOI: 10.1016/j.cie.2019.106242.

Enthoven, D. L., B. Jargalsaikhan, K. J. Roodbergen, M. A. J. uit het Broek, and A. H. Schrotenboer (2020). “The two-echelon vehicle routing problem with covering options: City logistics with cargo bikes and parcel lockers”. In: *Computers & Operations Research* 118, p. 104919. DOI: 10.1016/j.cor.2020.104919.

Eren Akyol, D. and R. B. de Koster (2018). “Determining time windows in urban freight transport: A city cooperative approach”. In: *Transportation Research Part E: Logistics and Transportation Review* 118, pp. 34–50. DOI: 10.1016/j.tre.2018.07.004.

Estrada, M. and M. Roca-Riu (2017). “Stakeholder’s Profitability of Carrier-led Consolidation Strategies in Urban Goods Distribution”. In: *Transportation Research Part E: Logistics and Transportation Review* 104, pp. 165–188.

European Commission, Directorate General for Mobility and Transport (2019). *EU transport in figures 2019*. EU transport in figures. Statistical pocketbook. Luxembourg: Publications office of the European Union. ISBN: 978-92-76-03842-9.

EuroTransportMedia Verlags- und Veranstaltungs-GmbH (2017). *lastauto omnibus Katalog 2018*. EuroTransportMedia Verlags- und Veranstaltungs-GmbH.

Figliozzi, M. A. (2010). “The impacts of congestion on commercial vehicle tour characteristics and costs”. In: *Transportation Research Part E: Logistics and Transportation Review* 46.4, pp. 496–506. DOI: 10.1016/j.tre.2009.04.005.

– (2012). “The time dependent vehicle routing problem with time windows: Benchmark problems, an efficient solution algorithm, and solution characteristics”. In: *Transportation Research Part E: Logistics and Transportation Review* 48.3, pp. 616–636. DOI: 10.1016/j.tre.2011.11.006.

Firdausiyah, N., E. Taniguchi, and A. G. Qureshi (2019). “Modeling city logistics using adaptive dynamic programming based multi-agent simulation”. In: *Transportation Research Part E: Logistics and Transportation Review* 125, pp. 74–96. DOI: 10.1016/j.tre.2019.02.011.

Fleischmann, B. (1990). *The vehicle routing problem with multiple use of vehicles*. Hamburg, Germany: Fachbereich Wirtschaftswissenschaften, Universität Hamburg.

Fleischmann, B., M. Gietz, and S. Gnutzmann (2004). “Time-Varying Travel Times in Vehicle Routing”. In: *Transportation Science* 38.2, pp. 160–173. DOI: 10.1287/trsc.1030.0062.

François, V., Y. Arda, and Y. Crama (2019). “Adaptive Large Neighborhood Search for Multitrip Vehicle Routing with Time Windows”. In: *Transportation Science* 53.6, pp. 1706–1730. DOI: 10.1287/trsc.2019.0909.

François, V., Y. Arda, Y. Crama, and G. Laporte (2016). “Large neighborhood search for multi-trip vehicle routing”. In: *European Journal of Operational Research* 255.2, pp. 422–441. DOI: 10.1016/j.ejor.2016.04.065.

Friedrich, C. (2022). *Urban Consolidation Centers and City Toll Schemes – Problem Instances and Solution Summary*. last accessed: 2022-01-30. URL: https://github.com/christian-2910/UCCs-and-City-Toll-Schemes-Problem-Instances-and-Solution-Summary.

Friedrich, C. and R. Elbert (2022). "Adaptive large neighborhood search for vehicle routing problems with transshipment facilities arising in city logistics". In: *Computers & Operations Research* 137, p. 105491. DOI: 10.1016/j.cor.2021.105491.

Fülbier, R. U. (2004). "Wissenschaftstheorie und Betriebswirtschaftslehre". In: *WiSt - Wirtschaftswissenschaftliches Studium* 33.5, pp. 266–271. DOI: 10.15358/0340-1650-2004-5-266.

Garaix, T., C. Artigues, D. Feillet, and D. Josselin (2010). "Vehicle routing problems with alternative paths: An application to on-demand transportation". In: *European Journal of Operational Research* 204.1, pp. 62–75. DOI: 10.1016/j.ejor.2009.10.002.

Gendreau, M., G. Ghiani, and E. Guerriero (2015). "Time-dependent routing problems: A review". In: *Computers & Operations Research* 64, pp. 189–197. DOI: 10.1016/j.cor.2015.06.001.

Glover, F. (1986). "Future paths for integer programming and links to artificial intelligence". In: *Computers & Operations Research* 13.5, pp. 533–549. DOI: 10.1016/0305-0548(86)90048-1.

Golden, B., A. Assad, L. Levy, and F. Gheysens (1984). "The fleet size and mix vehicle routing problem". In: *Computers & Operations Research* 11.1, pp. 49–66. DOI: 10.1016/0305-0548(84)90007-8.

Gonzalez-Feliu, J., C. Pronello, and J. M. S. Grau (2018). "Multi-Stakeholder Collaboration in Urban Transport: State-of-the-Art and Research Opportunities". In: *Transport* 33.4, pp. 1079–1094. DOI: 10.3846/transport.2018.6810.

Grabenschweiger, J., K. F. Doerner, R. F. Hartl, and M. W. P. Savelsbergh (2021). "The vehicle routing problem with heterogeneous locker boxes". In: *Central European Journal of Operations Research* 29.1, pp. 113–142. DOI: 10.1007/s10100-020-00725-2.

Grubler, A., X. Bai, T. Buettner, S. Dhakal, D. Fisk, T. Ichinose, J. Keirstead, G. Sammer, D. Satterthwaite, N. Schulz, N. Shah, J. Steinberger, H. Weisz, G. Ahamer, T. Baynes, D. Curtis, M. Doherty, N. Eyre, J. Fujino, and A. Sverdlik (2012). "Urban Energy Systems". In: *Global Energy Assessment (GEA)*. Ed. by A. P. Patwardhan, L. Gomez-Echeverri, N. Nakićenović, and T. B. Johansson. Cambridge: Cambridge University Press, pp. 1307–1400. ISBN: 9780521182935. DOI: 10.1017/CBO9780511793677.024-.

Guastaroba, G., M. G. Speranza, and D. Vigo (2016). "Intermediate Facilities in Freight Transportation Planning: A Survey". In: *Transportation Science* 50.3, pp. 763–789. DOI: 10.1287/trsc.2015.0631.

Handoko, S. D., H. C. Lau, and S.-F. Cheng (2016). "Achieving Economic and Environmental Sustainabilities in Urban Consolidation Center With Bicriteria Auction". In: *IEEE Transactions on Automation Science and Engineering* 13.4, pp. 1471–1479. DOI: 10.1109/TASE.2016.2563459.

Handoko, S. D., D. T. Nguyen, and H. C. Lau (2014). "An auction mechanism for the last-mile deliveries via urban consolidation centre". In: *2014 IEEE International Conference on Automation Science and Engineering (CASE 2014). Taipei, Taiwan, 18 - 22 August 2014*. Piscataway, NJ: IEEE, pp. 607–612. ISBN: 978-1-4799-5283-0. DOI: 10.1109/CoASE.2014.6899390.

Heinen, E. (1971). "Entwicklungstendenzen in der entscheidungsorientierten Betriebswirtschaftslehre". In: *Die Unternehmung* 25.2, pp. 89–99.

– (1985). *Einführung in die Betriebswirtschaftslehre*. 9., verb. Aufl. Wiesbaden: Gabler. ISBN: 978-3-322-82929-0.

Helfrich, H. (2016). *Wissenschaftstheorie für Betriebswirtschaftler*. 1. Auflage. Wiesbaden: Springer Gabler. ISBN: 978-3-658-07036-6. DOI: 10.1007/978-3-658-07036-6.

Hernandez, F., D. Feillet, R. Giroudeau, and O. Naud (2014). "A new exact algorithm to solve the multi-trip vehicle routing problem with time windows and limited duration". In: *4OR* 12.3, pp. 235–259. DOI: 10.1007/s10288-013-0238-z.

Hernandez, F., D. Feillet, R. Giroudeau, and O. Naud (2016). "Branch-and-price algorithms for the solution of the multi-trip vehicle routing problem with time windows". In: *European Journal of Operational Research* 249.2, pp. 551–559. DOI: 10.1016/j.ejor.2015.08.040.

Hezarkhani, B., M. Slikker, and T. van Woensel (2019). "Gain-sharing in urban consolidation centers". In: *European Journal of Operational Research* 279.2, pp. 380–392. DOI: 10.1016/j.ejor.2019.05.028.

Hiermann, G., R. F. Hartl, J. Puchinger, M. Schiffer, and T. Vidal (2019). *Sustainable city logistics via access restrictions? An impact assessment of city center policies*. GERAD, HEC.

Hiermann, G., J. Puchinger, S. Ropke, and R. F. Hartl (2016). "The Electric Fleet Size and Mix Vehicle Routing Problem with Time Windows and Recharging Stations". In: *European Journal of Operational Research* 252.3, pp. 995–1018. DOI: 10.1016/j.ejor.2016.01.038.

Hoff, A., H. Andersson, M. Christiansen, G. Hasle, and A. Løkketangen (2010). "Industrial aspects and literature survey: Fleet composition and routing". In: *Computers & Operations Research* 37.12, pp. 2041–2061. DOI: 10.1016/j.cor.2010.03.015.

Holguín-Veras, J., J. Amaya Leal, I. Sanchez-Diaz, M. Browne, and J. Wojtowicz (2020). "State of the art and practice of urban freight management Part II: Financial approaches, logistics, and demand management". In: *Transportation Research Part A: Policy and Practice* 137, pp. 383–410. DOI: 10.1016/j.tra.2018.10.036.

Huang, Y., L. Zhao, T. van Woensel, and J.-P. Gross (2017). "Time-dependent vehicle routing problem with path flexibility". In: *Transportation Research Part B: Methodological* 95, pp. 169–195. DOI: 10.1016/j.trb.2016.10.013.

Hughes, S., S. Moreno, W. F. Yushimito, and G. Huerta-Cánepa (2019). "Evaluation of machine learning methodologies to predict stop delivery times from GPS data". In: *Transportation Research Part C: Emerging Technologies* 109.3, pp. 289–304. DOI: 10.1016/j.trc.2019.10.018.

Huschebeck, M. and J. Allen (2005). *BESTUFS Policy and Research Recommendations I: Urban Consolidation Centres, Last Mile Solutions*. http://www.bestufs.net. Best Urban Freight Solutions II, BESTUFS Consortium. (Visited on 09/07/2021).

Ichoua, S., M. Gendreau, and J.-Y. Potvin (2003). "Vehicle dispatching with time-dependent travel times". In: *European Journal of Operational Research* 144.2, pp. 379–396. DOI: 10.1016/S0377-2217(02)00147-9.

Institute for Operations Research and the Management Sciences (2021). *What is O.R.?* URL: https://www.informs.org/Explore/What-is-O.R.-Analytics/What-is-O.R. (visited on 08/03/2021).

Irnich, S. and G. Desaulniers (2005). "Shortest path problems with resource constraints". In: *Column Generation*. Ed. by G. Desaulniers, J. Desrosiers, and M. M. Solomon. GERAD 25th anniversary series. Boston, MA: Springer Science+Business Media Inc, pp. 33–65. ISBN: 978-0-387-25486-9.

Irnich, S., P. Toth, and D. Vigo (2014). "Chapter 1: The Family of Vehicle Routing Problems". In: *The vehicle routing problem. Problems, methods, and applications*. Ed. by P. Toth. 2. ed. MOS-SIAM

series on optimization. Philadelphia, Pa.: SIAM, pp. 1–33. ISBN: 978-1-61197-359-4. DOI: 10.1137/1.9781611973594.ch1.
Janjevic, M., D. Knoppen, and M. Winkenbach (2019). “Integrated decision-making framework for urban freight logistics policy-making”. In: *Transportation Research Part D: Transport and Environment* 72.Supplement C, pp. 333–357. DOI: 10.1016/j.trd.2019.05.006.
Janjevic, M. and A. Ndiaye (2017a). “Investigating the Financial Viability of Urban Consolidation Centre Projects”. In: *Research in Transportation Business & Management* 24, pp. 101–113.
– (2017b). “Investigating the theoretical cost-relationships of urban consolidation centres for their users”. In: *Transportation Research Part A: Policy and Practice* 102, pp. 98–118. DOI: 10.1016/j.tra.2016.10.027.
Jlassi, S., S. Tamayo, and A. Gaudron (2018). “Simulation Applied to Urban Logistics: A State of the Art”. In: *City logistics. 3: Towards sustainable and liveable cities*. Ed. by E. Taniguchi and R. G. Thompson. Systems and industrial engineering series. Hoboken, NJ and London: John Wiley & Sons Inc and ISTE Ltd, pp. 65–87. ISBN: 9781119425472. DOI: 10.1002/9781119425472.ch4.
Johansson, H. and M. Björklund (2017). “Urban consolidation centres: Retail stores’ demands for UCC services”. In: *International Journal of Physical Distribution & Logistics Management* 47.7, pp. 646–662.
Johnson, A. C., P. R. Coleman-Norton, F. C. Bourne, and C. Pharr (2003). *Ancient Roman statutes. A translation with introduction, commentary, glossary, and index*. Clark N.J.: Lawbook Exchange. ISBN: 9781584772910.
Kallehauge, B. (2008). “Formulations and exact algorithms for the vehicle routing problem with time windows”. In: *Computers & Operations Research* 35.7, pp. 2307–2330. DOI: 10.1016/j.cor.2006.11.006.
Kiba-Janiak, M. (2017). “Urban freight transport in city strategic planning”. In: *Research in Transportation Business & Management* 24, pp. 4–16. DOI: 10.1016/j.rtbm.2017.05.003.
Kin, B., J. Spoor, S. Verlinde, C. Macharis, and T. van Woensel (2018). “Modelling alternative distribution set-ups for fragmented last mile transport: Towards more efficient and sustainable urban freight transport”. In: *Case Studies on Transport Policy* 6.1, pp. 125–132. DOI: 10.1016/j.cstp.2017.11.009.
Kin, B., S. Verlinde, and C. Macharis (2017). “Sustainable urban freight transport in megacities in emerging markets”. In: *Sustainable Cities and Society* 32.2, pp. 31–41. DOI: 10.1016/j.scs.2017.03.011.
Kin, B., S. Verlinde, T. van Lier, and C. Macharis (2016). “Is there Life After Subsidy for an Urban Consolidation Centre? An Investigation of the Total Costs and Benefits of a Privately-initiated Concept”. In: *Transportation Research Procedia* 12, pp. 357–369. DOI: 10.1016/j.trpro.2016.02.072.
Koç, Ç., T. Bektaş, O. Jabali, and G. Laporte (2014). “The fleet size and mix pollution-routing problem”. In: *Transportation Research Part B: Methodological* 70, pp. 239–254. DOI: 10.1016/j.trb.2014.09.008.
– (2015). “A hybrid evolutionary algorithm for heterogeneous fleet vehicle routing problems with time windows”. In: *Computers & Operations Research* 64, pp. 11–27. DOI: 10.1016/j.cor.2015.05.004.

Koç, Ç., T. Bektaş, O. Jabali, and G. Laporte (2016a). "The fleet size and mix location-routing problem with time windows: Formulations and a heuristic algorithm". In: *European Journal of Operational Research* 248.1, pp. 33–51. DOI: 10.1016/j.ejor.2015.06.082.

– (2016b). "The impact of depot location, fleet composition and routing on emissions in city logistics". In: *Transportation Research Part B: Methodological* 84, pp. 81–102. DOI: 10.1016/j.trb.2015.12.010.

– (2016c). "Thirty years of heterogeneous vehicle routing". In: *European Journal of Operational Research* 249.1, pp. 1–21. DOI: 10.1016/j.ejor.2015.07.020.

Köhler, U. (2004). "New Ideas for the City-Logistics Project in Kassel". In: *Logistics systems for sustainable cities: Proceedings of the 3rd International Conference on City Logistics (Madeira, Portugal, 25-27 June, 2003)*. Ed. by E. Taniguchi and R. G. Thompson. Amsterdam and Boston: Elsevier, pp. 321–332. ISBN: 978-0-08-047322-2.

Lagorio, A., R. Pinto, and R. Golini (2016). "Research in urban logistics: a systematic literature review". In: *International Journal of Physical Distribution & Logistics Management* 46.10, pp. 908–931. DOI: 10.1108/IJPDLM-01-2016-0008.

Lahyani, R., M. Khemakhem, and F. Semet (2015). "Rich vehicle routing problems: From a taxonomy to a definition". In: *European Journal of Operational Research* 241.1, pp. 1–14. DOI: 10.1016/j.ejor.2014.07.048.

Lai, D. S., O. Caliskan Demirag, and J. M. Leung (2016). "A tabu search heuristic for the heterogeneous vehicle routing problem on a multigraph". In: *Transportation Research Part E: Logistics and Transportation Review* 86, pp. 32–52. DOI: 10.1016/j.tre.2015.12.001.

Laporte, G. (2009). "Fifty Years of Vehicle Routing". In: *Transportation Science* 43.4, pp. 408–416. DOI: 10.1287/trsc.1090.0301.

Laporte, G., S. Ropke, and T. Vidal (2014). "Chapter 4: Heuristics for the Vehicle Routing Problem". In: *The vehicle routing problem. Problems, methods, and applications*. Ed. by P. Toth. 2. ed. MOS-SIAM series on optimization. Philadelphia, Pa.: SIAM, pp. 87–116. ISBN: 978-1-61197-359-4. DOI: 10.1137/1.9781611973594.ch4.

Lebeau, P., C. de Cauwer, J. van Mierlo, C. Macharis, W. Verbeke, and T. Coosemans (2015). "Conventional, Hybrid, or Electric Vehicles: Which Technology for an Urban Distribution Centre?" In: *TheScientificWorldJournal* 2015, p. 302867. DOI: 10.1155/2015/302867.

Lebeau, P., C. Macharis, J. van Mierlo, and M. Janjevic (2018). "Improving policy support in city logistics: The contributions of a multi-actor multi-criteria analysis". In: *Case Studies on Transport Policy* 6.4, pp. 554–563. DOI: 10.1016/j.cstp.2018.07.003.

Lebeau, P., S. Verlinde, C. Macharis, and J. van Mierlo (2017). "How can authorities support urban consolidation centres? A review of the accompanying measures". In: *Journal of Urbanism: International Research on Placemaking and Urban Sustainability* 10.4, pp. 468–486. DOI: 10.1080/17549175.2017.1310747.

Leonardi, J., M. Browne, and J. Allen (2012). "Before-After Assessment of a Logistics Trial with Clean Urban Freight Vehicles: A Case Study in London". In: *Procedia - Social and Behavioral Sciences* 39, pp. 146–157. DOI: 10.1016/j.sbspro.2012.03.097.

Letchford, A. N., S. D. Nasiri, and A. Oukil (2014). "Pricing routines for vehicle routing with time windows on road networks". In: *Computers & Operations Research* 51, pp. 331–337. DOI: 10.1016/j.cor.2014.06.022.

Letnik, T., M. Marksel, G. Luppino, A. Bardi, and S. Božičnik (2018). “Review of policies and measures for sustainable and energy efficient urban transport”. In: *Energy* 163, pp. 245–257. DOI: 10.1016/j.energy.2018.08.096.

Lin, S. (1965). “Computer Solutions of the Traveling Salesman Problem”. In: *Bell System Technical Journal* 44.10, pp. 2245–2269. DOI: 10.1002/j.1538-7305.1965.tb04146.x.

Lindholm, M. (2012). “How Local Authority Decision Makers Address Freight Transport in the Urban Area”. In: *Procedia - Social and Behavioral Sciences* 39, pp. 134–145.

– (2013). “Urban freight transport from a local authority perspective – a literature review”. In: *European Transport \ Trasporti Europei* 54.3.

Lindholm, M. E. and M. Blinge (2014). “Assessing knowledge and awareness of the sustainable urban freight transport among Swedish local authority policy planners”. In: *Transport Policy* 32, pp. 124–131. DOI: 10.1016/j.tranpol.2014.01.004.

Liu, F.-H. and S.-Y. Shen (1999). “The Fleet Size and Mix Vehicle Routing Problem with Time Windows”. In: *Journal of the Operational Research Society* 50.7, pp. 721–732. DOI: 10.2307/3010326.

López-Ibáñez, M., J. Dubois-Lacoste, L. Pérez Cáceres, M. Birattari, and T. Stützle (2016). “The irace package: Iterated racing for automatic algorithm configuration”. In: *Operations Research Perspectives* 3, pp. 43–58. DOI: 10.1016/j.orp.2016.09.002.

Lundesjö, G. (2019). “Consolidation centres in construction logistics”. In: *Urban logistics. Management, policy and innovation in a rapidly changing environment*. Ed. by M. Browne. London and New York: Kogan Page Limited, pp. 210–230. ISBN: 9780749478711.

Luxen, D. and C. Vetter (2011). “Real-time routing with OpenStreetMap data”. In: *Proceedings of the 19th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*. GIS ’11. New York, NY, USA: ACM, pp. 513–516. ISBN: 978-1-4503-1031-4. DOI: 10.1145/2093973.2094062.

Macharis, C. and B. Kin (2017). “The 4 A’s of sustainable city distribution: Innovative solutions and challenges ahead”. In: *International Journal of Sustainable Transportation* 11.2, pp. 59–71. DOI: 10.1080/15568318.2016.1196404.

Maggi, E. and E. Vallino (2016). “Understanding Urban Mobility and the Impact of Public Policies: The Role of the Agent-based Models”. In: *Research in Transportation Economics* 55, pp. 50–59.

Mancini, S. and M. Gansterer (2021). “Vehicle routing with private and shared delivery locations”. In: *Computers & Operations Research* 133.1, p. 105361. DOI: 10.1016/j.cor.2021.105361.

Maniezzo, V., M. A. Boschetti, and T. Stützle (2021). *Matheuristics*. Cham: Springer International Publishing. DOI: 10.1007/978-3-030-70277-9.

Marcucci, E. and R. Danielis (2008). “The potential demand for a urban freight consolidation centre”. In: *Transportation* 35.2, pp. 269–284. DOI: 10.1007/s11116-007-9147-3.

McDermott, D. R. (1975). “An Alternative Framework for Urban Goods Distribution: Consolidation”. In: *Transportation Journal* 15.1, pp. 29–39. URL: http://www.jstor.org/stable/20712349.

MDS Transmodal Limited (2012). *DG MOVE European Commission: Study on Urban Freight Transport*. Chester, UK.

Mepparambath, R. M., L. Cheah, and C. Courcoubetis (2021). “A theoretical framework to evaluate the traffic impact of urban freight consolidation centres”. In: *Transportation Research Part E: Logistics and Transportation Review* 145.4, p. 102134. DOI: 10.1016/j.tre.2020.102134.

Mirhedayatian, S. M. and S. Yan (2018). “A framework to evaluate policy options for supporting electric vehicles in urban freight transport”. In: *Transportation Research Part D: Transport and Environment* 58, pp. 22–38. DOI: 10.1016/j.trd.2017.11.007.

Mladenović, N. and P. Hansen (1997). “Variable neighborhood search”. In: *Computers & Operations Research* 24.11, pp. 1097–1100. DOI: 10.1016/S0305-0548(97)00031-2.

Moghdani, R., K. Salimifard, E. Demir, and A. Benyettou (2021). “The green vehicle routing problem: A systematic literature review”. In: *Journal of Cleaner Production* 279, p. 123691. DOI: 10.1016/j.jclepro.2020.123691.

Morganti, E. and J. Gonzalez-Feliu (2015). “City Logistics for Perishable Products. The Case of the Parma’s Food Hub”. In: *Case Studies on Transport Policy* 3.2, pp. 120–128.

Muñuzuri, J., J. Larrañeta, L. Onieva, and P. Cortés (2005). “Solutions applicable by local administrations for urban logistics improvement”. In: *Cities* 22.1, pp. 15–28. DOI: 10.1016/j.cities.2004.10.003.

Nagata, Y. and O. Bräysy (2009). “A powerful route minimization heuristic for the vehicle routing problem with time windows”. In: *Operations Research Letters* 37.5, pp. 333–338. DOI: 10.1016/j.orl.2009.04.006.

Nagata, Y., O. Bräysy, and W. Dullaert (2010). “A penalty-based edge assembly memetic algorithm for the vehicle routing problem with time windows”. In: *Computers & Operations Research* 37.4, pp. 724–737. DOI: 10.1016/j.cor.2009.06.022.

Nataraj, S., D. Ferone, C. Quintero-Araujo, A. A. Juan, and P. Festa (2019). “Consolidation centers in city logistics: A cooperative approach based on the location routing problem”. In: *International Journal of Industrial Engineering Computations*, pp. 393–404. DOI: 10.5267/j.ijiec.2019.1.001.

Neira, D. A., M. M. Aguayo, R. de La Fuente, and M. A. Klapp (2020). “New compact integer programming formulations for the multi-trip vehicle routing problem with time windows”. In: *Computers & Industrial Engineering* 144, p. 106399. DOI: 10.1016/j.cie.2020.106399.

Nemoto, T. (1997). “Area-wide inter-carrier consolidation of freight in urban areas”. In: *Transport Logistics* 1.2, pp. 87–101. DOI: 10.1163/156857097300151624.

Nguyen, V.-P., C. Prins, and C. Prodhon (2012). “Solving the two-echelon location routing problem by a GRASP reinforced by a learning process and path relinking”. In: *European Journal of Operational Research* 216.1, pp. 113–126. DOI: 10.1016/j.ejor.2011.07.030.

Nolz, P. C. (2021). “Optimizing construction schedules and material deliveries in city logistics: a case study from the building industry”. In: *Flexible Services and Manufacturing Journal* 33.3, pp. 846–878. DOI: 10.1007/s10696-020-09391-7.

Nordtømme, M. E., K. Y. Bjerkan, and A. B. Sund (2015). “Barriers to Urban Freight Policy Implementation: The Case of Urban Consolidation Center in Oslo”. In: *Transport Policy* 44, pp. 179–186.

Nuzzolo, A., A. Comi, A. Ibeas, and J. L. Moura (2016). “Urban freight transport and city logistics policies: Indications from Rome, Barcelona, and Santander”. In: *International Journal of Sustainable Transportation* 10.6, pp. 552–566. DOI: 10.1080/15568318.2015.1014778.

OECD (2003). *Delivering the Goods – 21st Century Challenges to Urban Goods Transport*. Paris: Organisation for Economic Co-operation and Development. URL: https://www.itf-oecd.org/delivering-goods-21st-century-challenges-urban-goods-transport (visited on 09/07/2021).

Ogden, K. W. (1992). *Urban Goods Movement: A Guide to Policy and Planning*. Aldershot: Ashgate. ISBN: 1857420292.

Olivera, A. and O. Viera (2007). “Adaptive memory programming for the vehicle routing problem with multiple trips”. In: *Computers & Operations Research* 34.1, pp. 28–47. DOI: 10.1016/j.cor.2005.02.044.

Olsson, J. and J. Woxenius (2014). “Localisation of freight consolidation centres serving small road hauliers in a wider urban area: Barriers for more efficient freight deliveries in Gothenburg”. In: *Journal of Transport Geography* 34, pp. 25–33.

Or, I. (1976). “Traveling Salesman-type Combinatorial Problems and Their Relation to the Logistics of Regional Blood Banking”. Department of Industrial Engineering and Management. Unpublished doctoral thesis. Evanston, IL: Northwestern University.

Orenstein, I., T. Raviv, and E. Sadan (2019). “Flexible parcel delivery to automated parcel lockers: models, solution methods and analysis”. In: *EURO Journal on Transportation and Logistics* 8.5, pp. 683–711. DOI: 10.1007/s13676-019-00144-7.

Osman, I. H. and G. Laporte (1996). “Metaheuristics: A bibliography”. In: *Annals of Operations Research* 63.5, pp. 511–623. DOI: 10.1007/BF02125421.

Ozbaygin, G., O. Ekin Karasan, M. Savelsbergh, and H. Yaman (2017). “A branch-and-price algorithm for the vehicle routing problem with roaming delivery locations”. In: *Transportation Research Part B: Methodological* 100, pp. 115–137. DOI: 10.1016/j.trb.2017.02.003.

Paddeu, D. (2017). “The Bristol-Bath Urban freight Consolidation Centre from the perspective of its users”. In: *Case Studies on Transport Policy* 5.3, pp. 483–491.

Paddeu, D., G. Parkhurst, G. Fancello, P. Fadda, and M. Ricci (2018). “Multi-Stakeholder Collaboration in Urban Freight Consolidation Schemes: Drivers and Barriers to Implementation”. In: *Transport* 33.4, pp. 913–929. DOI: 10.3846/transport.2018.6593.

Pan, B., Z. Zhang, and A. Lim (2021). “Multi-trip time-dependent vehicle routing problem with time windows”. In: *European Journal of Operational Research* 291.1, pp. 218–231. DOI: 10.1016/j.ejor.2020.09.022.

Panero, M. A., H.-S. Shin, and D. P. Lopez (2011). *Urban Distribution Centers – A Means to Reducing Freight Vehicle Miles Traveled*. New York: New York University. URL: https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-08-23_0.pdf (visited on 09/07/2021).

Penna, P. H. V., A. Subramanian, and L. S. Ochi (2013). “An Iterated Local Search heuristic for the Heterogeneous Fleet Vehicle Routing Problem”. In: *Journal of Heuristics* 19.2, pp. 201–232. DOI: 10.1007/s10732-011-9186-y.

Penna, P. H. V., A. Subramanian, L. S. Ochi, T. Vidal, and C. Prins (2019). “A hybrid heuristic for a broad class of vehicle routing problems with heterogeneous fleet”. In: *Annals of Operations Research* 273.1-2, pp. 5–74. DOI: 10.1007/s10479-017-2642-9.

Pishue, B. (2021). *2020 Global Traffic Scorecard*. INRIX Research. URL: https://inrix.com/scorecard/ (visited on 09/07/2021).

Pisinger, D. and S. Ropke (2007). “A general heuristic for vehicle routing problems”. In: *Computers & Operations Research* 34.8, pp. 2403–2435. DOI: 10.1016/j.cor.2005.09.012.

– (2019). “Large Neighborhood Search”. In: *Handbook of Metaheuristics*. Ed. by M. Gendreau and J.-Y. Potvin. 3rd ed. 2019. Vol. 272. International Series in Operations Research & Management Science 272. Cham: Springer International Publishing, pp. 99–127. ISBN: 978-3-319-91086-4. DOI: 10.1007/978-3-319-91086-4_4.

Potvin, J.-Y. and J.-M. Rousseau (1995). "An Exchange Heuristic for Routeing Problems with Time Windows". In: *Journal of the Operational Research Society* 46.12, p. 1433. doi: 10.2307/2584063.

Prins, C., C. Prodhon, and R. Wolfler Calvo (2004). "Nouveaux algorithmes pour le problème de localisation et routage sous contraintes de capacité". In: *MOSIM'04*. Ed. by D.-P. S. Dolgui A, pp. 1115–1122.

Qiu, Y., D. Zhou, Y. Du, J. Liu, P. M. Pardalos, and J. Qiao (2021). "The two-echelon production routing problem with cross-docking satellites". In: *Transportation Research Part E: Logistics and Transportation Review* 147, p. 102210. doi: 10.1016/j.tre.2020.102210.

Quak, H. J. and M. B. M. de Koster (2009). "Delivering Goods in Urban Areas: How to Deal with Urban Policy Restrictions and the Environment". In: *Transportation Science* 43.2, pp. 211–227. doi: 10.1287/trsc.1080.0235.

Quak, H. J. and M. de Koster (2007). "Exploring retailers' sensitivity to local sustainability policies". In: *Journal of Operations Management* 25.6, pp. 1103–1122. doi: 10.1016/j.jom.2007.01.020.

Quak, H. J., M. Lindholm, L. Tavasszy, and M. Browne (2016). "From Freight Partnerships to City Logistics Living Labs – Giving Meaning to the Elusive Concept of Living Labs". In: *Transportation Research Procedia* 12, pp. 461–473. doi: 10.1016/j.trpro.2016.02.080.

Quak, H. J. and L. Tavasszy (2011). "Customized Solutions for Sustainable City Logistics: The Viability of Urban Freight Consolidation Centres". In: *Transitions Towards Sustainable Mobility: New Solutions and Approaches for Sustainable Transport Systems*. Ed. by J. A. van Nunen, P. Huijbregts, and P. Rietveld. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 213–233. isbn: 978-3-642-21192-8. doi: 10.1007/978-3-642-21192-8_12.

Quak, H. J., R. van Duin, and B. Hendriks (2020). "Running an urban consolidation centre: Binnenstadservice 10 years back and forth". In: *Transportation Research Procedia* 46.4, pp. 45–52. doi: 10.1016/j.trpro.2020.03.162.

Quak, H. J. (2008). *Sustainability of urban freight transport retail distribution and local regulations in cities. Duurzaamheid van stedelijk goederenvervoer retail distributie en lokale regelgeving in steden*. Zugl.: Rotterdam, Univ., Diss., 2008. Vol. 124. ERIM Ph.D. series research in management. Rotterdam: ERIM. isbn: 978-90-5892-154-3.

Rabe, M., A. Klueter, U. Clausen, and M. Poeting (2016). "An Approach for Modeling Collaborative Route Planning in Supply Chain Simulation". In: *Proceedings of the 2016 Winter Simulation Conference*. WSC '16. Piscataway, NJ, USA: IEEE, pp. 2228–2238. isbn: 978-1-5090-4484-9.

Raeesi, R. and K. G. Zografos (2019). "The multi-objective Steiner pollution-routing problem on congested urban road networks". In: *Transportation Research Part B: Methodological* 122, pp. 457–485. doi: 10.1016/j.trb.2019.02.008.

Reinhardt, L. B., M. K. Jepsen, and D. Pisinger (2016). "The Edge Set Cost of the Vehicle Routing Problem with Time Windows". In: *Transportation Science* 50.2, pp. 694–707. doi: 10.1287/trsc.2015.0620.

Reyes, D., M. Savelsbergh, and A. Toriello (2017). "Vehicle routing with roaming delivery locations". In: *Transportation Research Part C: Emerging Technologies* 80, pp. 71–91. doi: 10.1016/j.trc.2017.04.003.

Rezgui, D., J. Chaouachi Siala, W. Aggoune-Mtalaa, and H. Bouziri (2019). "Application of a variable neighborhood search algorithm to a fleet size and mix vehicle routing problem with electric modular vehicles". In: *Computers & Industrial Engineering* 130, pp. 537–550. doi: 10.1016/j.cie.2019.03.001.

Rincon-Garcia, N., B. Waterson, T. J. Cherrett, and F. Salazar-Arrieta (2020). “A metaheuristic for the time-dependent vehicle routing problem considering driving hours regulations – An application in city logistics”. In: *Transportation Research Part A: Policy and Practice* 137, pp. 429–446. DOI: 10.1016/j.tra.2018.10.033.

Rivera, J. C., H. M. Afsar, and C. Prins (2015). “A multistart iterated local search for the multitrip cumulative capacitated vehicle routing problem”. In: *Computational Optimization and Applications* 61.1, pp. 159–187. DOI: 10.1007/s10589-014-9713-5.

Roca-Riu, M. and M. Estrada (2012). “An Evaluation of Urban Consolidation Centers Through Logistics Systems Analysis in Circumstances Where Companies have Equal Market Shares”. In: *Procedia - Social and Behavioral Sciences* 39.5, pp. 796–806. DOI: 10.1016/j.sbspro.2012.03.148.

Roca-Riu, M., M. Estrada, and E. Fernández (2016). “An Evaluation of Urban Consolidation Centers Through Continuous Analysis with Non-equal Market Share Companies”. In: *Transportation Research Procedia* 12, pp. 370–382.

Rohmer, S., G. Claassen, and G. Laporte (2019). “A two-echelon inventory routing problem for perishable products”. In: *Computers & Operations Research* 107, pp. 156–172. DOI: 10.1016/j.cor.2019.03.015.

Ropke, S. and D. Pisinger (2006a). “A unified heuristic for a large class of Vehicle Routing Problems with Backhauls”. In: *European Journal of Operational Research* 171.3, pp. 750–775. DOI: 10.1016/j.ejor.2004.09.004.

– (2006b). “An Adaptive Large Neighborhood Search Heuristic for the Pickup and Delivery Problem with Time Windows”. In: *Transportation Science* 40.4, pp. 455–472. DOI: 10.1287/trsc.1050.0135.

Rose, W. J., D. A. Mollenkopf, C. W. Autry, and J. E. Bell (2016). “Exploring urban institutional pressures on logistics service providers”. In: *International Journal of Physical Distribution & Logistics Management* 46.2, pp. 153–176. DOI: 10.1108/IJPDLM-03-2015-0068.

Roy, B. (1993). “Decision science or decision-aid science?” In: *European Journal of Operational Research* 66.2, pp. 184–203. DOI: 10.1016/0377-2217(93)90312-B.

Ruesch, M. (2009). *Good Practices in Urban Freight in Europe*. URL: https://www.rapp.ch/wAssets-de/docs/trans/fachartikel-referate/2009/dokumente/piarc_wellington_bestufs_ruesch_cp.pdf (visited on 04/04/2018).

Ruesch, M. and C. Glückler (2001). *Best Practice Handbook Year 1 (2000). Statistical data, data acquisition and data analysis regarding urban freight transport City access, parking regulations and access time regulations and enforcement support*. Ed. by BESTUFS.net. URL: http://www.bestufs.net/bestufs1_bp_handbook.html.

Russo, F. and A. Comi (2010). “A Classification of City Logistics Measures and Connected Impacts”. In: *Procedia - Social and Behavioral Sciences* 2.3, pp. 6355–6365.

– (2011). “Measures for Sustainable Freight Transportation at Urban Scale: Expected Goals and Tested Results in Europe”. In: *Journal of Urban Planning and Development* 137.2, pp. 142–152. DOI: 10.1061/(ASCE)UP.1943-5444.0000052.

Sadler Consultants Europe GmbH (2021). *Urban Access Regulations in Europe. Map*. URL: https://urbanaccessregulations.eu/userhome/map (visited on 09/01/2021).

Sánchez-Díaz, I. (2017). “Modeling urban freight generation: A study of commercial establishments’ freight needs”. In: *Transportation Research Part A: Policy and Practice* 102, pp. 3–17. DOI: 10.1016/j.tra.2016.06.035.

Santini, A., S. Ropke, and L. M. Hvattum (2018). "A comparison of acceptance criteria for the adaptive large neighbourhood search metaheuristic". In: *Journal of Heuristics* 24.5, pp. 783–815. DOI: 10.1007/s10732-018-9377-x.

Savelsbergh, M. and T. van Woensel (2016). "50th Anniversary Invited Article—City Logistics: Challenges and Opportunities". In: *Transportation Science* 50.2, pp. 579–590. DOI: 10.1287/trsc.2016.0675.

Savelsbergh, M. W. P. (1992). "The Vehicle Routing Problem with Time Windows: Minimizing Route Duration". In: *ORSA Journal on Computing* 4.2, pp. 146–154. DOI: 10.1287/ijoc.4.2.146.

Schmid, V., K. F. Doerner, and G. Laporte (2013). "Rich routing problems arising in supply chain management". In: *European Journal of Operational Research* 224.3, pp. 435–448. DOI: 10.1016/j.ejor.2012.08.014.

Schneider, M., B. Sand, and A. Stenger (2013). "A note on the time travel approach for handling time windows in vehicle routing problems". In: *Computers & Operations Research* 40.10, pp. 2564–2568. DOI: 10.1016/j.cor.2013.02.002.

Schoemaker, J., J. Allen, M. Huschebek, and J. Monigl (2006). *Quantification of urban freight transport effects I*. BESTUFS.net. URL: http://www.bestufs.net/download/BESTUFS_II/key_issuesII/BESTUF_Quantification_of_effects.pdf (visited on 01/21/2021).

Schrimpf, G., J. Schneider, H. Stamm-Wilbrandt, and G. Dueck (2000). "Record Breaking Optimization Results Using the Ruin and Recreate Principle". In: *Journal of Computational Physics* 159.2, pp. 139–171. DOI: 10.1006/jcph.1999.6413.

Schröder, S. (2017). *jsprit: 1.7.2*. URL: https://github.com/graphhopper/jsprit (visited on 04/04/2018).

Shaw, P. (1997). *A new local search algorithm providing high quality solutions to vehicle routing problems*. Department of Computer Science, University of Strathclyde.

Shaw, P. (1998). "Using Constraint Programming and Local Search Methods to Solve Vehicle Routing Problems". In: *Principles and Practice of Constraint Programming — CP98*. Ed. by M. Maher and J.-F. Puget. Springer Berlin Heidelberg, pp. 417–431. ISBN: 978-3-540-49481-2.

Simoni, M. D., P. Bujanovic, S. D. Boyles, and E. Kutanoglu (2018). "Urban Consolidation Solutions for Parcel Delivery Considering Location, Fleet and Route Choice". In: *Case Studies on Transport Policy* 6.1, pp. 112–124.

Sitek, P. and J. Wikarek (2019). "Capacitated vehicle routing problem with pick-up and alternative delivery (CVRPPAD): model and implementation using hybrid approach". In: *Annals of Operations Research* 273.1-2, pp. 257–277. DOI: 10.1007/s10479-017-2722-x.

Slack, B., J.-P. Rodrigue, and T. Notteboom (2020). "The Nature of Transport Policy". In: *The Geography of Transport Systems*. Ed. by J.-P. Rodrigue. Fifth edition. New York, NY, USA: Routledge.

Solomon, M. M. (1987). "Algorithms for the Vehicle Routing and Scheduling Problems with Time Window Constraints". In: *Operations Research* 35.2, pp. 254–265. DOI: 10.1287/opre.35.2.254.

Sopha, B. M., A. M. S. Asih, F. D. Pradana, H. E. Gunawan, and Y. Karuniawati (2016). "Urban distribution center location". In: *International Journal of Engineering Business Management* 8. DOI: 10.1177/1847979016678371.

Soriano, A., T. Vidal, M. Gansterer, and K. Doerner (2020). "The vehicle routing problem with arrival time diversification on a multigraph". In: *European Journal of Operational Research* 286.2, pp. 564–575. DOI: 10.1016/j.ejor.2020.03.061.

Spliet, R. and G. Desaulniers (2015). "The discrete time window assignment vehicle routing problem". In: *European Journal of Operational Research* 244.2, pp. 379–391. DOI: 10.1016/j.ejor.2015.01.020.
Stathopoulos, A., E. Valeri, and E. Marcucci (2012). "Stakeholder reactions to urban freight policy innovation". In: *Journal of Transport Geography* 22, pp. 34–45. DOI: 10.1016/j.jtrangeo.2011.11.017.
Subramanian, A., L. M. Drummond, C. Bentes, L. S. Ochi, and R. Farias (2010). "A parallel heuristic for the Vehicle Routing Problem with Simultaneous Pickup and Delivery". In: *Computers & Operations Research* 37.11, pp. 1899–1911. DOI: 10.1016/j.cor.2009.10.011.
Subramanian, A., P. H. V. Penna, E. Uchoa, and L. S. Ochi (2012). "A hybrid algorithm for the Heterogeneous Fleet Vehicle Routing Problem". In: *European Journal of Operational Research* 221.2, pp. 285–295. DOI: 10.1016/j.ejor.2012.03.016.
Swedish Transport Agency (2020). *Congestion taxes in Stockholm and Gothenburg*. URL: https://www.transportstyrelsen.se/en/road/road-tolls/Congestion-taxes-in-Stockholm-and-Goteborg (visited on 06/21/2021).
Taillard, E. D. (1999). "A heuristic column generation method for the heterogeneous fleet VRP". In: *RAIRO - Operations Research* 33.1, pp. 1–14. DOI: 10.1051/ro:1999101.
Taillard, E. D., G. Laporte, and M. Gendreau (1996). "Vehicle Routeing with Multiple Use of Vehicles". In: *Journal of the Operational Research Society* 47.8, p. 1065. DOI: 10.2307/3010414.
Tamagawa, D., E. Taniguchi, and T. Yamada (2010). "Evaluating City Logistics Measures Using a Multi-agent Model". In: *Procedia - Social and Behavioral Sciences* 2.3, pp. 6002–6012.
Taniguchi, E. (2001). *City logistics. Network modelling and intelligent transport systems*. 1. ed. Amsterdam and New York: Pergamon. ISBN: 978-0080439037.
– (2014). "Concepts of City Logistics for Sustainable and Liveable Cities". In: *Procedia - Social and Behavioral Sciences* 151, pp. 310–317. DOI: 10.1016/j.sbspro.2014.10.029.
Taniguchi, E., M. Noritake, T. Yamada, and T. Izumitani (1999). "Optimal size and location planning of public logistics terminals". In: *Transportation Research Part E: Logistics and Transportation Review* 35.3, pp. 207–222. DOI: 10.1016/S1366-5545(99)00009-5.
Teo, J. S.-E., E. Taniguchi, and A. G. Qureshi (2015). "Evaluation of Urban Distribution Centers Using Multiagent Modeling with Geographic Information Systems". In: *Transportation Research Record: Journal of the Transportation Research Board* 2478.1, pp. 35–47. DOI: 10.3141/2478-05.
The Norwegian Public Roads Administration (2019). *Bompengesystemet i Oslo*. URL: https://www.vegvesen.no/vegprosjekter/oslopakke3/nytt-bompengesystem (visited on 10/14/2020).
Tilk, C., K. Olkis, and S. Irnich (2020). *The Last-mile Vehicle Routing Problem with Delivery Options: Discussion paper number 2017*. Mainz: Gutenberg School of Management and Economics, Johannes Gutenberg University Mainz.
– (2021). "The last-mile vehicle routing problem with delivery options". In: *OR Spectrum* 43.4, pp. 877–904. DOI: 10.1007/s00291-021-00633-0.
Transport for London (2021a). *Congestion Charge payments*. URL: https://tfl.gov.uk/modes/driving/congestion-charge/paying-the-congestion-charge (visited on 06/21/2021).
– (2021b). *How to pay a LEZ charge*. URL: https://tfl.gov.uk/modes/driving/low-emission-zone/make-a-payment (visited on 06/21/2021).
Tsang, E. W. K. (2017). *The philosophy of management research*. Vol. 64. Routledge advances in management and business studies. London and New York: Routledge. ISBN: 978-1-315-46321-6.

Ulrich, H. (1970). *Die Unternehmung als produktives soziales System : Grundlagen der allgemeinen Unternehmungslehre*. 2., überarb. Aufl. Bern: Haupt.

– (1981). "Die Betriebswirtschaftslehre als anwendungsorientierte Sozialwissenschaft". In: *Die Führung des Betriebes. Curt Sandig zu seinem 80. Geburtstag gewidmet*. Ed. by M. Geist and R. Köhler. Stuttgart: Poeschel, pp. 1–25. ISBN: 3-7910-0308-9.

United Nations (2015). *World Urbanization Prospects: The 2014 Revision*. New York: Department of Economic and Social Affairs, Population Division.

– (2019). *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. New York: Department of Economic and Social Affairs, Population Division.

Van Duin, J., H. J. Quak, and J. Muñuzuri (2010). "New Challenges for Urban Consolidation Centres: A Case Study in The Hague". In: *Procedia - Social and Behavioral Sciences* 2.3, pp. 6177–6188.

Van Duin, J., L. A. Tavasszy, and H. J. Quak (2013). "Towards E(lectric)-urban Freight: First Promising Steps in the Electric Vehicle Revolution". In: *European Transport / Trasporti Europei* 54, pp. 1–19.

Van Duin, J., T. van Dam, B. Wiegmans, and L. A. Tavasszy (2016). "Understanding Financial Viability of Urban Consolidation Centres: Regent Street (London), Bristol/Bath & Nijmegen". In: *Transportation Research Procedia* 16, pp. 61–80.

Van Duin, J., A. van Kolck, N. Anand, L. A. Tavasszy, and E. Taniguchi (2012). "Towards an Agent-Based Modelling Approach for the Evaluation of Dynamic Usage of Urban Distribution Centres". In: *Procedia - Social and Behavioral Sciences* 39, pp. 333–348. DOI: 10.1016/j.sbspro.2012.03.112.

Van Duin, R., M. Slabbekoorn, L. Tavasszy, and H. J. Quak (2018). "Identifying dominant stakeholder perspectives on urban freight policies: a q-analysis on urban consolidation centres in the netherlands". In: *Transport* 33.4, pp. 867–880. DOI: 10.3846/16484142.2017.1350996.

Van Heeswijk, W. J. A., R. Larsen, and A. Larsen (2019a). "An urban consolidation center in the city of Copenhagen: A simulation study". In: *International Journal of Sustainable Transportation* 13.9, pp. 675–691. DOI: 10.1080/15568318.2018.1503380.

Van Heeswijk, W. J. A., M. R. K. Mes, and J. M. J. Schutten (2019b). "The Delivery Dispatching Problem with Time Windows for Urban Consolidation Centers". In: *Transportation Science* 53.1, pp. 203–221. DOI: 10.1287/trsc.2017.0773.

Van Heeswijk, W. J. A., M. R. K. Mes, J. M. J. Schutten, and W. H. M. Zijm (2020). "Evaluating Urban Logistics Schemes Using Agent-based Simulation". In: *Transportation Science* 54.3, pp. 651–675. DOI: 10.1287/trsc.2019.0971.

Van Heeswijk, W. J. A., M. R. K. Mes, and M. Schutten (2016). "An Agent-Based Simulation Framework to Evaluate Urban Logistics Schemes". In: *Computational Logistics*. Ed. by A. Paias et al. Cham: Springer International Publishing, pp. 369–383. ISBN: 978-3-319-44896-1.

Van Rooijen, T. and H. J. Quak (2010). "Local impacts of a new urban consolidation centre – the case of Binnenstadservice.nl". In: *Procedia - Social and Behavioral Sciences* 2.3, pp. 5967–5979.

Verlinde, S. (2015). "Promising but challenging urban freight transport solutions : freight flow consolidation and off-hour deliveries". PhD Thesis. Ghent University. URL: https://biblio.ugent.be/publication/5985077.

Verlinde, S., C. Macharis, and F. Witlox (2012). "How to Consolidate Urban Flows of Goods Without Setting up an Urban Consolidation Centre?" In: *Procedia - Social and Behavioral Sciences* 39, pp. 687–701. DOI: 10.1016/j.sbspro.2012.03.140.

Verlinden, T., E. de van Voorde, and W. Dewulf (2020). "Ho.Re.Ca. logistics and European medieval structured cities: A search for cost generators". In: *Transport Policy* 99, pp. 419–429. DOI: 10.1016/j.tranpol.2020.07.013.

Vidal, T., T. G. Crainic, M. Gendreau, and C. Prins (2013a). "A hybrid genetic algorithm with adaptive diversity management for a large class of vehicle routing problems with time-windows". In: *Computers & Operations Research* 40.1, pp. 475–489. DOI: 10.1016/j.cor.2012.07.018.

– (2013b). "Heuristics for multi-attribute vehicle routing problems: A survey and synthesis". In: *European Journal of Operational Research* 231.1, pp. 1–21. DOI: 10.1016/j.ejor.2013.02.053.

– (2014). "A unified solution framework for multi-attribute vehicle routing problems". In: *European Journal of Operational Research* 234.3, pp. 658–673. DOI: 10.1016/j.ejor.2013.09.045.

– (2015). "Time-window relaxations in vehicle routing heuristics". In: *Journal of Heuristics* 21.3, pp. 329–358. DOI: 10.1007/s10732-014-9273-y.

Vidal, T., G. Laporte, and P. Matl (2020). "A concise guide to existing and emerging vehicle routing problem variants". In: *European Journal of Operational Research* 286.2, pp. 401–416. DOI: 10.1016/j.ejor.2019.10.010.

Ville, S., J. Gonzalez-Feliu, and L. Dablanc (2013). "The Limits of Public Policy Intervention in Urban Logistics: Lessons from Vicenza (Italy)". In: *European Planning Studies* 21.10, pp. 1528–1541. DOI: 10.1080/09654313.2012.722954.

Visser, J., A. van Binsbergen, and T. Nemoto (1999). "Urban freigth transport policy and planning". In: *City Logistics I. International Conference on City Logistics, 1st, 1999, Cairns, Queensland, Australia*. Ed. by E. Taniguchi and R. G. Thompson.

Wang, Z., W. Liang, and X. Hu (2014). "A metaheuristic based on a pool of routes for the vehicle routing problem with multiple trips and time windows". In: *Journal of the Operational Research Society* 65.1, pp. 37–48. DOI: 10.1057/jors.2013.4.

Wangapisit, O., E. Taniguchi, J. S. Teo, and A. G. Qureshi (2014). "Multi-agent Systems Modelling for Evaluating Joint Delivery Systems". In: *Procedia - Social and Behavioral Sciences* 125, pp. 472–483.

Wen, L. and R. Eglese (2015). "Minimum cost VRP with time-dependent speed data and congestion charge". In: *Computers & Operations Research* 56, pp. 41–50. DOI: 10.1016/j.cor.2014.10.007.

– (2016). "Minimizing CO2e emissions by setting a road toll". In: *Transportation Research Part D: Transport and Environment* 44, pp. 1–13. DOI: 10.1016/j.trd.2015.12.019.

Whitley, R. (1984). "The Scientific Status of Management Research as a Practically-oriented Social Science". In: *Journal of Management Studies* 21.4, pp. 369–390. DOI: 10.1111/j.1467-6486.1984.tb00234.x.

World Bank (2021). *Urban population (% of total population)*. URL: https://databank.worldbank.org/data/reports.aspx?source=2&series=SP.URB.TOTL.IN.ZS (visited on 07/05/2021).

Zhang, K., S. Batterman, and F. Dion (2011). "Vehicle emissions in congestion: Comparison of work zone, rush hour and free-flow conditions". In: *Atmospheric Environment* 45.11, pp. 1929–1939. DOI: 10.1016/j.atmosenv.2011.01.030.

Zhang, S., A. M. Campbell, and J. F. Ehmke (2019). "Impact of congestion pricing schemes on costs and emissions of commercial fleets in urban areas". In: *Networks* 73.4, pp. 466–489. DOI: 10.1002/net.21872.

Zhou, L., R. Baldacci, D. Vigo, and X. Wang (2018). "A Multi-Depot Two-Echelon Vehicle Routing Problem with Delivery Options Arising in the Last Mile Distribution". In: *European Journal of Operational Research* 265.2, pp. 765–778. doi: 10.1016/j.ejor.2017.08.011.