Design, planning and evaluation of two-tier distribution systems in the context of city logistics

Bruno Miguel Craveiro de Oliveira

Thesis submitted to the Faculty of Engineering, University of Porto for the
Doctoral Program in Transportation Systems
MIT Portugal Program

Supervisors

Professor Jorge Manuel Pinho de Sousa
Faculdade de Engenharia, Universidade do Porto

Professor António José Galrão Ramos
Instituto Superior de Engenharia do Porto, Instituto Politécnico do Porto

April 2023

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This material is based upon the work supported by the Fundação para a Ciência e Tecnologia under grant number: PD/BD/128093/2016. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the Fundação para a Ciência e Tecnologia.

Resumo

A *logística urbana* tem vindo a assumir uma importância crescente devido ao aumento da população, aos crescentes níveis de urbanização e à melhoria económica nas áreas urbanas, o que se traduz numa procura crescente de bens e serviços nos centros urbanos.

Neste contexto, o transporte urbano de cargas é um importante fator facilitador do crescimento económico e das atividades sociais nas cidades, mas, apesar de todos os seus benefícios, é também responsável por externalidades negativas, como congestionamentos de tráfego e emissões poluentes.

Desafios adicionais para o transporte urbano de carga, como as restrições de acesso de veículos, o aumento da realocação de espaço viário para o transporte público e ciclovias, o custo crescente dos imóveis nos centros das cidades, bem como o desejo de mitigar problemas económicos, impactos ambientais e sociais, motivaram a consideração de novos sistemas de distribuição.

Os sistemas de distribuição em dois níveis, em particular os baseados em depósitos móveis, têm sido propostos como uma alternativa para mitigar os impactos negativos do transporte urbano de cargas. O objetivo deste trabalho é identificar e caracterizar estes sistemas de distribuição, bem como desenvolver métodos para a sua definição, planeamento e avaliação.

Em primeiro lugar, apresenta-se uma revisão sobre sistemas de dois níveis aplicados à logística urbana. Propõe-se uma classificação dos sistemas de distribuição em dois níveis com depósitos móveis, baseada no grau de mobilidade e acessibilidade aos clientes por parte dos veículos vindos da periferia. Nestes sistemas destaca-se a falta de infraestrutura física para armazenamento de curto prazo, exigindo a sincronização entre os veículos que operam em cada um dos níveis, de forma a realizar transferências diretas de carga entre eles.

Foi desenvolvido um modelo genérico de programação inteira mista, extensível de forma a modelar todos os tipos de sistemas de distribuição baseados em depósitos móveis. Propõe-se também um conjunto de desigualdades válidas para reforçar a formulação desenvolvida, incluíndo restrições de quebra de simetria baseadas em ordenação lexicográfica, bem como restrições de arredondamento de capacidades de veículos e satélites. Propõe-se ainda um procedimento *warm-start* para resolver os modelos.

Foi ainda implementada abordagem heurística híbrida, baseada no método *variable neighbourhood search*, guiado por um esquema de aceitação de soluções com base em *simulated annealing*, para a determinação das rotas dos veículos num problema de distribuição em dois níveis com sincronização nos satélites, viagens múltiplas no segundo nível, e uma frota heterogénea de veículos.

Finalmente, é apresentado o conceito de um sistema de apoio à decisão para o planeamento e avaliação de sistemas de distribuição de dois níveis, com base no qual foi desenvolvido e testado um protótipo.

Palavras chave: logística urbana, sistemas de distribuição em dois níveis, optimização combinatória, heurísticas, sistemas de apoio à decisão

Abstract

City Logistics has become increasingly important due to the population growth, the increase in urbanisation and the economic improvement in metropolitan areas, which have resulted in a growing demand of goods and services in urban centres.

In this context, urban freight transport is an important enabling factor for economic growth and social activities in cities, but despite all its benefits, it also generates an important share of negative externalities, including traffic congestion, and polluting emissions.

Furthermore, additional challenges for urban freight transport such as vehicle access constraints, the increase in reallocation of road space to pavement widening and to bus and cycle lanes, the increasing cost of real estate in the city centres as well as the desire to mitigate economic, environmental, and social impacts, have motivated the study of novel distribution systems.

Two-echelon distribution systems, in particular those based on mobile depots, have been therefore proposed as an alternative to mitigate the negative impacts of urban freight transport. The aim of this work is to identify and characterise two-echelon distribution systems, as well as to develop methods for their design, planning and evaluation.

First, a review on two-echelon systems applied to city logistics is presented. We propose a classification of two-echelon distribution systems with mobile depots, based on the degree of mobility and accessibility to customers by the feeder vehicles. In these cases, there is usually a lack of a physical infrastructure for short term storage, therefore requiring space-time synchronisation between vehicles operating at each echelon, as to perform direct load transfers between them.

We have developed a generic 3-index arc-based mixed integer programming model easily extendable to model all types of distribution system based on mobile depots. We also propose a set of valid inequalities to tighten the formulation, including symmetry breaking constraints based on lexicographical ordering, as well as vehicle and satellite rounded capacity constraints. Moreover, we designed a *warm-start* procedure to help solve the models.

We also propose a heuristic approach based on a hybrid *variable neighbourhood search*-based heuristic guided by a *simulated annealing* acceptance criterion scheme to solve a two-echelon vehicle routing problem with synchronisation at satellites, multi-trips at the second echelon, and a heterogeneous fleet of city freighters.

Finally, we present a concept of a *decision support system* for the planning and evaluation of two-echelon distribution systems, based on which a prototype was developed and tested.

Keywords: city logistics, two-echelon distribution systems, combinatorial optimisation, heuristics, decision support systems

“The scientists of today think deeply instead of clearly. One must be sane to think clearly, but one can think deeply and be quite insane.”

Nikola Tesla

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Acronyms

B2B	Business-to-Business
B2C	Business-to-Consumer
BAU	Business-as-Usual
CEP	Courier, Express and Parcel
GUI	Graphic User Interface
HORECA	Hotels, Restaurants and Cafes
MCC	Micro-consolidation Centre
OR	Operational Research
TEU	Twenty-foot Equivalent Unit
UCC	Urban Consolidation Centre
UFT	Urban Freight Transport
ULS	Urban Logistic Space
UPS	United Parcel Service

Optimisation related acronyms

2E-VRP	Two-echelon Vehicle Routig Problem
2E-CVRP-MT-SS	Two-echelon Capacitated Vehicle Routing Problem with Multi-Trips and Synchronisation at Satellites
ALNS	Adaptive Large Neighbourhood Search
GAVP	Global Aggregated Vehicle Performance
GRASP	Greedy Randomised Adaptive Search Procedure
LCUR	Load Capacity Utilisation Ratio
LNS	Large Neighbourhood Search
LTDR	Laden Travelled Distance Ratio
MIP	Mixed Integer Programming
OVRP	Open Vehicle Routing Problem
PTR	Productive Time Ratio
SA	Simulated Annealing
TS	Tabu Search
VNS	Variable Neighbourhood Search
VRP	Vehicle Routing Problem
VRPATW	Vehicle Routing Problem with Access Time Windows

Chapter 1

Introduction

1.1 Motivation

Freight transport is a fundamental component of urban life. It allows citizens to meet their needs and plays an important role on the economic development, quality of life, accessibility, and attractiveness of urban areas (OECD, 2003). However, urban freight transport (UFT) also entails significant negative externalities such as air and noise pollution, congestion, and road accidents (Demir et al., 2015). Furthermore, global trends such as growing population and urbanisation (UN Department of Economic and Social Affairs, 2018) and the rise of e-commerce (Lone et al., 2021), increasingly require more urban freight transport, further exacerbating its negative impacts.

A number of innovative measures have been employed to tackle these externalities. One of such measures is the establishment of two-echelon distribution systems. These types of distribution systems require the creation of an additional load transshipment operation in the logistic chain, where freight coming from depots located at the periphery of the city is transferred from larger vehicles to smaller more environmentally friendly vehicles, such as small electric vehicles, cargo bikes or even walking porters, which will perform the last leg of delivery. Nonetheless, the costs of installing and running a physical infrastructure for load transshipments and short-time storage can be prohibitive, as space in the city centre is often limited and expensive. Therefore, and as a way to circumvent these issues, there has been an increased interest in two-echelon distribution systems using mobile depots, as one possible alternative.

This thesis focuses on the study of two-echelon distribution systems, particularly those based on mobile depots where exact space-time synchronisation between vehicles operating at each echelon is required so that loads can be transferred directly between those vehicles.

1.2 Thesis objectives

The main objectives of this research are:

- Understand and characterise two-echelon urban freight distribution systems, particularly those based on mobile depots;

- Develop both exact and heuristic solution methods for the design and planning of two-echelon urban freight distribution systems, and particularly for those encompassing exact space-time synchronisation between vehicles operating at different echelons, under different operational business rules;
- Design and develop a prototype for a a decision support system (DSS) for decision makers to solve, visualise and analyse the operational plans of different two-echelon distribution systems and facilitate the assessment of trade-offs between those alternatives.

1.3 Methodology

To conduct this research project a 4 step methodology was undertaken:

1. The first step was to understand the use of multi-echelon distribution systems, particularly two-echelon distribution systems, in the context of city logistics. To this end, a review and analysis of the state-of-practice of two-echelon distribution systems was performed. The reviewed cases were collected from the scientific literature, trial reports and online resources. During this phase, the research focused on the analysis of two-echelon distribution systems based on mobile depots, where transshipment locations do not have storage capabilities. There is therefore a need for space-time synchronisation between vehicles operating at each echelon at transshipment locations so that loads are transferred directly between vehicles. Given this review, we identified and proposed a classification of these systems according to the degree of mobility and accessibility to customers by the larger feeder vehicles operating at the first echelon.
2. After establishing the classification of two-echelon distribution systems based on mobile depots, the next step entailed the development, modelling and implementation of a generic mixed integer linear model for two-echelon vehicle routing problems with synchronisation at satellites and multi-trips at the second echelon. The generic model was formulated for the most restrictive distribution system based on mobile depots designated as T1 type in such a way that it could be extended to address all other three types. In order to strengthen the formulation, we also proposed and tested several valid inequalities, and symmetry breaking constraints. Next, a more thorough evaluation of a model for a *Two-echelon Capacitated Vehicle Routing Problem with Multi-Trips* (2E-CVRP-MT-SS) arising in T3 type systems was performed, for which we tested an alternative solution method based on a "warm-start" procedure. Despite some positive results, it became clear that the proposed exact methods would not be able to address larger instances of the problem.
3. Given these weaknesses of exact methods to address the 2E-CVRP-MT-SS arising in T3 type systems, the next step entailed the development of a heuristic solution method based on a variable neighbourhood search guided by a simulated annealing procedure designed

to solve an extension of the original problem. The new problem extended the problem previously tackled using exact solution methods by further considering time windows at customers, and a heterogeneous fleet of vehicles operating at the second echelon, where the routing of one of the vehicle types followed a open routing problem.

4. The last step of this research project encompassed the development of a prototype of a decision support system (DSS) embedding the heuristic solution method developed in the previous step. This prototype was developed with the objective of providing a starting point for the development of a full-fledged DSS that would allow decision makers to have access to relevant information about the final routing plans and better assess the trade-offs between alternative distribution policies.

1.4 Thesis outline

This thesis is structured in eight chapters. In this first chapter (Chapter 1), the motivation is presented, as well as the main research objectives and used methodology. This chapter ends with the thesis outline. The rest of the thesis, encompasses seven other chapters which are briefly described below.

Chapter 2 presents an overview of the concepts of urban freight transportation and city logistics, presenting the most common solutions proposed to address the negative impact of urban freight transport. A particular focus is given to multi-echelon distribution systems, and to the description of urban logistic spaces supporting the delivery of goods in the urban centres.

Chapter 3 presents an overview on the state-of-practice of two-echelon distribution systems in the context of city logistics. Two types of two-echelon distribution systems are addressed. First, a brief overview of some initiatives implementing distribution systems encompassing satellites with storage capabilities is presented. Then, the analysis focuses on initiatives in which satellites do not have storage capabilities and first echelon vehicles act as mobile depots, therefore requiring space-time synchronisation between vehicles operating at each echelon. For these systems, a classification based on the the degree of mobility and accessibility to customers by vehicles operating at the first echelon is proposed.

Chapter 4 encompasses a literature review on Operational Research (OR) methods for the design and planning of two-echelon distribution systems. The strategic and tactical planning levels are addressed, but solely the most relevant references are presented. The review then focuses on the *two-echelon vehicle routing problem* (2E-VRP) and its variants, particularly those encompassing multi-trips at the second echelon, and temporal considerations such as time windows and space-time synchronisation between vehicles operating in different echelons at transshipment points.

Chapter 5 is dedicated to the presentation of mathematical formulations for two-echelon vehicle routing problems with exact synchronisation at satellites and multi-trips at the second echelon. First, we propose a generic mixed integer programming (MIP) formulation for two-echelon distribution systems where synchronisation and multiple-trips at the second echelon arise. The generic model is formulated for the most restrictive type of two-echelon distribution system based on mobile depots (type T1 in the proposed classification), and we show how it can be extended as to model all other 3 types of two-echelon distribution systems based on mobile depots. Next, we propose and thoroughly test a MIP formulation for a type T3 system, formulated as a two-echelon vehicle routing problem with synchronisation constraints at the satellites, direct deliveries and multi-trips at the second echelon, where some first-echelon customers can also be used as satellites. We then assess the impacts of the proposed valid inequalities and symmetry breaking constraints, and present the results of using a warm-start procedure to solve the problem.

In Chapter 6, we propose a heuristic solution method based on a variable neighbourhood search (VNS) guided by a simulated annealing (SA) framework to solve a two-echelon vehicle routing problem that extends the problem addressed in the previous chapter by considering time windows, and a heterogeneous city freighter fleet. To test the proposed heuristic approach, we developed an instance generator with which novel instances were generated encompassing all problem characteristics. We tested the impacts of different operational characteristics, including alternative time windows spans and the impacts of considering an heterogeneous fleet of vehicles operating at the second echelon, against using a homogeneous fleet of each type of the considered vehicles. Furthermore, we compared the use of two-echelon distribution system with exact space-time synchronisation at satellites with different distribution policies, including the business-as-usual, in which only urban freighters are used, and considering storage capabilities at satellites, where only time precedence between urban and city freighters at satellites is required.

In Chapter 7, we present a prototype of a DSS for the design and planning of two-echelon distribution systems, with the objective of providing a starting point for a full-fledged DSS.

Finally, Chapter 8 ends the thesis with the conclusions, where the main findings and contributions are summarised, and some possible future research lines arising from this work are presented.

Chapter 2

Context

Freight transport is a fundamental component of urban life, and has an important impact on economic development, quality of life, accessibility and attractiveness of urban areas (OECD, 2003). Despite its importance, urban freight transport also entails significant negative externalities including air and noise pollution, congestion, and road accidents (Demir et al., 2015). To mitigate these negative effects there has been an increasing interest in establishing novel and improved processes for urban freight distribution, under the concept of *City Logistics*. This concept is broad, and several definitions have been proposed in the literature:

- Taniguchi & Thompson (2001) defines it as: "*...the process for totally optimise the logistics and transport activities by private companies in urban areas while considering the traffic environment, the traffic congestion and energy consumption within the framework of market economy*".

- Rodrigue et al. (2016) defines it as: "*The means over which freight distribution can take place in urban areas as well as the strategies that can improve its overall efficiency while mitigating congestion and environmental externalities. It includes the provision of services contributing to efficiently managing the movements of goods in cities and providing innovative responses to customer demands*".

- Bektaş et al. (2017) defines it as: "*City Logistics are transportation and logistics systems, meaning that they deploy infrastructure and service networks to move, and eventually, store freight on its way from origins to destinations. Designing and planning the operations of City Logistics systems therefore directly raises the need to design and evaluate physical and service networks, route vehicles of various modes, and determine how to best move freight using these services and vehicles*".

These definitions of *City Logistics* present a common focus on the design and planning of logistic and freight transportation strategies and operations, with the objective of minimising the negative externalities resulting from urban freight transport.

Other related concepts such as *Urban logistics* or "urban goods movement" (OECD, 2003; Ambrosini & Routhier, 2004) are broader terms, as they encompass not only the perspective of private logistic companies and retail, but also household purchasing trips, urban road maintenance and building, as well as waste collection.

For the purpose of this doctoral thesis, we focus on a more restricted view of *City Logistics*, from the perspective of private logistic companies and their effort to design and plan two-echelon distribution systems transport operations.

2.1 City logistics initiatives

City Logistics plays an important role in creating efficient, environmentally friendly and safe urban freight transport systems. A number of policy measures such as urban consolidation centres, regulations of access control to city centres, off-peak hour deliveries or low emission zones, just to give some examples, have been tested and implemented, alone or in tandem, in urban areas of cities around the world to achieve the goals of mobility, sustainability and liveability (Muñuzuri et al., 2005; Russo & Comi, 2010, 2011; De Marco et al., 2018).

One of the central points in *City Logistics* is freight consolidation. By consolidating freight, one aims to reduce the number of vehicles operating with only partial loading by combining loads for the same destination or adjacent venues. This would improve the load factors of used vehicles delivering in city centres, which still remains very low (Holguín-Veras & Sánchez-Díaz, 2016), and should also result in the reduction of the number of vehicles, therefore reducing congestion and pollutant emissions.

Urban freight consolidation can be achieved in the transportation demand or supply side. Most efforts have focused on supply-side consolidation solutions. Holguín-Veras & Sánchez-Díaz (2016) identify 6 major supply-side oriented solutions namely: i) infrastructure management; ii) parking and loading management; iii) vehicle-related initiatives; iv) traffic management activities; v) financial mechanisms; and vi) logistics management. On the other hand, it is also possible to consider demand-side consolidation solutions. The argument for studying and developing demand-side consolidation solutions is that receivers are the primary customers in supply chains and thus, they have a great deal of influence on establishing the operational constraints that must be satisfied by carriers and shippers.

In this work, we focus on supply-side consolidation solutions. Nonetheless, we start by providing a short overview of demand-side consolidation solutions applied to *City Logistics*, following with supply-side solutions, particularly related with the introduction of additional infrastructure in the logistic chain for the consolidation and transshipment of loads having their destination the city centre.

Demand-side consolidation solutions A definition of transport demand-side solutions, or *freight demand management*, is presented in Holguín-Veras & Sánchez-Díaz (2016) as measures *"...to use the power of receivers to affect supply chains to foster economic productivity and efficiency; and to enhance sustainability, quality of life, and environmental justice in urban areas"*. According to the authors, freight demand consolidation-based solutions aim to change the amount, timing, destination or mode of deliveries. These solutions encompass, for example: i) off-hour delivery programs, where customers accept loads during the off-hours; ii) staggered delivery programs, as an incentive for customers to spread their deliveries throughout the day; and iii) receiver load consolidation, aiming to change the destination of loads into communal delivery points, such as delivery lockers or urban logistics boxes, where carriers are able to leave their loads to be picked up later by the customers.

Supply-side consolidation solutions As for supply-side consolidation solutions we will focus on logistics management initiatives. These initiatives are based on having multiple suppliers and/or carriers consolidating loads to increase the efficiency of their operations and reduce the negative impacts of urban freight transport (Holguín-Veras & Sánchez-Díaz, 2016). Most of these consolidation-based solutions regard the implementation of multi-echelon distribution systems where additional transshipment points or *urban logistic spaces* in the supply chain are considered.

2.2 Multi-echelon distribution systems and urban logistic spaces

Multi-echelon distribution systems usually rely on setting some infrastructure, or *urban logistic spaces* (ULS), to transship, store, sort and consolidate loads, with the objective of reducing the number of vehicles required to enter the city, as well as to allow the use of more environmentally friendly transport modes for last-mile delivery. Fundamentally, multi-echelon distribution systems imply using: 1) different freight transportation modes along the delivery route; and 2) intermediate logistics platforms or satellites where freight can be stored, sorted, consolidated and transshipped between vehicles operating at each echelon. Particularly in the context of city logistics, these systems are usually based on two echelons (Crainic et al., 2004; Mancini et al., 2014).

The concept of ULS is broad, and covers different sizes, types of handled goods, possible activities performed, and the area they serve. The choice in their implementation is dependent on the characteristics of the involved economic sectors, city geography and stakeholder objectives.

ULS can be broadly defined as "... *a facility intended to optimise the delivery of goods in cities, on the functional and environmental levels, by setting up break-in-bulk points*" (Patier & Toilier, 2018). A ULS encompasses the establishment of additional consolidation/storage/transshipment points in the supply chain and relies on using different transportation modes for urban freight transport, particularly for last-mile deliveries. The establishment of these infrastructures allows for the consolidation of loads, thus reducing the number of vehicles entering the city and improving their load factors. It also enables companies to comply with regulations, such as vehicle access restrictions based on load factors and/or emissions, aiming to reduce the negative externalities of logistics operations in urban centres.

Different classifications have been proposed for ULS focusing on their topology, their characteristics and their operational particularities (Boudouin, 2012; Verlinde et al., 2012; Janjevic et al., 2013; Boudouin et al., 2014; Meza-Peralta et al., 2020). A common starting point for these classifications is the ULS typology presented in Figure 2.1 as proposed by Boudouin (2012).

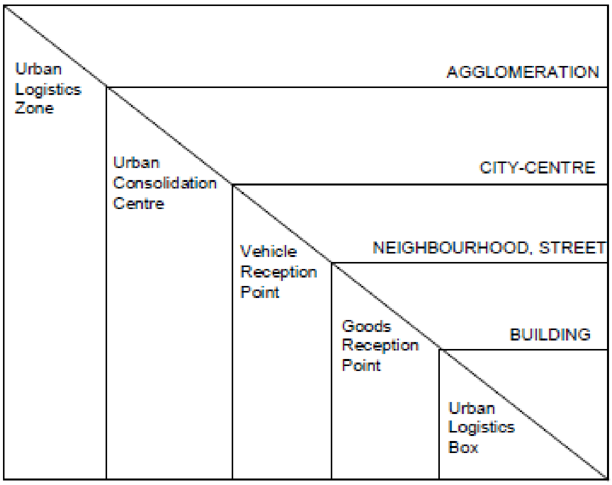


Figure 2.1: Urban logistic spaces (Boudouin, 2012).

Urban Logistics Zones or freight villages are larger infrastructures located in the periphery of the city which serve as the interface between the interurban areas and the city, and usually have an interface with the railway, shipping ports and airports (Rodrigue et al., 2016). They allow for the transshipment of loads and have some storage capabilities allowing to perform all required operations, such as labelling, sorting and packing before delivery.

As for *Urban Consolidation Centres* (UCC), a great deal of research has been conducted. However, the definition of UCC is often ambiguous and different names for these infrastructures are used in the literature, such as urban transshipment centre or urban distribution centre. Nonetheless, according to Allen et al. (2007), an UCC can be defined as "... *a logistic facility situated in relatively close proximity to the geographical area it serves (be that a city centre, an entire town or a shopping centre), to which many logistic companies deliver goods destined for the area, from which consolidated deliveries are carried out within that area, in which a range of other value added logistic and retail services can be provided*".

The main purpose of an UCC is to avoid vehicles small load factors when delivering freight in urban areas, decreasing the total number of required vehicles and the total distance travelled, thus reducing their associated negative impacts. Loads can be consolidated into appropriately sized vehicles for the products and locations being served by the UCC. Therefore, the vehicles operated from these facilities for the last leg of delivery are not necessarily small and light weight vehicles, and can range form cargo-cycles and vans to larger rigid vehicles (Allen et al., 2012). Besides consolidation, load transshipment and sorting for final deliveries, an UCC can also provide other value-added services including stock holding, consignment unpacking, preparation of products for display and price labelling (Browne et al., 2011).

Allen et al. (2012) propose a classification scheme of urban consolidation initiatives based on a review of 114 UCC schemes in 17 countries worldwide, taking into account the geographical area served and the type of performed operations. The authors identify three main types of urban consolidation centres, namely: i) UCCs serving all or part of an urban area; ii) UCCs serving large sites with a single landlord; and iii) UCCs for construction projects. Due to the specificity of the latter type of UCC, we only focus on the first two types.

The first class of UCCs are usually associated with the supply of retail products, office centres and supplies for the HORECA sector. The UCCs belonging to this category are usually used to serve a particular urban area with characteristics such as narrow streets, vehicles access restrictions, limited parking infrastructure, pedestrian areas or dealing with congestion or high levels of pollution. The second class of UCC usually serve one or a few large sites containing many different outlets, such as various retailers in a shopping centre or airport. According to the authors, this type of UCCs differs from the first one in the sense that: i) the sites and the UCC are usually accounted together with the site development; ii) the site landlord can enforce on tenants the requirement of using the UCC for their replenishment; iii) the unloading points tend to be located off-street in a specially designed delivery area; and iv) the UCC operation can be made self-financing through charges included in the tenants rental arrangements. According to the authors, these UCCs are easier to implement and to remain operational since they are usually based on centralised management, enabling a greater control over potential carriers and receivers of goods.

A concept similar to that of the UCC is the so-called *micro-consolidation centre* (MCC), also called *micro-fulfilment centre*, *delivery microhub* or *micro-distribution hub*. A MCC also provides the ability to consolidate, sort and store freight, and allows for load transfers between different transport modes for last mile delivery. The main difference is that MCCs are located much closer to the reception points, are usually used to serve smaller areas, and handle mostly small and lightweight goods. MCCs may be used for the replenishment of brick-and-mortar, but the main driver of their implementation has been the rise of e-commerce and the growth of home deliveries. They allow for mode shifts from large heavier vehicles to environmentally-friendly transport modes to perform the last mile (such as small electric vans, cargo-bikes or walking porters), thus contributing to the reduction of the negative externalities of urban freight transport. Nonetheless there are clear trade-offs between the benefits of implementing systems using MCCs and their costs. MCCs are located in urban areas where space is limited and expensive (Arvidsson & Pazirandeh, 2017; Patier & Toilier, 2018) and using them requires additional handling of goods. Furthermore, the establishment of a MCC usually also entails costs associated with the acquisition and maintenance of the fleet performing the last mile as well as higher personnel costs. The use of MCCs is closely related with the establishment of two-echelon distribution systems for urban freight distribution, and several initiatives have been put in place where MCCs have been used. An overview of some two-echelon distribution systems using MCCs are presented is Section 3.2.

Vehicle Reception Points, also referred in the literature as *nearby delivery areas*, consist in establishing locations where carriers can load and unload consignments destined to nearby customers. According to Patier & Toilier (2018), two types of vehicle reception points can be identified. The first type are on-street loading bays, also referred as proximity logistic spaces, which are locations where distributors can leave their vehicle while delivering loads on foot to nearby customers. These spaces may be equipped with small transshipment/handling facilities and with dedicated personnel who help with dispatching consignments for the last-mile and/or watch over the vehicles while deliveries are being performed. The second type of vehicle reception point encompasses road time-sharing spaces. In this case, sections of the road that are usually dedicated to the circulation of all types of vehicles become dedicated parking spaces for delivery vehicles at specific times of day. The role of local public authorities is crucial in the establishment of these ULS as they are responsible for the deployment and access to these spaces, and for clearly defining who can use these spaces and under what conditions. In general, vehicle reception points are better suited for the *Courier, Express and Parcel* (CEP) sector, and their limited coverage area has been identified as one of their main limitations.

Good Reception Points and *Urban Logistic Boxes* can be considered as supply or demand-side solutions. They consist in setting up urban distribution services where carriers deliver consignments to communal or individual delivery points. In this case, carriers leave the consignments at these locations instead of delivering them directly to customers. This solution has the benefit of avoiding missed deliveries due to absent customers and can be used as a buffer storage space allowing for a reduction of storage space in stores.

2.3 Chapter summary

Urban freight transport is of outmost importance to urban life, but it entails several negative externalities, including air and noise pollution, congestion and road accidents. To address these issues, a new area of transport planning has emerged, broadly referred as *City Logistics*.

One of the central points in city logistics is freight consolidation, which can be attained both from the demand and from the supply side. Measures applied at the supply side usually regard the establishment of multi-echelon distribution systems, particularly two-echelon distribution systems, that rely on the establishment of additional transshipment points in the logistic chain that are used to tranship, store, sort, and consolidate loads. Furthermore, establishing such distribution systems provides the opportunity for using transport modes more suited to operate in city centres, thus allowing for the reduction of the negative impacts associated with urban freight transportation.

In the next chapter, we present an overview of two-echelon distribution systems, their context in city logistics, and an overview on the state-of-practice of two alternative systems, namely: i) those encompassing transshipment points with storage capabilities; and ii) those in which there is no infrastructure where loads can be stored, therefore requiring that feeder vehicles act as a mobile depot, and are synchronised, both in time and in space, with vehicles performing the last leg of delivery, so that loads are transferred directly between them.

Chapter 3

Two-echelon distribution systems: state of practice

Multi-echelon distribution systems have been proposed as a solution to mitigate the negative externalities of urban freight transport. In this chapter, we focus specifically on two-echelon distribution systems, and present an overview of their state-of-practice in the context of city logistics, based on a review and analysis of cases found in the scientific literature, trial reports and online resources.

We start by introducing the concept of two-echelon distribution systems in the context of city logistics, in Section 3.1. These systems can be broadly split into two main types, namely where: i) the intermediary transshipment locations have some short-term storage capacity, where feeder vehicles can leave the loads to be picked up later by the vehicles performing the last leg of delivery; and, ii) the intermediary transshipment locations do not have storage capacity, therefore requiring space-time synchronisation between the feeder vehicles, serving as mobile depots, and the vehicles performing the last leg of delivery.

In Section 3.2 we present examples of two-echelon distribution systems based on transshipment locations with some storage capacity, such as micro-consolidation centres.

Section 3.3 is dedicated to two-echelon distribution systems based on mobile depots, where there is a lack of a physical infrastructure for short term storage, therefore requiring space-time synchronisation between vehicles operating at each echelon as to perform direct load transfers between them. We propose a classification of these types of distribution systems, based on the degree of mobility and accessibility to customers by the feeder vehicles, and provide an overview of the related projects and their characteristics.

3.1 Introduction

The implementation of two-echelon distribution systems in the context of *City Logistics* was first addressed in Crainic et al. (2004, 2009). According to the authors, these distribution systems are usually more suited for larger and congested urban areas, particularly for urban centres with high population density, and high levels of commercial and leisure activities, that result in high demand levels for freight transportation. These areas often present a very dense road network of narrow and one way streets, access constraints, as well as limited kerbside and private parking sites, particularly when it comes to dedicated loading and unloading areas for freight transport (Crainic et al., 2004). Furthermore, policies to improve walkability and public transportation have resulted in the reallocation of road and kerbside space to pavement widening, as well as to bicycle and public transport lanes. This further increases the constraints for urban freight access to city centre areas, therefore increasing the need for the development and evaluation of novel *last mile* transportation solutions (Muñuzuri et al., 2012; Allen et al., 2018).

Two-echelon distribution systems expand the concept of single-echelon distribution systems, by organising consolidation and distribution activities in a hierarchical structure with two main layers. These systems consider an additional site, or *satellite*, such as a micro-depot or a vehicle reception point, located closer to the city centre, where freight coming from facilities in the periphery of the city is transferred, and possibly consolidated, into smaller and more environmentally friendly transport modes, better suited to operate at the city centre (Crainic et al., 2004).

One of the downfalls of considering single-echelon consolidation-distribution systems for urban freight transport is the addition of a break-up point in the logistic chain which increases delivery time and financial costs. Therefore, two-echelon distribution systems, being an extension of the single-echelon, should have these points twice, once for each echelon. Furthermore, the use of transportation modes with less capacity, performing the last leg of delivery, also results in an increased number of vehicles or trips to deliver the same loads, although load factors of larger vehicles, such as trucks and vans, still remain low (Holguín-Veras & Sánchez-Díaz, 2016).

Another issue regards the need for load transfer locations between first- and second-echelon transport modes. Given the increasing competition for kerbside space, and the premium value of space in city centres, the determination of the possible locations and characteristics of these transfer sites, as well as the type of operations that should be performed there, becomes critical.

Nonetheless, two-echelon distribution systems represent an interesting opportunity, since they can have positive environmental impacts due to the use of environmentally friendly vehicles operating at the second echelon, and may allow for the reduction of the vehicle/km of larger first-echelon transport modes due to the reduction of the distance between the consolidation facilities located in the outskirts of the city and the city centre. Other reported impacts are the reduction of time spent at the kerbside, and the search for a parking space for loading and unloading.

Next, we present the main components of two-echelon distribution systems, as well as some considerations about their characteristics, which are important for their accurate representation and for the definition and implementation of viable business rules.

Main components of the system Much like other distribution systems, two-echelon distribution systems encompass some main components. Identifying the characteristics of such components will allow for an overall better representation of the system, and the definition of viable operational rules to be implemented. These components can be split into: i) infrastructure components, encompassing the peripheric facilities such as depots and warehouses, *satellite* locations where loads can be transferred between transport modes operating at each echelon, as well as the transportation network; ii) transportation mode; and, iii) transported loads.

Infrastructure components

Peripheric locations/depots These locations represent facilities where loads with the city centre as destination are sorted and consolidated. These locations can be, for example, UCCs or depots/warehouses for single private companies. Furthermore, in the context of two-echelon distribution systems, it is usually considered that some form of coordinated planning exists between flows transported from these peripheric locations to the *satellites*, and the transportation of loads between *satellites* and the final customers.

***Satellite*s** According to Crainic et al. (2004), *satellites* are locations where loads can be transferred between first- and second-echelon transport modes. *Satellites* would not have any storage capacity and should have very little infrastructure and thus, cross-dock transshipment would be the operational model. This emphasises the need for coordination and synchronisation between transport modes operating in both echelons, with the objective of having vehicles parked at *satellites* for the least time possible. *Satellites*' capacity can be measured as the number of vehicles they can accommodate at the same time and/or the number of vehicles that may visit the *satellite* during its operating hours. Examples of *satellites* could include kerbside or dedicated parking spaces, underground parking lots, municipal bus stops or even public transport stops.

Regarding the operations that can be conducted at the *satellites*, it is not clear if they should be used solely for load transfers or if consolidation should also be permitted (Crainic et al., 2004). According to these authors, both activities should be able to be performed. Despite this, as stated before, the definition of *satellite* also states that these transfer locations should have a minimum to no infrastructure and no storage capabilities, implying that loads should be transferred directly from first- to second-echelon transport modes. Furthermore, consolidation at the satellites implies that more than one peripheric consolidation facility must be considered, or else consolidation would have already been performed at the peripheric facility.

Thus, we argue that, if *satellites* have no storage capabilities, consolidation at *satellites* may only be assumed if more than one peripheric consolidation facility is considered, and if at least two first-echelon vehicles and one second-echelon vehicle are at the same *satellite* during a specific time window, so that loads can be directly transferred to the second-echelon vehicle. We note that, despite the fact that the original concept clearly states that the *satellites* would not have any storage capabilities, most literature regarding two-echelon distribution optimisation considers that freight is able to be stored at *satellites* for a "short" period of time (Perboli et al., 2011),thus avoiding space-time synchronisation of vehicles at the *satellites*.

The presented definition is in line with the concerns of other authors who have mentioned the increased time spent by vehicles occupying kerbside space to make deliveries (Goodchild & Ivanov, 2017; Clarke et al., 2018; Allen et al., 2018), as the driver usually parks the van and makes the deliveries in the surrounding area by foot. This has led to the proposition of mobile depots which would park at transfer locations only to transship loads to other transport modes in a *need-to-be* basis.

Transportation network The transportation network encompasses not only the road network, but also inland waterways, bicycle and public transport dedicated lanes, which allow the use of other transportation modes for freight delivery in city centres. The accessibility constraints associated with each type of transport network should be recognised and accounted for, as they strongly influence operations in certain areas and/or at certain times.

Transportation modes

First-echelon transport modes In two-echelon distribution systems, we assume that different modes of transport should be used in different areas. Transport modes used at the first-echelon are considered to be larger vehicles with more capacity, that may have limited access to some areas. Additionally, they are usually responsible for greater negative externalities due to their size, weight, pollutant emissions or fuel consumption levels. First-echelon transport modes can be used solely for the transportation of loads from the peripheric consolidation facilities to the transfer locations (*satellites*), or they may also be used to perform direct deliveries to the customers.

Second-echelon transport modes Second-echelon transport modes are usually smaller, with less capacity and range, and more environmentally friendly. They can be electric vans, cargo-cycles (both electric or not) and walking porters (McLeod et al., 2020). These transport modes are considered to be more flexible, in the sense that they may have access to dedicated infrastructure such as bicycle paths, pedestrian areas and even bus lanes, otherwise restricted to larger transport modes. They are also usually easier to park, although some kerbside space is still required. From a societal point of view, these transport modes are also considered to have a smaller visual impact, and represent less of a threat to pedestrians and cyclists. Nonetheless, these transport modes have less capacity, so for the same amount of load to be transported, we need more vehicles to be deployed, or multiple trips during a working day.

Transported loads

Types of loads Regarding the type of product transported in these systems, we can distinguish between two large groups of products, namely, palletized goods and parcels/packages. Palletized goods are associated with activities such as the *HORECA* (Hotels, Restaurants and Cafés) sector and retail, while parcels and packages are usually associated with postal and e-commerce goods distribution.

Types of flows Urban freight can be classified in different ways depending on the context and objectives under consideration (Cattaruzza et al., 2017), namely according to: i) the actors involved; ii) the direction of flows; and, iii) the flow transportation strategy. Regarding the actors involved, we can distinguish between three main types of flows: B2B (business-to-business), B2C (business-to-consumer) and generic reverse flows. As for the direction of flows, particularly in the context of two-echelon urban freight transport systems, some authors also consider the cases of E2C (external-to-central), C2E (central-to-external), related with *first mile* pickups and reverse flows, and C2C (flows within the city centre)(Crainic et al., 2016; Nguyen et al., 2017). Finally, flow transportation strategies encompass full truckload (FTL) or less-then-truckload (LTL). According to Cattaruzza et al. (2017), FTL approaches mainly cover hypermarket distribution and urban industry, while LTL is related with retailing and tertiary activities, including parcel and express delivery services, small retail, and loads for the *HORECA* sector.

3.2 Systems based on transfer locations with storage capacity

Satellites are usually micro-consolidation centres (MCCs) with short term storage capabilities (see Section 2.2). Next, we present an overview of some initiatives that have been put in place, encompassing the use of MCCs for urban freight distribution.

The SMILE project (ValenciaPort, 2015; Navarro et al., 2016) encompassed two pilot projects for distribution systems, based on the establishment of MCCs and distribution of parcels by cargo-cycles, in the historic centres of Barcelona and Valencia. These pilots were undertaken by a consortium of the municipalities, 2 research centres, 4 CEP operators, and a company that managed public and private parking spaces used for the installation of the transshipment terminals (*satellites*).

Figure 3.1: Barcelona transshipment terminal.

In Barcelona, the transshipment terminal (Figure 3.1) was formed by a space for cargo-cycles drivers to process information, some shelves for temporary parcel storage, and a dressing room for the drivers. This terminal also encompassed space for overnight parking and re-charging of the cargo-cycles, toilet facilities for the workers and storage for cargo-cycle batteries. In Valencia, the transshipment terminal was composed by a 15.15 m^2 module used to receive, process and temporarily store parcels, and a 1 TEU container used for overnight parking of the cargo-cycles.

Navarro et al. (2016) present a comparison between both pilots in terms of economic, energy and environmental aspects, but no comparison with the usual operation is presented. Nonetheless, they mention that there might be some potential benefits in implementing this type of two-echelon distribution systems based on micro-consolidation centres, particularly regarding the reduction of polluting emissions. Several challenges in the implementation of such distribution systems are highlighted, including the difficulty for these distribution systems to attain economic equilibrium, particularly without subsidies by public authorities, and the difficulty to reach an agreement between transport operators. Furthermore, the placement of the transshipment depot entails several barriers, as it is difficult to find appropriate locations that are close and with good access to delivery areas, and that minimise the visual impacts in the surrounding areas.

Another example is reported in Browne et al. (2011) and Clarke & Leonardi (2017). The Agile Gnewt Cargo trial aimed at replacing the use of diesel vehicles operating in a highly dense area of $2.9Km^2$ in the City of London with electric vans and cargo-cycles. The trial involved the establishment of a MCC where loads were transshipped from larger vehicles coming from a suburban depot onto electric vans and cargo-cycles for last-mile deliveries. The MCC was also used as a storage facility for overnight parking of the electric vans and cargo-cycles. Results showed that the trial allowed for a reduction of CO_2 and other pollutant emissions of over 80%, a distance reduction per parcel of over 52%, and a reduction of empty distances of 74%. Nonetheless, the travelled distance per parcel, and the road occupancy increased substantially due to the smaller capacity of the electric vans and cargo cycles when compared with the diesel vans. However, the kerbside occupancy during deliveries was reduced.

Recently, the project KoMoDo was piloted in the city of Berlin during twelve months (LNC, 2019). The objective was to test the use of an open system of micro-depots, and the use of cargo-bikes to perform last-mile parcel deliveries in one of the city districts. Given the scarcity of available public spaces in densely populated inner zones, the idea was to establish a service that could be used cooperatively with several parcel delivery service providers. Renowned service providers, namely DHL, GLS, Hermes and UPS, participated in the project (see Figure 3.2). The project was put in place and funded within the National Climate Initiative (NKI) of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, that covered part of the fixed costs, while the operators supported the running costs of the operations.

The logistics infrastructure consisted in seven sea-shipping containers located in Prenzleuer Berg that could be used by any project partner as a central collection and distribution point. In the morning, the micro-depots were supplied by larger trucks, and used by the companies as temporary storage spaces. During the day, the cargo bikes delivered the parcels in the surrounding

Figure 3.2: KoMoDo collaborative micro-hub (LNC, 2019).

area within a radius of 2/3 km, and could return to the micro-depots to reload, if needed. After a twelve-month trial, results showed that micro-depot and cargo-bikes could be used efficiently, particularly in areas with high density of recipients and for shipments with quantities, volume and weight suitable for cargo-bike delivery. During the trial, a total distance of 28000 Km done by conventional diesel vans was avoided, thus greatly reducing CO_2 and other pollutant emissions, but the total distance travelled by cargo-cycles amounted to 38000 Km, as cargo cycles required to return to the micro-depot several times to reload. Regarding the economic evaluation of the project, despite some financial support from the public authorities, CEP companies reported an increase in operational costs associated with the establishment and running costs of the micro-depots, purchase and maintenance of cargo cycles, as well as additional personnel costs.

The establishment of micro-depots for city centre deliveries have also been independently implemented by larger CEP operators. For example, DHL has opened *CityHubs* in Antweup (Belgium), Groningen, Tilburg (Netherlands) and Manhattan (USA) (van Amstel, 2018; DC Velocity, 2016; DHL, 2018), while Chronopost of the DPDgroup has launched their *ChronoCity* concept in Paris (DPDgroup, 2019). Usually these micro-depots are formed by two main areas: i) a space dedicated to the general public, for sending, receiving or returning parcels; and, ii) an operational section used as an overnight parking space for low emission vehicles, and to store and sort consignments.

The suitability of establishing a *satellite* in a given area depends on various criteria, and each case must be considered taking into account its specific characteristics. Some characteristics can be beneficial for a feasible establishment of two-echelon distribution systems using MCC as satellites. These includes, but are not limited to, considerations about demand characteristics, infrastructure and stakeholder engagement.

In terms of demand, MCC based distribution systems seem to be more suited in areas with high volumes of consignments and high stop density. Furthermore, since the vehicles performing the last leg of delivery have a smaller capacity, these systems are better suited for the CEP sector, due to its common consignment characteristics (smaller weight, size, and number of items per consignment). Regarding the infrastructure, it is important to account not only for the existing conditions, but also to the the requirements of the MCC to be installed. It is important for the MCC to be located in areas with good accessibility to the delivery area, and in large enough spaces to allow for short term storage of loads, parking for the cargo-cycles, and for the parking and manoeuvring of the feeder vehicles. These locations should have an assured and permanent connection to a power grid, particularly if they are going to be used as a parking and charging area for electric cargo-cycles. As for the stakeholders engagement, it is important to guarantee that both private and public sectors engage in meaningful collaboration for a successful implementation of these systems.

3.3 Systems based on mobile depots

Setting up infrastructure with space for temporary storage, where loads can be sorted and transshipped, is not easy in an urban setting where space is limited and expensive (Alice/Ertrac, 2015). These often prohibitive costs of installing and running a physical infrastructure in the urban centres have promoted the development of urban distribution systems based on mobile depots (Arvidsson & Pazirandeh, 2017; Patier & Toilier, 2018). The main characteristic of these distribution systems is the lack of a physical infrastructure for short term storage. Therefore, by not considering such a space, this distribution type requires loads to be consolidated upstream by a single operator, it also requires that loads are sorted and rounds prepared at the suburban depot, or in the vehicle transporting goods to the city centre. Additionally, both the feeder and the vehicle performing the last leg of delivery must be at the same place at the same time in order to transfer loads directly between them. The expected gains of this type of operation include time-savings and positive environmental impacts, resulting from the re-organisation of logistics procedures and the use of more environmentally-friendly transport modes for last mile delivery (Patier & Toilier, 2018). There has been an increasing interest in distribution systems based on mobile depots for urban freight transport, but not much literature exists regarding these types of systems (Savelsbergh & Van Woensel, 2016).

We have collected and analysed cases of this operational model from the scientific literature, trial reports and online resources. We propose a classification based on the degree of mobility and accessibility to customers of urban freighters. First, we consider whether urban freighters visit more than one transfer location in a single day. If so, we then distinguish systems in which they can, or cannot, deliver loads directly to customers. Finally, if urban freighters can deliver loads to customers, we distinguish between those that can visit only a subset of customers and those that can visit all customers (Figure 3.3).

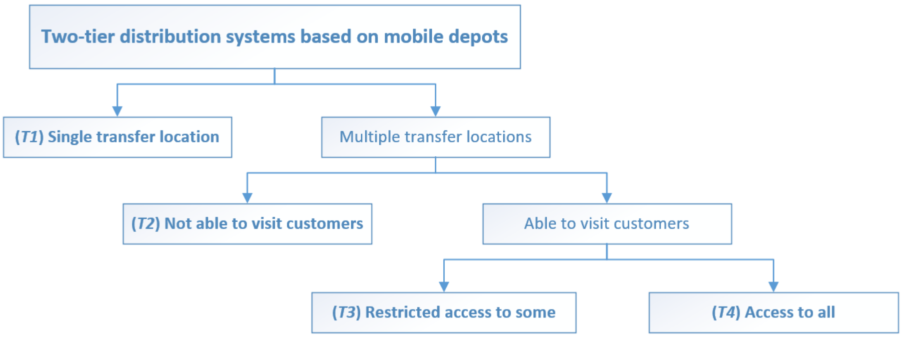


Figure 3.3: Classification of two-echelon distribution systems based on mobile depots.

3.3.1 T1 systems

Systems of type T1 consider that urban freighters are used only as “static” mobile depots. "Static", in this context, means that urban freighters do not move after arriving at a designated location except to return to the depot, i.e., the transfer location is always the same within a given day. The system is considered to be mobile in the sense that it does not require any permanent infrastructure aside from a parking space. This allows for a more flexible system, since by not being limited by a physical infrastructure, the urban freighters can park at different locations in different days if needed, as to better respond to changes in demand distribution.

An example of this type of system is presented in Verlinde et al. (2014) and in Verlinde & Macharis (2016). The concept was tested by TNT in Brussels over a highly urbanised area of about 12 km^2 with relatively high density of small consignments, during a period of three months in 2013, as part of the FP7 European Research project STRAIGHTSOL (Straightsol, 2014). A truck-trailer was used as a mobile depot from where first mile pickups and last mile deliveries of parcels and documents were performed. The truck-trailer had a loading dock, warehouse facilities, and an office (Figure 3.4). In the morning, the truck-trailer would be loaded at the suburban TNT depot with parcels to be delivered during that day to a specific area, and then brought to a public park in a central location in Brussels where it remained to be used as a central depot. Four electrically assisted cargo-cycles were used for the last mile deliveries. At the end of the day, the truck-trailer would return to the TNT Express depot located in the outskirts of the city. The last mile delivery was subcontracted to a local bike courier company that used their own garage to store and charge the cargo-cycles overnight.

Over the three month trial, the project had positive results regarding the reduction of diesel/km and the consequent estimated reduction of polluting emissions, such as CO_2 (-24%) and $PM_{2.5}$ (-59%), although estimated NO_x emissions rose due to the low utilisation rate of the mobile depot. Furthermore, the use of the truck-trailer and cargo-bikes also allowed for the reduction of the estimated road and kerb space use.

Nonetheless, the project revealed several disadvantages of this approach. First, there were

Figure 3.4: TNT's mobile depot trailer (Verlinde et al., 2014).

challenges in finding an appropriate location to park the trailer with the required space, good accessibility, access to electricity, and close enough to the cargo-bike garage in order to reduce the stem time of cargo-cycles. Furthermore, the use of public space also required obtaining permissions from several public authorities, which was perceived as a challenge. Moreover, the service levels, i.e., timely deliveries, were slightly hindered mainly due to the additional time to sort parcels at the mobile depot and load them into the cargo cycles, and to the overall adaptation to the novel operational procedures, which also increased the stem time. Other disadvantages were the limited space for sorting the parcels in the trailer, and the capacity of the cargo-cycles, which made it so that larger parcels continued to be delivered by the usual vans.

As for the economic impact, the costs of operating the mobile depot system during the trial were estimated to be the double of the costs of the business-as-usual (BAU) using regular vans. These costs include the costs for the cargo bikes deliveries, the truck-trailer used as the mobile depot, the estimated maintenance costs of the mobile depot, the costs for the parking ban (so that other vehicles would not block the road for the mobile depot), and the rental of the parking location. Nonetheless, it should be possible to decrease the operational costs as the mobile-depot was used at only 40%. Furthermore, when asked to express their satisfaction with the mobile depot concept against the BAU, both planners and dispatch riders preferred the BAU. This initiative was stopped and the company did not continue the project.

A similar distribution system has been deployed by UPS in Hamburg (UPS/GreenBiz, 2017), Dublin (Times, 2017) and Leuven (UPS, 2016). The system used truck-trailers that, once a day, after being loaded at the depot in the periphery of the city, were parked in preestablished central locations to be used as delivery hubs. From these locations, cargo bicycles, electrically assisted cargo tricycles, and walking porters would load, perform deliveries, and return multiple times per day to reload. At the end of the day the truck-trailer would return to the depot (Parr, 2017b).

According to (Ninnemann et al., 2017), four trailers were used in Hamburg, serving areas with radius of about 800 to 1000 meters. The delivery to the customers was performed using cargo-cycles (electrically assisted and not) and walking porters. These were used in different mixes depending on the delivery area, the drop-off density and the traffic conditions. Overall, cargo-cycles were mostly used in larger areas with smaller delivery densities, while the use of walking porters was more prevalent in smaller areas with higher drop-off density. Given the small capacity of these transportation modes, regular vans also had to be used to transport deliveries with more items, and items that would be too large or heavy to be transported by the walking porters or cargo cycles.

The project had a positive environmental impact, as it allowed for an estimated reduction of about 50% in CO_2 emissions, NO_x and PM emissions, although the use of a large diesel truck to bring and retrieve the mobile depot (trailer) from the city centre still contributed for a non-negligible amount of polluting emissions. An additional benefit was the reduction of the required stoppage time of vans for delivery purposes, thus avoiding the need for vans to find parking spaces or having to double park, particularly during the early morning period where the congestion was greater.

One of the main issues in implementing this system was the definition and search of appropriate locations to park the mobile depot in public spaces. It took about one year, and the approval process required very complex procedures and involved several specialised authorities from several public entities. Furthermore, there was an increase in space usage as trailers were required to be placed in selected areas of the city. Besides the area required for the mobile depot, there were additional requirements regarding the surrounding area, as it was necessary to guarantee that there was enough space for the truck to set and pickup the mobile depot, and for loading and unloading of the cargo-cycles. A diagram of the required configuration for UPS's mobile depot is presented in Figure 3.5.

To park each mobile depot there was a need of at least $32m^2$ (about 3 parking spots) and so, for all 4 locations there was a need of a total of about $130m^2$ of parking space in the central area of Hamburg. Additionally, there was also the need of space for storing the cargo-cycles after delivery hours. The pilot project considered 7 larger and 4 smaller bikes which required an estimated storage space of about $35m^2$. The public authority subsidised the areas where the mobile depot was located and supported the project by allowing the use of underground garages as a storage space for the cargo-cycles.

According to the report, UPS did not provide enough information to perform a proper cost benefit evaluation of the project. Despite this, it is reported that the use of the truck-trailer had additional costs including the rental of the location to park the mobile depot, the added personnel costs, and vehicle costs which included the development and purchase of the cargo cycles.

Another example is presented in Marujo et al. (2018), where the authors present an assessment of the economic and environmental impacts of a "mobile depot-based procedure" using trucks alongside with electrically-assisted cargo tricycles, to transport loads for a beverage company, as

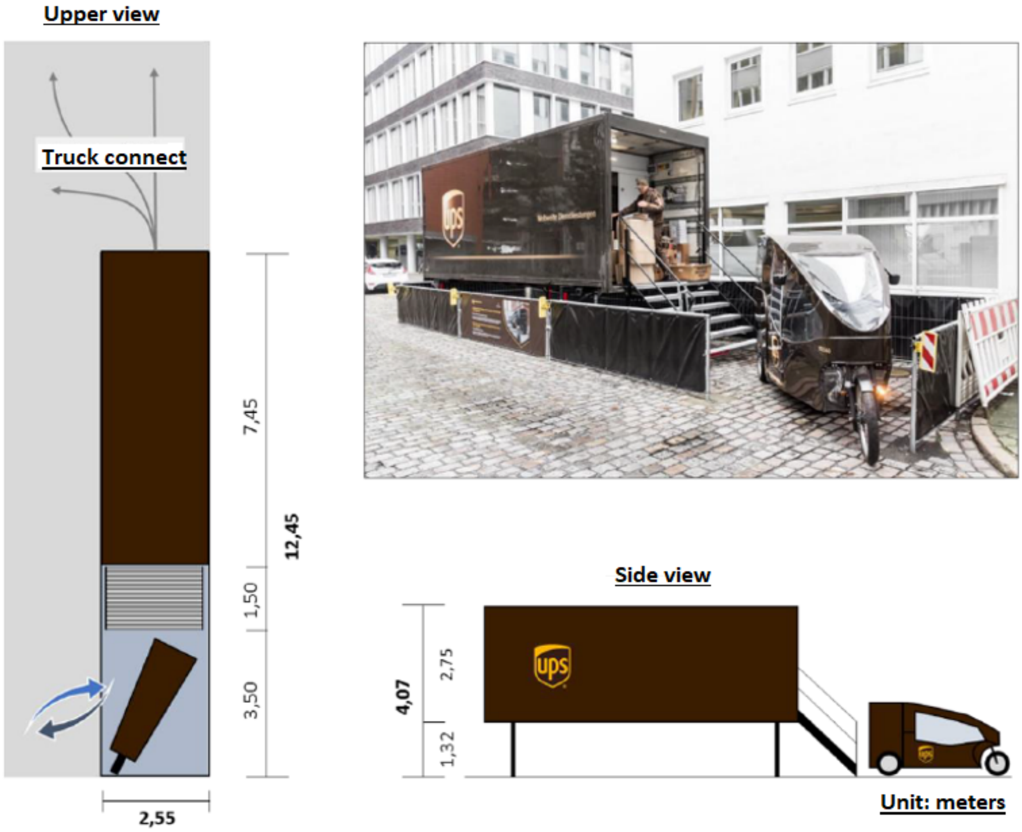


Figure 3.5: Diagram of UPS's mobile depot (Ninnemann et al., 2017).

a way to address the constraints imposed on heavy freight vehicle access in the centre of Rio de Janeiro, Brazil. Trucks would stop at private parking lots to transfer loads to cargo tricycles, that would perform the last leg of delivery. Besides using cargo tricycles, the system also considered the use of walking porters that delivered loads by foot, using a handcart to customers located closer to the mobile depot. To perform the analysis, the authors use Monte Carlo simulation.

Results of the study show that the use of the mobile depot system would have a positive environmental impact, with a reduction of 52% in CO_2 emissions, 58% of NO_x and 49% in PM. On the other hand, the use of the truck and cargo tricycles required a higher number of stops and more time/distance travelled, due to the small capacity of the tricycles, which had to return multiple times to the trucks to reload, particularly in areas with higher average drop sizes. Furthermore, the frequent transshipment operations, performed manually at the sidewalk, required significantly more product handling, were very time consuming, and increased the risk of product loss or damage. In economic terms, results showed that the mobile depot system was overall more expensive than using solely the trucks, and that it would only yield lower costs in urban areas with high density of stops and with small average drop sizes. This can be due to the small capacity of the cargo tricycles, because, as the average drop size increases, the number of customers able to be served in each trip reduces, thus requiring more reloading trips by the cargo tricycles.

CITYLOG project Another example of a T1 system was tested in Turin under the FP7 European Research project CITYLOG (Dell'Amico & Hadjidimitriou, 2012; Corongiu, 2013), than ran from 2010 to 2012. One of the project's aims was to define common specifications for a loading/unloading system for vehicle-to-vehicle transshipment of standard load units (containers) between trucks ("freight buses") and vans for urban delivery. Focus was given to vehicle technology and to standardised units aiming to achieve a greater interoperability among vehicles, especially in terms of load unit handling. The freight vehicle was a 16-ton truck with a capacity of 2 cubic load units, with 2,2 m side, designed with the intent of not having additional infrastructure or auxiliary equipment for unit load transfers between vehicles (Figure 3.6).

Figure 3.6: CityLog freight vehicle (collected from dissemination video).

This unit load design was meant to lead to a transshipment solution in which the truck and the delivery vans would not require to be synchronised in space and time, i.e., the unit load could be left in a secured transshipment area for later collection by the vans. No validation or impact assessment information could be collected as the project's deliverables are not available and the project website is no longer active. Nonetheless, it is mentioned that one of the most difficult aspects was to find a proper location in the city centre which was secure, and easily accessible by the freight truck, with enough area for vehicle manoeuvrability.

Conclusions The use of "static" mobile depots, together with the use of more environmentally friendly transport modes performing the last mile, can have significant positive impacts. Usually, there is an overall positive environmental impact when compared with the BAU, where only diesel trucks are used. Furthermore, it allows for a reduction of the need for parking areas and for a reduction of double parking situations, with a positive impact in traffic congestion.

The major downfalls of this type of systems is the need for relatively large parking spaces (usually public spaces) near or in the city centre. Furthermore, the choice of the location requires the consideration of several criteria, such as the existence of an access that would minimise the impacts of bringing a large trailer into the city, having the depot at a location with high drop densities in the surrounding areas, access to electricity and water, space to park and to safely transship loads. Furthermore, the added costs associated with these systems, and the resulting difficulty in guaranteeing economic sustainability, make these projects highly reliable on public subsidies to be economically viable.

Furthermore, the need for a lot of public space with the proper conditions, and the large visual impact of having these trailers in the city centre, can make this solution infeasible if many different service providers adopt this system (Ninnemann et al., 2017). The environmental impact of using large diesel trucks to bring the trailer to the city centre is not negligible, and hinders the overall environmental benefit of using soft modes to perform the last leg of delivery. The legal regulations for the use of alternative transportation vehicles, such as larger cargo-bikes, are not very clear, being therefore an obstacle for their adoption. The selection of the parking space and the procedures to obtain the required licenses to park the mobile-depot can be very complex and require the involvement of many stakeholders. In all cases, the operational costs related with implementing these systems are higher than the BAU, due to additional costs of renting the parking spaces, and storage spaces for the bikes.

We note that, to our knowledge, only the UPS examples might still be in use, although we were unable to confirm it. Furthermore, although most of these initiatives are driven by the private sector, the inclusion of the public sector seems crucial for their implementation, by contributing with some kind of funding, and with the emission of licences for the use of public infrastructure.

3.3.2 T2 systems

Contrary to the "static" depot-based systems of type T1, where urban freighters are only able to visit a single transfer location per day, T2 systems consider that urban freighters may visit multiple transfer locations in a day, but are unable to make direct deliveries to customers.

In these systems, urban vehicles serve only as mobile "warehouses" that transport freight from the outskirts of the city to *satellites* near the city centre, where freight is transferred to and from city freighters. Systems of type T2 are usually associated with two-echelon distribution systems where urban freighters are bounded to specific network corridors, and are required to respect strict schedules to be at transshipment locations. Next, we present some examples of these systems, split into three main categories, namely: i) inland waterways; ii) light-rail and trams; and iii) buses.

Use of inland waterways The use of inland waterway transport has been acknowledged as having a considerable potential for urban freight transport, including for the HORECA sector, parcel distribution and waste collection (Diziain et al., 2014; Maes et al., 2015; Janjevic & Ndiaye, 2014). For the proposed classification, we identified and reviewed some representative initiatives based on two-echelon distribution systems.

Vert Chez Vous A system involving barges as mobile depots was implemented by the French service provider *Vert Chez Vous* to distribute parcel and packages up to 30kg to the city centre of Paris (Janjevic & Ndiaye, 2014; Patier & Toilier, 2018). The parcels were first brought from different transporters to the company's depot to be consolidated and transferred to a barge. The barge would then sail down the Seine with precise timetables to berth at mooring sites serving e-tricycles which performed the last mile. The barge had a sorting area to prepare the packages into city freighter trips, as well as space to park the cargo-cycles overnight. Cargo-cycles were loaded and unloaded by a crane using a suspended cage (Figure 3.7). Each cargo-cycle was expected to returned to the barge three or four times per day, not necessarily at the same mooring site, to pick up or drop off packages (Parr, 2017c).

Figure 3.7: Vert Chez Vous's barge unloading trikes and packages (Parr, 2017c).

The initiative allowed for a reduction of the road occupancy time and for a reduction of distance travelled by vans (Patier & Toilier, 2018). Nonetheless, there were non negligible negative environmental and economical impacts. The barge was an adapted old traditional barge with a high fuel consumption. Furthermore, due to the lack of charging infrastructure at the quays, and the need of a continued use of the diesel engine to provide electricity, the use of the barge became quite inefficient (Patier & Toilier, 2018). *Vert Chez Vous* stopped using the barge-based system in September 2014, as the initiative business model proved not to be profitable (Parr, 2017c).

DHL Floating Service Centre Another example is the "DHL Express Floating Service Centre" used in Amsterdam (Maes et al., 2015; Parr, 2017a). The "floating service" is a barge used to transport, store and sort loads, as well as to carry cargo-bikes from the outskirts of the city to the city centre for last mile delivery. The distribution starts with a pre-haulage of loads from DHL's sorting depot, located in the outskirts of Amsterdam, to the dock to transfer loads to the barge. The barge follows a fixed route through the canals of Amsterdam, stopping at preestablished mooring sites in the city centre, where loads are transferred to cargo bikes and electric vans (used to transport larger and heavier loads) for the last leg of delivery (Figure 3.8). The project is still ongoing, and there is the intent to replace the old diesel-based barge by an electric one.

The main benefits of using inland waterways are related to the reduction of road vehicles entering the city centre, thus reducing noise, polluting emissions and congestion (Maes et al., 2015). Another benefit regards the capacity of using the barge as an overnight storage location for the cargo-cycles, therefore avoiding the need for the establishment of additional infrastructure to park the city freighters.

Figure 3.8: DHL's barge meeting up with a delivery bicycle and cargo-cycles stored inside the barge (Parr, 2017a).

On the other hand, there are several challenges in distribution systems based on inland waterways transport. When compared with the road transport, the use of inland waterways is usually more costly, because it requires additional specialised transshipment locations, tariffs related to fare charges, as well as increased handling operations (Janjevic & Ndiaye, 2014). Additionally, it is less flexible, as the density of inland waterways in most cities is not enough to deliver a substantial part of the urban freight volume. Furthermore, most suppliers and receivers are usually not located next to the waterways. This results not only in the need for an additional leg for last mile transport, but also in additional pre-haulage legs from the suppliers facilities to a waterside facility, where goods are to be bundled and transshipped to the vessels.

The use of inland waterways have other weaknesses that may hinder the adoption of this alternative, such as the existence of low bridges, narrow passages, shallow waters or even freezing over of the canals. Regarding the required infrastructure, there is a need for a close interaction with public authorities. Given the high costs of urban freight waterways projects, these initiatives are usually dependent on financial support by public entities to be viable, and must coordinate with these entities the provision of proper infrastructure for transshipment operations (Janjevic & Ndiaye (2014)).

Light-rail and trams Regarding the use of light rail and trams as urban freighters, several interesting initiatives across Europe have been implemented in recent years (Arvidsson & Browne, 2013; Marinov et al., 2013; De Langhe, 2014; De Langhe et al., 2019). These systems have considered the simultaneous transport of both freight and passengers, as well as the dedicated transport of goods, including parcels, palletized goods for the *HORECA*, retail, and industrial sectors.

CityCargo CityCargo Amsterdam launched in 2007 a cargo tram project, aiming to shift some urban freight from trucks to trams, for the distribution of goods to retail and for the HORECA sector, in the city centre of Amsterdam (Chiffi, 2015; Arvidsson & Browne, 2013; Marinov et al., 2013). Freight was pre-hauled from the suppliers to the end stop of the tram. There, freight was loaded to the tram with a payload of 30 ton (Marinov et al., 2013), after being sorted in the delivery area (Arvidsson & Browne, 2013). From there, the trams followed a specific route towards the centre of Amsterdam, travelling behind passenger trams as not to interfere with the schedules of public transport (Arvidsson & Browne, 2013). Two transshipment locations were considered, where freight was transferred from trams onto small delivery vehicles (e-cars) for last mile delivery (Figure 3.9). The distribution system was presented as being very cost efficient, as 1 cargo tram would transport the same amount of freight as 4 (7,5 ton) trucks. The estimated environmental impacts pointed towards a reduction of about 16% in polluting emissions (including PM, CO_2 and NO_x) (Chiffi, 2015). After the success of the trial, CityCargo Amsterdam was allowed to use the Amsterdam tram network to transport freight with a 10 years concession from the municipality. Nonetheless, the initiative eventually went bankrupt in 2009 due to the lack of public subsidies for the construction of the required extra tracks (Chiffi, 2015).

Figure 3.9: Transshipment of freight from the cargo-tram to an electric delivery vehicle.

LastMileTram Another pilot project was put in place in the city of Frankfurt in 2018 for a period of 14 months, in a joint collaboration between the public authorities, CEP providers and the academia (Schocke et al., 2020). The objective of the *LastMileTram* project was to assess the potential of using trams together with cargo-cycles, to transport parcels and packages using standardised containers, as an alternative to road transportation. The delivery process would start with the pre-haulage of containers with pre-sorted parcels, from the CEP providers depot to the end-stop of a tram. After being loaded, the tram would then travel to the city centre stopping at transshipment points, where the containers would be transferred to cargo-cycles for last mile delivery. The cargo-cycles would return multiple times to the tram, keeping in contact with the tram by phone to establish the next transshipment point where to return the empty container and reload.

The pilot ran for 4 days, and considered only one tram running on a dedicated track and one transshipment point, as to not affect the public transport. For last mile deliveries, two different types of cargo bikes/container sets were tested, namely: i) a 0,7 m^3 Riemann transport box and trailer system, and; ii) 1 m^3 containers for Velove Armadillo cargo-cycles (Commission, June 2018). The cargo cycles and trailers were stored in garages near the tram depot. Tests showed that the transshipment of the containers can be quite efficient, especially when using the Velove Armadillo cargo-bike and container (Figure 3.10). Nonetheless, it would be necessary to adapt the transshipment points (tram stations) and the trams to transport and transship the containers fast and safely.

Furthermore, stakeholders identified potential problems arising from the need to synchronise the trams and the cargo bikes. To avoid synchronisation issues, it was suggested that the system should consider some infrastructure where to unload and store the containers. By doing so, cargo-cycles could return to these locations to reload, instead of having to coordinate with the trams the next transshipment point. The downside of this solution is that this would require the additional adaptation of large spaces at the tram platforms, as to not interfere with public transport. Setting these storage locations would also entail additional setup and maintenance costs.

The pilot test showed that it is technically possible to use trams together with cargo-cycles for parcel distribution. Results have showed that the tram-based system, when compared with using only trucks, had an increase in the cost per parcel by 17%, but it would allow for a reduction of 57% in CO_2 emissions.

Figure 3.10: Container transported inside tram, and its transshipment to a Velove cargo-cycle.

The benefits of using light-rail and trams for urban distribution mostly regard environmental benefits due to the reduced number of trucks required to transport loads into the city centre. Despite this, several barriers for successful implementation of an intermodal freight distribution system using trams as feeder vehicles have been identified, namely: i) interference with passenger traffic, as it may compete with passenger services for line capacity; ii) lack of a legislative framework; iii) resistance from different stakeholders; iv) high initial investment in vehicles and infrastructure adaptation; v) radius of action and lack of flexibility; and vi) need of pre-haulage from the suppliers to the feeder vehicle depot.

Buses Arvidsson & Pazirandeh (2017) present an *ex-ante* evaluation of the potential economic, environmental, and social impacts of a distribution system based on "freight buses" with access to corridors, much like bus rapid transit (BRT) systems (Figure 3.11). These buses would travel throughout the city, and stop at specific locations to transfer loads to smaller and more environmentally friendly transport modes such as bicycles, tricycles and walking porters. The base scenario compared the use of two diesel vans against using a freight bus and two cargo bikes to transport 160 parcels, based on data from a medium size parcel distributor in Gothenburg, Sweden, in 2015. The performed economic analysis showed that the solution using the buses as mobile depots would be about 24% more expensive than using the two vans. As for the environmental impact, when comparing with the base scenario, there was no substantial reduction in CO_2 emissions. Nonetheless, the analysis showed that the system could have a positive environmental impact, and be economically viable, when the amount of loads to deliver is large. According to the stakeholders, the main advantages of this solution would be the reduction of polluting emissions, noise and visual impact, and congestion. As for the main barriers, the stakeholders pointed out the difficulty to synchronise the bus and the cargo-cycles so that direct transfers could be performed, along with business risks and reward sharing issues, as well as an overall resistance to change by the operators.

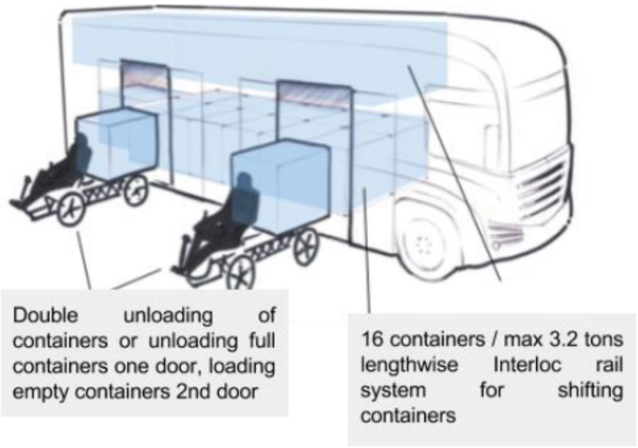


Figure 3.11: A suggestion of load transfers by Per Gyllenspetz in the Vinnova project Mobil Depa (Arvidsson & Pazirandeh, 2017).

A similar system is addressed by Masson et al. (2017), who introduce the *Mixed Urban Transportation Problem* (MUPT). The problem arises in the context of B2B parcel delivery, where buses are used to transport containers with parcels from a consolidation centre located in the outskirts of the city to bus stops, where they are directly transferred to smaller, more environmentally friendly vehicles operating at the second echelon (not specified) to perform the last mile. This synchronisation requirement is reflected in the need to plan the city freighters routes so that whenever a container needs to be unloaded at a bus station, at least one city freighter should already be present. The paper proposes an *adapted large neighbourhood search* (ALNS) procedure to solve the problem, but does not compare this distribution approach with the current use of vans. Nonetheless, results using smaller instances based on data collected from the city of La Rochelle, France, show that as the average demand increases, the distance travelled by the trucks does not always increase, while for city freighters it does, as they have smaller load capacities and are required to return several times to a bus stop, to load a new container for additional deliveries. Furthermore, results highlight the need for efficient transshipment operations and the risks of bad synchronisation between the city freighters and the bus.

3.3.3 T3 and T4 systems

Both T3 and T4 types consider that urban freighters can visit more than one transshipment location in a given day, and that they can perform direct deliveries from the depot to the customers.

The difference between systems of type T3 and T4 is the extent to which the urban freighters can perform direct deliveries from the depot to final customers. If they can only perform direct deliveries to a subset of all customers, then the system is of type T3. On the other hand, if the urban freighters can deliver to all customers, the system is of type T4. The inability of urban freighters to deliver loads directly to some customers can be due to: i) policy constraints or regulations that limit the access to a given area, such as Low Emission Zones (LEZ) or time window constraints for deliveries; ii) a stated intention of not accessing certain areas; iii) the intention of not having the drivers of urban freighters making a delivery route on foot while the vehicle remains parked.

The main reason for this subdivision between T3 and T4 is due to the planning flexibility of each of these types. In T3 systems, much like in systems T1 and T2, there is always the need to use city freighters, as it is established upfront that some customers cannot be served by urban freighters. On the other hand, there is more flexibility when planning for T4 type systems, as planners can deploy the best vehicle mix without having to account for preestablished customer assignment to urban or city freighters.

Pharmacies in Vienna A T3 type system is addressed in Anderluh et al. (2017, 2021) regarding the delivery of goods to pharmacies in Vienna, Austria. The system in based on a single depot located in the outskirts of the city, from which all loads destined to the city originate. Loads are transported by vans, that can perform direct deliveries to customers located further from the city centre, as well as transfer loads to cargo bikes for last mile deliveries in the city centre. After delivering all loads, the cargo-cycles meet with the van at a transshipment point, where they reload and perform an additional delivery route. By solving the underlying vehicle routing problem, the authors show that combining both cargo-cycles and vans results in higher operational costs when compared to delivering with only vans, but with a positive impact in terms of polluting emissions. Results also show that the need of vehicle synchronisation leads to additional waiting times and increased operational costs when compared with systems where satellites have storage capabilities.

DHL *CityHub* project DHL Express has piloted two different distribution systems under its *CityHub* project, where containers were transported by vans to the city centre, to be transferred directly to cargo-cycles to perform the last mile.

The system piloted in 2015 considered vans carrying a single container in the back, which would be transferred to a Velove armadillo cargo-cycle (Figure 3.12) at locations close to the city centre. After transferring the container, the van would continue its delivery route outside the city centre, and later would pickup the empty container and return to the depot (Erlandsson, 2016).

Figure 3.12: DHL container transfer between van and cargo-cycle (Erlandsson, 2016).

In 2017, DHL Express piloted another similar distribution system, the *CityHub* project, in the cities of Frankfurt, Germany and Utrecht, Netherlands (Deutsche Post DHL Group, 2017; Erlandsson, 2018). This distribution system was based on the use of a customised trailer able to carry up to four 1 m^3 containers, with a capacity of about 125 kg, which were pre-loaded at parcel sorting centres located at the periphery of the city, and transported by trailer into the city centre by a van. The van-trailer would park at a given location, where the containers would be transferred to the cargo-cycles for last mile deliveries (Figure 3.13). After completing each round, the cargo-cycles would return to the trailer to reload or to return the container so that they would be transported back to the sorting depot.

To better understand the DHL pilots, we interviewed Mr. Marijn Slabbekoorn, the GoGreen Europe Program Manager at DHL Express. Both systems underwent short period trials, and were not being used anymore. The main reason for abandoning these systems, were: i) the large volume of the the container in the back of the van, leaving little space for van deliveries, ii) the difficulty in synchronising the meetings of both vans and cargo-cycles, since long waiting times would always occur due to unforeseen events; iii) the need to find somewhere to store and charge the cargo-bikes; and, iv) problems finding locations with appropriate space for the container transfers.

UPS pilot UPS deployed a delivery pilot project in Seattle, using a concept similar to the approach taken by DHL, with detachable, modular boxes with a capacity of 95 cubic feet and 400

Figure 3.13: DHL container transfer from trailer (Erlandsson, 2018).

lbs, that were directly transferred between vans and pedal-assisted cargo e-bikes for last mile deliveries (UPS, 2018). The proposed distribution system considers that these containers are be pre-sorted according to neighbourhood or route, at sorting centres located in the outskirts of the city (McQuate, 2018). The vans make deliveries to customers, and meet with the cargo-bikes at specific locations to directly transfer the container to the cargo-bikes using a specially designed trailer (Figure 3.14). The cargo e-bikes operated in the historic Pike Place Market, and downtown Seattle, aiming to lower congestion in these areas, by reducing van dwell time, double parking and other unintended consequences associated with downtown deliveries.

Figure 3.14: UPS modular box transfer to cargo-cycle (McQuate, 2018).

Gnewt Cargo initiative Another system has been tested by the Gnewt company in 2018, under the TfL consolidation Demonstrator project (Clarke et al., 2018), integrated in the Fright Traffic Control (FTC) research project (FTC2050, 2015). The trial consisted in using walking porters in the delivery of parcels and packages in Central London, as an alternative to having only electric vans delivering the parcels (Allen et al., 2018; Bates et al., 2018). The goals were to reduce the parking time spent by vans at the kerbside/on-street, as well as reduce vans' driving time and distance, in the city centre.

The delivery process started at the main depot with the sorting and assignment of parcels to vans and walking porters (Figure 3.15). The vans were used to transport and deliver larger parcels which would be too large or heavy to be transported by porters, and to carry the trolleys to be transshipped to the walking porters.

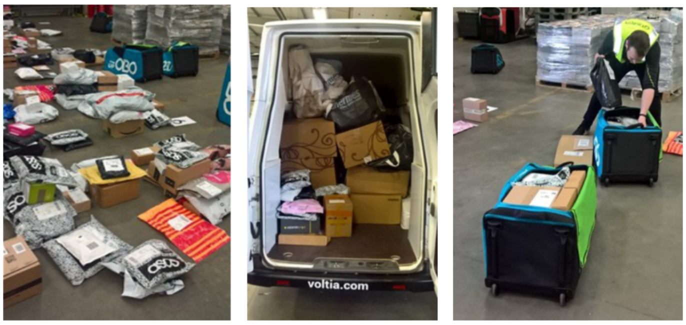


Figure 3.15: Sorting and loading of van and trolleys (Clarke et al., 2018).

The vans and porters would briefly meet at the kerbside (outside busy streets) to transfer the pre-sorted trolleys from the vans to the walking porters (Figure 3.16). Then, both vans and walking porters would go on with their delivery routes. Whenever porters would finish a route, they used a mobile app to coordinate with the vans the next meeting point to replenish or switch the trolley.

Figure 3.16: Van arriving at transfer location for trolley replenishment and porter working (Clarke et al., 2018).

The project results showed that the portering system allowed for a reduction of the kerbside parking of 50%, and for a reduction in vehicle driving times and distances, when compared with delivering only with the van. Nonetheless, the portering trial increased delivery costs by around 43%. This was greatly influenced by the increase in total labour time (20 % per parcel and 65% per consignee). According to the authors, the system would be cost neutral if porters carried 90% of all parcels.

Furthermore, in 2019, Gnewt Cargo, in collaboration with Ford Last Mile Delivery tested a similar portering system, supported by Ford's cloud based, multi modal routing and logistics planning software *MoDe:Link* (Ford Media Centre, 2019), allowing for the coordination of multiple modes of transport including vans, cargo cycles and walking porters (3.17).

Figure 3.17: Ford MoDe:Link freight transfer demonstration (Ford Media Centre, 2019).

3.4 Chapter summary

In this chapter, we have presented and described the state-of-practice of two-echelon urban distribution systems used for urban freight distribution. In some of these systems, satellites have short time storage capabilities, and in others satellites do not have storage capabilities. The latter systems consider that urban freighters serve as mobile depots, and require space and time synchronisation between urban and city freighters to allow a direct transfer of loads.

Most of the analysed cases have been implemented in European cities, and have been used in the CEP sector for parcel/package distribution, but not for palletized loads. The main type of vehicles operating at the second-echelon are usually electrically assisted cargo-cycles, although e-vans (used to transport larger or heavier loads), and walking porters have also been reported. It should be noted that, despite the concerns of having environmentally friendly vehicles operating at the second echelon, most urban freighters still use diesel fuel. As for the existence of multi-trips, all reviewed cases consider multi-trips performed only by city freighters. This can be explained by the fact that city freighters have smaller load capacity, and that they deliver in city centres with higher concentration of delivery points, therefore allowing them to perform multiple trips during a working day.

An interesting finding regards the number of cases considering the use of standardised and modular containers for the seamless transfer of loads between vehicles operating at different echelons. The idea is to mimic the concept of the shipping container, but in a smaller scale, allowing for better load factors of vehicles operating in city centres, interoperability between different transport modes, and overall faster transfers of loads between urban and city freighters, since repacking/resorting of loads is avoided. This is in line with the need for the development of standardised and modular logistic units and of technology to transfer loads between different sized vehicles/transport modes, as proposed in Alice/Ertrac (2015). Furthermore, the use of these standardised and modular containers has also been considered when evaluating city logistic solutions in the context of the Physical Internet (Crainic & Montreuil, 2016).

Most of the analysed cases are mainly operated by carrier companies with the support of city municipalities that want to experiment novel distribution systems to mitigate the environmental impacts of freight distribution in urban areas, and to anticipate more restrictive policies in the access of dense urban areas. The role of public authorities in the successful implementation of two-echelon distribution systems based on mobile depots cannot be understated. Public authorities seem particularly important in partially financing operations in the beginning of the projects as to guarantee their (economic) viability. As public support dwindles, two-echelon distribution systems based on mobile depots seem to lose their (economic) viability, which may explain the high number of initiatives that are no longer in operation. Furthermore, public authorities are also important in the provision of proper infrastructure for transshipment operations. This includes the provision of public spaces for the establishment of micro-consolidation centres, parking locations for containers used as mobile depots, locations for storing cargo-cycle storage, and of mooring sites with the minimum infrastructure for load transshipment. Only T3/T4 systems may avoid the need for public support, as load transfers may occur seamlessly at the kerbside. Nonetheless, even in this case, there is usually the need to account for some physical infrastructure for overnight parking and possible re-charging of electric vehicles. However, the inclusion of all relevant stakeholders, both private and public, seems to be a crucial element for the success of these solutions.

Chapter 4

Operational research methods for two-echelon distribution systems

In this chapter, we present a literature review on operational research approaches for the design and planning of two-echelon distribution systems in the context of *City logistics*.

Since the *Vehicle Routing Problem* (VRP) was first introduced by Dantzig & Ramser (1959), there has been extensive research on many different VRP variants and applications. However, in the context of *city logistics*, only recently have these problems received a significant attention in the literature (see, for example, the surveys presented in Kim et al. (2015), Savelsbergh & Van Woensel (2016), and Cattaruzza et al. (2017)). The problems addressed in this work encompass several characteristics of known VRP variants, including the *Two-Echelon (Capacitated) VRP* (2E-CVRP), the *VRP with Multiple Synchronisation Constraints* (VRPMS) and the *Multi-trip VRP* (MTVRP). Next, we present a review on two-echelon vehicle routing problems and variants.

The decisions around the design and planning of two-echelon distribution systems can be split into strategic, tactical and operational levels. First, in Section 4.1, we present a brief overview on the strategic and tactical problems, and Section 4.2 is dedicated to the operational level planning.

4.1 Strategic and tactical planning

At the strategic level, decisions are usually related with infrastructure investments, such as the determination of the number, location and characteristics of urban consolidation centres and/or *satellites*, as well as the definition of freight corridors and loading bays required to support the distribution system (Crainic et al., 2009; Cuda et al., 2015). These problems have been mostly modelled as multi- or two-echelon location routing problems (2E-LRP), for which Drexl & Schneider (2015) present a comprehensive survey.

According to Cuda et al. (2015), 2E-LRPs regard both strategic and tactical decisions, and consider that there are goods available at peripheric locations (depots) which have to be delivered to their respective destination in the city centre, moving them mandatorily through intermediate facilities (*satellites*). According to Crainic, Sforza, & Sterle (2011), the main decisions in 2E-LRP encompass: i) facility location, i.e., the determination of the number and location of depots and *satellites*; ii) allocation, i.e., the assignment of each customer to a *satellite* and the assignment of each *satellite* to a depot; and iii) fleet size and routing, i.e., the determination of the number (and possibly type) of vehicles to be used in each fleet and the associated routes in each echelon. The capacitated 2E-LRP is the most studied problem among 2E-LRP. In the 2E-CLRP, both types of vehicles are capacitated and homogeneous within the same echelon, there is a fixed cost for using a vehicle, and both fleets are assumed to be unlimited. The 2E-CLRP aims at finding the optimal set of location sites and/or *satellites*, as well as the optimal set of routes of vehicles necessary to satisfy all customer demands, while respecting vehicle and *satellite* capacity constraints (Crainic et al., 2010). Most variants usually consider one or more depots (UCCs) and decisions on the locations of facilities of a single echelon, or both. A thorough classification, based on Crainic, Sforza, & Sterle (2011), is presented in Cuda et al. (2015).

A novel approach to solve large scale 2E-LRPs is presented by Winkenbach et al. (2015) when addressing the problem of a large postal operator in France. The proposed MIP model encompasses decisions regarding the number, size and location and of facilities at both levels, as well as the determination of how many vehicles of each type should transport loads from each facility. The most important contribution is the proposed route length estimation considering mixed fleets, destination-specific vehicle capacities, global maximum service time, and joint pick-up and delivery in the same routes. Merchan et al. (2015) present the same modelling framework to solve a 2E-LRP in the city of Bogotá, Colombia, where the results for the analysed case study show that, for urban zones with higher retail density, bicycle deliveries are the most cost effective delivery option, mostly due to fixed cost considerations. A similar model is presented in Merchan & Winkenbach (2018) and applied to e-commerce parcel delivery operations in São Paulo, Brazil.

Tactical planning models for two-echelon distribution systems usually concern the determination of the schedules, routes and loads of vehicles, the routing of demand and the assignment of customers to *satellites* (Crainic, Errico, et al., 2015a; Cuda et al., 2015). A discussion on the main definitions and solution methods for tactical level planning is presented in Mancini et al. (2014).

Crainic & Sgalambro (2014) address the issue of planning the services of the first-echelon system, i.e., select the services, their routes and schedules (between distribution centres on the outskirts of the city to *satellite* platforms), as well as determine the itineraries of customer demand flows through the facilities and transport services. To solve this problem, the authors propose a general scheduled service network design modelling framework based on a fixed charge network design mathematical model, and discuss different operational characteristics of urban fleet management, as well as some algorithmic perspectives on how to solve these problems.

Crainic, Errico, et al. (2015a) propose a two-stage stochastic programming model where the first stage establishes the first-echelon service network design. This stage gives an indication of the workload of *satellites*, as well as the required fleet to be used in the second-echelon. The second stage determines the actual vehicle routing of second-echelon vehicles, and it is also used to perform minor changes to the service network design decisions made at the first stage. The authors propose four different recourse strategies and formulations, which are compared using an evaluation procedure based on Monte Carlo simulation.

Fontaine et al. (2017) present a novel formulation for the service network design problem in two-echelon distribution systems, similar to the knapsack or bin packing problems, where services are modelled as bins to which demands are assigned, with the main difference being the complex cost structure of services assignment. To solve the problem, the authors propose a Benders decomposition technique where the problem is decomposed into two easier to solve subproblems.

4.2 Operational planning

The use of two-echelon distribution systems in the context of *city logistics* was first addressed in Crainic et al. (2004, 2009), but a formal definition for the *two-echelon (capacitated) vehicle routing problem* (2E-CVRP) was introduced by Gonzalez-Feliu (2008) and Perboli et al. (2011). The basic variant of the 2E-CVRP aims at determining the routes of vehicles operating at both echelons, such that the demand of all customers is satisfied, while respecting vehicles capacity. In the basic variant of the problem, all loads must be delivered through the *satellites*, i.e., there are no direct deliveries from the depot, and it is possible to have load consolidation at the *satellites*. Additionally, city freighters may only perform a single trip, and they are assumed to be stationed at the *satellites*. Both exact and heuristic solution methods have been proposed to solve the 2E-CVRP. Next, we present an overview of the main literature on 2E-CVRP. For a more detailed analysis, we refer the reader to the survey by Cuda et al. (2015) and the recent literature review by Sluijk et al. (2022).

Exact methods Regarding the use of exact methods, Gonzalez-Feliu (2008) proposes two flow-based formulations for which he presents some valid inequalities. Similarly, Perboli et al. (2011) also propose a flow-based MIP formulation and two families of valid inequalities derived from the VRP literature. Additional valid inequalities, as presented in (Perboli & Tadei, 2010) were also tested but, as the improvement was quite marginal when compared to the high computational effort required, those inequalities were not considered. To solve the problem, the authors propose two matheuristics based on the information obtained from solving the model's linear relaxation. Jepsen et al. (2013) show that the model proposed in Perboli et al. (2011) may not provide the correct upper bounds when more than two *satellites* are used in the solution. To address this issue, the authors propose a formulation similar to the one presented in Perboli et al. (2011), but add a vehicle index k on the first echelon decision variables, making the model highly symmetric. To overcome the symmetry issue and improve the lower bounds, the authors propose an edge-based model, which is a relaxation of the flow-based model that does not necessarily yield feasible solutions for the 2E-CVRP. To overcome this downfall, the authors use a feasibility test and a specialised branching scheme in their *branch-and-cut* (B&C) algorithm as to obtain feasible solutions. Santos et al. (2014) present a route-based IP formulation for the 2E-CVRP, which does not include an index for vehicles as a previous model did (Santos et al. (2013)), thus overcoming the symmetry issues. The authors propose a *branch-and-cut-and-price* (*B&C&P*) algorithm, derive several valid inequalities and include tighter coupling constraints that allow for stronger LP bounds. Baldacci et al. (2013) propose a route-based IP formulation which is used to derive both continuous and integer relaxations. They also propose a bounding procedure based on dynamic programming, a dual ascent method, and an exact algorithm that decomposes the 2E-CVRP into a limited set of *multi-depot capacitated vehicle routing problems* (MDCVRP) with side constraints. The final solution is then obtained by solving the resulting set of MDCVRPs. Marques et al. (2020) present a route-based formulation which does not use variables to determine the product flows in *satellites*, but instead uses new balancing constraints to guarantee flow conservation. The problem is solved using a *B&C&P* algorithm that incorporates valid inequalities from the VRP literature as well as new sets of valid inequalities. The algorithm also has a set of improvements including a bucket graph based labelling algorithm for the pricing problem, limited memory rank 1 cuts, and a tailored branching strategy.

Heuristic methods Given the complexity of the problem, several heuristic methods have been proposed to solve the 2E-CVRP. Crainic, Mancini, et al. (2011) present a set of multi-start heuristics based on the separation between the routing problems in the first and the second echelons. First, customers are clustered and assigned to *satellites*, and the complete solution is computed by solving the resulting first- and second-echelon VRPs using an exact method. The heuristic then applies small perturbations to the solution, by changing the assignment of customers to clusters, and the problems are solved again. A similar problem separation approach is used by Crainic et al. (2013), who propose a metaheuristic based on a *Greedy Randomised Adaptive Search Procedure* (GRASP) and path-relinking. Hemmelmayr et al. (2012) propose an *Adaptive Large Neighbourhood Search* (ALNS) heuristic where several *destroy-and-repair* operators are selected and used independently based on their success in previous iterations. Similarly, Breunig et al. (2016) propose a hybrid metaheuristic based on the *Large Neighbourhood Search* (LNS) heuristic combining *destroy-and-repair* principles with a local search procedure. Results show that this method is able to find higher quality solutions than the ALNS proposed in Hemmelmayr et al. (2012), and requires, on average, less local and global operators. Zeng et al. (2014) propose a hybrid heuristic combining a GRASP to generate the initial feasible solutions and a *Variable Neighbourhood Descent* (VND) algorithm during the solution improvement phase.

A summary of the literature review on both exact and heuristic methods to solve the basic variant of the 2E-CVRP is presented in Table 4.1.

Variants with time considerations The basic 2E-CVRP has been the most studied variant of the problem. Other variants such as those including time aspects such as time windows, time-dependent travel times, and/or vehicles synchronisation have received less attention in the literature.

First, we present a brief overview of the literature addressing 2E-CVRP with time windows and time-dependent travel times. We then follow with a more comprehensive review of 2E-CVRP

Table 4.1: 2E-CVRP related literature.

	Reference	Math. formulation	Decision variable type	Solution approach
Exact methods	Gonzalez-Feliu (2008)	MIP;IP	Arc	B&B
	Perboli & Tadei (2010)	MIP	Arc	B&C
	Perboli et al. (2011)	MIP	Arc	Matheuristics
	Jepsen et al. (2013)	MIP	Arc, edge	B&C + branching scheme
	Baldacci et al. (2013)	IP	Route	Problem specific
	Santos et al. (2013)	IP	Route	B&P
	Santos et al. (2014)	IP	Route	B&C&P
	Marques et al. (2020)	IP	Route	B&C&P
Heuristic methods	Crainic, Mancini, et al. (2011)	-	-	Multi-start heuristics
	Crainic et al. (2013)	-	-	GRASP + path-relinking
	Hemmelmayr et al. (2012)	-	-	ALNS
	Zeng et al. (2014)	IP	Route	GRASP + VND
	Breunig et al. (2016)	-	-	Hybrid LNS

considering vehicle synchronisation between vehicles at satellites, as it is closely related with the problems arising in two-echelon distribution system based on mobile depots (see Section 3.3), where vehicles are required to be synchronised both in time and in space at satellites, in order to transship loads directly between vehicles operating at each echelon.

Regarding only the inclusion of time-windows, Dellaert et al. (2019) present one arc-based and two path-based mathematical formulations for the 2E-CVRPTW. The two latter formulations are then solved using a *branch-and-price* (B&P) algorithm, along with an adapted labelling algorithm and a set of combined branching strategies. Recently, the authors extended their work in Dellaert et al. (2021) by considering the case with multiple commodities.

Another time aspect often considered is time-dependent travel times. One of the characteristics of most 2E-VRPs is that they assume constant cost/travel times between locations, which is a strong assumption when considering planning for urban scenarios where congestion levels usually differ throughout the day (Cattaruzza et al., 2017). By considering time-dependent travel times it is possible to better plan vehicle routes (Ehmke et al., 2012) as well as reduce pollutant emission and time windows violations (Figliozzi, 2011; Fleischmann et al., 2004).

Travelling times change continuously throughout the planning horizon but for modelling purposes they are considered as changing discretely in time slots. Different solution methods have been presented for the time-dependent vehicle routing problem (TDVRP) such as multi ant-colony systems (Donati et al., 2008), tabu-search (Ichoua et al., 2003; Ehmke et al., 2012) and other adaptations of constructive heuristics for the VRP (Fleischmann et al., 2004; Ehmke et al., 2012; Figliozzi, 2012).

Time-dependency in two-echelon distribution systems in the context of city logistics has been seldom addressed in the literature. Some authors have considered time-dependent arc characteristics to account for congestion levels during different times of day, in order to better estimate the environmental impact of vehicle routing in an urban scenario. For example, Soysal et al. (2015)

propose a arc-based MIP model for the 2E-CVRP based on the formulation presented in Jepsen et al. (2013). Environmental considerations are taken into account by including time-dependent travel times as well as fuel consumption. Time-dependent travel times are only considered for some arcs in the city centre, which may only be transversed by second-echelon transport modes. The authors address a case study in the Netherlands, encompassing one depot, 2 *satellites* and 16 customers, and solve the model using CPLEX. The results of the two-echelon distribution system are evaluated and compared against a single-echelon alternative according to four Key Performance Indicators (KPI): total distance, total time, total fuel consumption, and total cost. The model is solved four times considering each KPI as the objective function while maintaining the base formulation. Results show that the proposed two-echelon distribution system is more advantageous in terms of travel distance, total time and total fuel consumption, which in turn reflects in lesser environmental pollution impacts.

This problem is also addressed by Wang et al. (2017) who propose a arc-and-route integer programming (IP) model where the arc formulation from Soysal et al. (2015) is kept, but second-echelon routes are modelled as routes instead. The authors consider four time/zones, and like in Soysal et al. (2015), time-dependent travel times only exist in some arcs in the city centre (second echelon). In order to solve the problem, the authors propose a matheuristic based on a Variable Neighbourhood Search (VNS) procedure, and the proposed IP model is solved using CPLEX. The IP is used as a post-optimisation technique to find better solutions, not found by the VNS, or to construct the least cost first-echelon routes, given the routes at the second echelon. The authors compare the base problem with the alternative of considering split deliveries at the first echelon, i.e., when more than one vehicle operating at the first echelon is able to visit the same *satellite* so that loads from both vehicles can be combined.

A related problem considering time related constraints in the context of city logistics can be found in Muñuzuri et al. (2013), where the authors present the Vehicle Routing Problem with Access Time Windows (VRPATW). The problem formulation differs from the classical VRPTW in two main aspects: i) the time window is not assigned to customer nodes but to a whole restricted zone; and ii) time windows corresponds to the time interval during which delivery vehicles are not allowed to drive or wait inside the restricted area. The authors do not present a mathematical formulation for the problem, and solely propose a heuristic based on a Genetic Algorithm (GA) and a constructive heuristic in which feasibility is assessed given the requirements of the restricted zones. They conclude that even small restricted zones with short banned periods result in significant cost increases, which grow exponentially as these restrictions increase. Results show that the cost increase does not seem to depend on the number of serviced customers, meaning that both large and small operators would be equally affected by access time windows policies. Furthermore, the impact of the restricted zone area and the range of the time windows increases when the number of customers is larger. This means that, although restriction zones with time windows may contribute for improving accessibility to the city centre and liveability, and for reducing noise, they may however have a negative impact on other indicators, such as economic and environmental sustainability, due to the increased number of required vehicles and total distance travelled.

Grosso et al. (2018) extend the work of Muñuzuri et al. (2013) by proposing a formulation for the VRPATW problem, as well as a Tabu Search and a GA heuristic. When comparing these heuristic solution methods, the authors conclude that, aside from the exact method, which is only able to solve the smaller instances, it was not possible to assess which of the other heuristics is the best for solving the problem. Quak & de Koster (2009) also address the implications of access time windows in *City Logistics* by focusing on multi-town scenario, which according to Muñuzuri et al. (2013), dilutes the effects of access time windows in vehicle routing problems. In their paper, the authors study the impact of time windows and vehicle restrictions in the financial and environmental performance of retailers. They do not present any model for the problem and solely use a generic vehicle routing software to perform their assessment.

Synchronisation and multi-trips The 2E-CVRP with vehicle synchronisation at satellites belongs to the class of *vehicle routing problems with multiple synchronisation constraints* (VRPMS), for which Drexl (2012) presents an excellent survey. The main characteristic that distinguishes this class of problems from standard VRPs is the presence of the so-called *interdependence* problem, where a change in one route may have effects on other routes, and in the worst case, it may render all other routes infeasible, greatly increasing the complexity when developing solution methods for these problems.

The synchronisation between urban and city freighters has been seldom addressed in the literature (Cuda et al., 2015; Guastaroba et al., 2016; Savelsbergh & Van Woensel, 2016; Cattaruzza et al., 2017). Nonetheless, two different modelling approaches have been used to address the synchronisation of vehicles at satellites, although only one truly suffers from the aforementioned *interdependence problem*.

The first approach considers that the time and place of possible load transfers is established *a priori*, and therefore this approach does not suffer from the *interdependence problem*. Given this, only second-echelon vehicles' routing and scheduling are taken into account. Instances of such situations are found, for example, when two-echelon distribution systems rely on public transportation or other scheduled transport systems, at the first echelon. Masson et al. (2017) propose an ALNS heuristic to solve the *Mixed Urban Transportation Problem* (MUPT) where buses are used to transport containers with parcels, that are directly transferred to city freighters at bus stops as to perform the last leg of delivery. A single bus line is considered and the schedules of the buses are given *a priori*. Thus, only the routing and scheduling of city freighters is considered. A similar system is presented in Ghilas et al. (2016), where first-echelon transport is performed by public transportation with a given timetable. The resulting problem for the second echelon then becomes a *pick-up and delivery problem with time windows and scheduled times* (PDPTW-ST), which is solved using an ALNS heuristic.

The second approach considers the joint routing and scheduling of vehicles operating at both echelons. For this problem, Perboli et al. (2011) consider time constraints on the arrival and departure of vehicles at *satellites*, which may be modelled as soft constraints or hard constraints.

In the first case, if city freighters are not available at satellites, the demand will be lost and a penalty paid. In the second case, urban and city freighters are required to be at the same *satellite* at the same time, as to transfer loads directly.

In 2E-VRPs, vehicle synchronisation has been considered along with multi-trips at the second-echelon. Multi-trips in the context of 2E-VRPs regard the ability of city freighters to return to satellites to reload. This characteristic arises from the fact that city freighters have a small carrying capacity and a short operational area radius, usually with high delivery density, thus allowing the vehicles to perform more than one delivery trip during a working day. Multi-trips in 2E-VRPs have the peculiarity of considering the existence of multiple depots (satellites) and thus, unlike the common *multi-trip vehicle routing problems* (MTVRP) where vehicles start and return to the same depot, city freighters are able to perform multiple trips starting and arriving at different satellites. For more information on MTVRPs, see Cattaruzza et al. (2016), where several formulations are presented and discussed.

In the literature, the issues of vehicle synchronisation and multi-trips in 2E-VRP have been seldom addressed. Crainic et al. (2009) introduce the time-dependent, two-echelon, multi-trip routing problem with synchronisation, for which they propose a general mathematical formulation and identify promising algorithmic directions, but no implementation is reported. Crainic, Errico, et al. (2015b) implement the decomposition-based heuristic proposed in Crainic et al. (2009), by sequentially solving a scheduled service network design problem for the first echelon, and then applying the metaheuristic presented in Crainic, Gajpal, & Gendreau (2015) to solve the routing and scheduling problem for the second echelon. This heuristic is based on decomposing the problem into several VRPTW according to customer zones, and uses hard time windows to synchronise the schedules of city freighters with the schedules of urban freighters, as given by the first stage solution.

Grangier et al. (2016) address a two-echelon multi-trip vehicle routing problem with time windows and synchronisation at satellites (2E-MTVRPTW-SS). The authors present an arc-based MIP model, and solve the problem using an ALNS heuristic for which several problem-specific *destroy and repair* operators are presented. Time characteristics such as time windows and the *interdependence* problem are addressed by implementing an extension of the feasibility algorithm based on forward-time slacks proposed by Masson et al. (2013). Computational results show that the heuristic is capable of finding good solutions in reasonable computational time, but no results are presented for the exact formulation.

Anderluh et al. (2017) address a 2E-MTVRP-SS with direct deliveries (2E-MTVRP-SS-DD) arising from a real problem where cargo-bikes and vans are able to meet at satellites without storage capabilities (parking lots), in order to replenish a set of pharmacies in a given area. An arc-based MIP formulation is proposed but no computational results on the exact solution method are provided. To solve the problem the authors present an approach based on GRASP and Path-Relinking. A similar problem is addressed in Anderluh et al. (2021) for a 2E-MTVRP-SS-DD with "grey zones", i.e, areas were customers are not assigned *a priori* to first- or second-echelon vehicles. The problem is studied under a multi-objective framework where financial costs and environmental impacts are taken into account. An arc-based MIP model is proposed but no computational results are presented. The authors propose a LNS heuristic, which allows an overall improvement in the solution quality when compared with the GRASP + Path-Relinking heuristic method previously presented in Anderluh et al. (2017). Regarding the problem variant in which urban freighters also perform direct deliveries, to our knowledge, it has only been addressed by Anderluh et al. (2017, 2021), and no references were found where customers' locations could be used to perform load transfers.

Recently, Marques et al. (2022) proposed a branch-and-cut-and-price (B&C&P) approach to solve a 2E-MTVRPTW-SS. The authors present a solution method for the single trip 2E-VRP as well as its adaptation for the multi-trips variant where the second echelon routing problem becomes a multi-depot multi-trip CVRP with time windows. Additionally, the authors propose a post processing phase used to solve problems where satellites have storage capacity, therefore allowing for load consolidation at satellites and requiring only precedence constraints between vehicles operating at the first- and second-echelons

A summary of the literature on 2E-VRP variants that are similar to the problem addressed in our work is presented in Table 4.2.

Table 4.2: Related 2E-CVRP variants.

Reference	Time windows	Synchronisation	Multi-trips	Direct deliveries	Transfers at customers	Heterogeneous fleet	Solution method
Crainic et al. (2009)	✓	✓	✓				Hierarchical decomposition
Crainic, Errico, et al. (2015b)	✓	✓	✓				Hierarchical decomposition
Grangier et al. (2016)	✓	✓	✓				ALNS
Anderluh et al. (2017)		✓	✓	✓			GRASP + path-relinking
Anderluh et al. (2021)		✓	✓	✓			LNS
Marques et al. (2022)	✓	✓	✓				B&C&P
Our problem	✓	✓	✓	✓	✓	✓	VNS + SA

In Chapter 5 we propose some novel three-index arc-based formulations for the *two-echelon, multi-trip vehicle routing problem with satellite synchronisation and direct deliveries* (2E-MTVRP-SS-DD) for which we derive lower and upper bounds for time-elapsed constraints, and model the flow conservation variables and constraints in a way inspired by the works of Bard et al. (1998). Furthermore, we also propose a set of valid inequalities including symmetry breaking constraints based on lexicographical ordering, vehicle rounded capacity constraints, and satellite rounded capacity constraints, with the purpose of tightening the formulation.

4.3 Chapter summary

Two-echelon distribution problems can be split into the usual 3 time-horizon decision levels: strategic, tactical and operational. At the strategic level, the literature has focused on the development of solution methods for the 2E-LRP and its variants. At the tactical level, research has focused on service network design problems, aiming at determining routes, loads and the assignment of customers to satellites.

The literature on operational planning has been mostly focused on solving the basic 2E-CVRP using both exact and heuristic solution methods. Besides the basic 2E-CVRP, research has also addressed additional operational characteristics, including environmental concerns and time related characteristics such as time windows, time-dependent travel times, and synchronisation constraints.

A particular characteristic arising in two-echelon distribution systems based on mobile depots is the need for exact space-time synchronisation of vehicles operating at each echelon at satellites so that loads can be directly transferred between them. Vehicle synchronisation at satellites has been considered alongside multi-trips at the second echelon, and two different modelling approaches have been proposed in the literature. The first approach is to consider that the arrival times of urban vehicles is established *a priori*, setting the time window in which city freighters are required to be at the satellites. The second approach relies on the joint routing and scheduling of both urban and city freighter vehicles. In this case, the *interdependence problem*, characteristic of vehicle routing problem with synchronisation constraints, is present, greatly increasing the difficulty of the underlying routing and scheduling problem.

Chapter 5

Mathematical formulations

There have been multiple studies on two-echelon vehicle routing problems, as presented in Chapter 4. Despite this, vehicle routing problems arising from two-echelon distribution systems based on mobile depots, where space-time synchronisation between vehicles operating at different echelons is required, have been seldom addressed. In this chapter, we propose novel mathematical optimisation models for the two-echelon vehicle routing problem with synchronisation at satellites and multiple trips at the second echelon.

First, in Section 5.1, we propose a generic three index arc-based MIP model easily extendable to model all four types of distribution system based on mobile depots as given by the classification proposed in Chapter 3.

In Section 5.2, we perform a more comprehensive study of a MIP model for a two-echelon, multi-trip vehicle routing problem with synchronisation at satellites and direct deliveries (2E-MTVRPSS-DD), as it is the case of the problem arising in T3 type systems, where loads can also be transferred at some customers' locations. We also propose a set of valid inequalities to tighten the proposed formulation, including symmetry breaking constraints based on lexicographical ordering, as well as vehicle and satellite rounded capacity constraints. The models are tested with a commercial solver, and using newly generated instances adapted from benchmark VRP instances. Additionally, we propose and evaluate a *warm-start* procedure to solve the MIP model for the T3 type system.

5.1 Generic 3-index arc-based mixed integer programming model

Two-echelon distribution systems have been proposed in the context of city logistics as one way to address the negative externalities of urban freight transport (Crainic et al., 2004). In particular, systems based on mobile depots have emerged as a response to the often prohibitive cost of installing urban logistics infrastructures in the city centre. The main principles of these systems are the use of larger vehicles (urban freighters) as mobile warehouses and the direct transfer of loads between urban freighters and smaller vehicles (city freighters) more suited to operate in city centres, instead of relying on static physical infrastructures where loads can be stored.

As proposed in Chapter 3, four types of two-echelon distribution systems based on mobile depots (2E-MD) can be identified, according to the degree of mobility of urban freighters and their accessibility to customers. In the first type (T1), urban freighters do not perform direct deliveries to customers and only visit a single transfer location (*satellite*) each day, before returning to the depot. In the second type (T2), urban freighters still do not deliver loads directly to customers but can visit more than one *satellite* a day. The third type of system (T3) considers that urban freighters can visit more than one *satellite*, and can perform direct deliveries to a subset of customers. Finally, the fourth type (T4) considers that urban freighters can visit more than one *satellite*, and can make deliveries to any of the customers.

In this section, we propose a generic 3-index arc-base formulation for the 2E-CVRP with synchronisation at satellites and multi-trips at the second echelon, formulated for the most restrictive 2E-MD (T1), and then show how this formulation can be extended to address the other three types of 2E-MD.

5.1.1 Base mathematical formulation

Two-echelon distribution systems of type T1 consider that urban freighters are only able to visit a single satellite a day, and that they cannot visit any customers. We assume there is a single urban freighter located at a depot in the periphery of the city, from where all loads originate, and a single satellite with a location that has been established *a priori*. The satellite can be visited multiple times by several city freighters, but only one city freighter can be at the satellite at a time. This means that, if a city freighter is able to reload but there is another city freighter already at the satellite, then the incoming city freighter will have to wait its turn to reload. Moreover, we consider multi-trips at the second echelon, i.e. city freighters can return multiple times to the satellite to reload, after delivering all loads from the previous trip, while there is enough time before returning back to the depot.

The problem is defined on a directed graph $G=(N,A)$, where N is the node set and A is the arc set. The node set N encompasses the depot nodes O, the customer nodes C and the satellites S, $N=O\cup C\cup S$. In order to define the problem as a 3-index arc-based formulation, the node set N is extended as explained next.

The set O includes the depots of vehicles operating at both echelons $e=\{1,2\}$, i.e. o_1 is the depot for urban freighters and o_2 is the depot for city freighters, $O=o_1\cup o_2$. To model the departure and arrival times of vehicles at the depot, each of these nodes is duplicated into a source and a sink node o_e and $o'_e : e=\{1,2\}$, respectively, yielding the extended depot node set $O^*=o_e\cup o'_e : e=\{1,2\}$. To simplify the notation, o_k and o'_k are used to represent the depot of vehicle k correspondent to its echelon.

The set of customers C includes only second-echelon customers C_2 which are served by city freighters, $C=C_2$, with a demand $q_i : i\in C_2$. The node set S represents the satellite but, since it may be visited more than once, it is necessary to uniquely identify each visit. This is accomplished by replicating the *satellite*'s node into a pre-established number of possible visits m. As only one single urban freighter and one single *satellite* are considered, the order of visits to the satellite is implicit, and we can lexicographically order these satellite/meeting nodes in such a away that $S^* = \{S_1^*, S_2^*, ...S_m^*\}$. This is of particular interest when constructing the underlying graph, as explained next.

Given the extended set of nodes $N^* = O^* \cup C \cup S^*$, we have an extended graph $G^* = (N^*, A)$, that can be viewed as two sub-graphs $G^* = G_1 \cup G_2$, one for the first echelon G_1 and one for the second echelon G_2, joined by the satellite/meeting nodes S^*, i.e. $G_1 \cap G_2 = S^*$. The first-echelon graph is defined by $G_1 = (N_1, A_1)$, with $N_1 = \{o_1, o_1'\} \cup N^F$, $N^F = S^*$, and $A_1 = (o_1, S_1^*) \cup \{(i,j) | i = S_\alpha^*, j = S_{\alpha+1}^* : \alpha = 1, ..., m-1\} \cup \{(i, o_1') | i \in S_\alpha^* : \alpha = \theta, ..., m\}$. Since the only urban freighter in the fleet is always used, there is only one directed arc from the source node to the first satellite/meeting node, and there are only directed arcs between the satellite/meeting nodes respecting the lexicographical order.

Additionally, we can state that the urban freighter may only leave the satellite towards its depot after a minimum number of mandatory load transfers have been performed, so that all the demands of second-echelon customers are transferred to city freighters for final delivery. Let $TD = \sum_{i \in C_2} q_i$ represent the total demand of C_2 and Q the capacity of city freighters. Then, $\theta = \lceil TD/Q \rceil$ is the minimum number of satellite/meeting nodes required to transfer all loads for second-echelon customers. Therefore, there are only directed arcs to the sink node from satellite/meeting nodes equal or greater than θ.

The second-echelon graph is defined by $G_2 = (N_2, A_2)$, with $N_2 = \{o_2, o_2'\} \cup N^H, N^H = C_2 \cup S^*$, and the arc set can be defined as $A_2 = (o_2, o_2') \cup \{(o_2, S^*)\} \cup \{(i,j) | i \in S^*, j \in C_2\} \cup \{(i,j) | i \in C_2, j \in S^*\} \cup \{(i,j) | i,j \in C_2 : i \neq j\} \cup \{(i, o_2') | i \in C_2\}$. The city freighters start and end their working day empty. Therefore, they will always leave the depot towards a satellite/meeting node in order to load, and will arrive to the depot coming directly from a second-echelon customer. Additionally, it is considered that city freighters cannot load at two satellite/meeting nodes in a row.

Each arc $(i,j) \in A$ has a travel time d_{ij}, and each node $i \in C_2 \cup S^*$ has an associated service duration st_i. For the sake of simplification, we consider that the service time at these nodes is constant and does not depend on the location, on the type of operation (delivering or transferring loads) or on the transferred amounts. Furthermore, we set $st_i = 0 : i \in O^*$.

The set of available vehicles K includes a set of urban freighters K_1 with only one vehicle, and a set of city freighters K_2, $K = K_1 \cup K_2$ of homogeneous vehicles within each type with capacity $Q_k : k \in K$. The fleet of city freighters has a fixed cost $f_k : k \in K_2$, and travel costs per unit c_{ij}^k. All vehicles have a maximum working time T, before which they must return to their depot. For modelling purposes, we define σ_i^+ as the set of nodes that succeed node i, and σ_i^- as the set of nodes that precede node i in their associated graph, such that $i \in N^*$.

Table 5.1: Sets, parameters and decision variables.

Sets	
O/O^*	set / extended set of depot nodes
C	set of customers
C_1	set of first-echelon customers
C_2	set of second-echelon customers
S	set of *satellites*
S^*	set of *satellite* replicas representing *satellite*/meetings
N^F	set of customers and *satellite*/meeting nodes able to be visited by urban freighters
N^H	set of customers and *satellite*/meeting nodes able to be visited by city freighters
K	fleet of all vehicles
K_1	fleet of urban freighters
K_2	fleet of city freighters
Parameters	
f_k	fixed cost of using vehicle $k \in K$
c_{ij}^k	cost of vehicle $k \in K$ for traversing arc $(i,j) \in A$
q_i	demand of customer $i \in C$
d_{ij}	time to transverse arc $(i,j) \in A$
st	service duration
Q_k	maximum capacity of vehicle $k \in K$
T	maximum working time
TD	total demand of second-echelon customers C_2
σ_i^+	set of nodes that succeed node i
σ_i^-	set of nodes that precede node i
Variables	
x_{ij}^k	binary variable, equal to 1 if vehicle $k \in K$ uses arc $(i,j) \in A$, and 0 otherwise
t_i^k	elapsed time as a vehicle $k \in K$ arrives at node i
y_i^k	load of vehicle $k \in K$ as it arrives to node i
u_i^{kz}	load transferred from $k \in K_1$ to $z \in K_2$, at transfer point $i \in S^*$

Given the definitions presented in Table 5.1, we propose the following 3-index arc-based *mixed integer programming* (MIP) model.

$$min\ \ Z = \sum_{k\in K_2}\sum_{j\in\sigma^+_{o_k}\backslash\{o'_k\}} f_k x^k_{o_kj} + \sum_{k\in K_2}\sum_{(i,j)\in A_k} c^k_{ij}(d_{ij}x^k_{ij}) \tag{5.1}$$

$$\sum_{j\in\sigma^+_{o_k}} x^k_{o_kj} = 1 \qquad \forall k\in K \tag{5.2}$$

$$\sum_{j\in\sigma^+_i} x^k_{ij} - \sum_{j\in\sigma^-_i} x^k_{ji} = 0 \qquad \forall (i,j)\in A_e, k\in K_e : e\{1,2\} \tag{5.3}$$

$$\sum_{k\in K_2}\sum_{j\in\sigma^+_i} x^k_{ij} = 1 \qquad \forall i\in C_2 \tag{5.4}$$

$$\sum_{k\in K_1}\sum_{j\in\sigma^+_i} x^k_{ij} = 1 \qquad \forall i\in S^*_\alpha, \alpha=\{1,...,\theta\} \tag{5.5}$$

$$\sum_{k\in K_2}\sum_{j\in\sigma^+_i} x^k_{ij} = 1 \qquad \forall i\in S^*_\alpha, \alpha=\{1,...,\theta\} \tag{5.6}$$

$$\sum_{k\in K_1}\sum_{j\in\sigma^+_i} x^k_{ij} \le 1 \qquad \forall i\in S^*_\alpha, \alpha=\{\theta+1,...,m\} \tag{5.7}$$

$$\sum_{k\in K_2}\sum_{j\in\sigma^+_i} x^k_{ij} \le 1 \qquad \forall i\in S^*_\alpha, \alpha=\{\theta+1,...,m\} \tag{5.8}$$

$$\sum_{k\in K_1}\sum_{j\in\sigma^+_i} x^k_{ij} = \sum_{k\in K_2}\sum_{j\in\sigma^+_i} x^k_{ij} \qquad \forall i\in S^* \tag{5.9}$$

$$t^k_{o_k} = 0 \qquad \forall k\in K_1 \tag{5.10}$$

$$\tau^k_i \sum_{j\in\sigma^+_i} x^k_{ij} \le t^k_i \le \hat{T}^k_i \sum_{j\in\sigma^+_i} x^k_{ij} \qquad \forall i\in N^*, k\in K \tag{5.11}$$

$$t^k_i + (d_{ij}+st_i)x^k_{ij} \le t^k_j + \hat{T}^k_{is}(1-x^k_{ij}) \qquad \forall (i,j)\in A_k, k\in K \tag{5.12}$$

$$y^k_{o'_k} = 0 \qquad \forall k\in K_1 \tag{5.13}$$

$$\bar{q}_i \sum_{j\in\sigma^+_i} x^k_{ij} \le y^k_i \le Q_k \sum_{j\in\sigma^+_i} x^k_{ij} \qquad \forall i\in N^F, k\in K_1 \tag{5.14}$$

$$y^k_{o_k} = \sum_{z\in K_2}\sum_{i\in S^*} u^{kz}_i \qquad \forall k\in K_1 \tag{5.15}$$

$$y^k_{o_k} \le y^k_i + Q_k(1-x^k_{o_ki}) \qquad \forall i\in\sigma^+_{o_k}, k\in K_1 \tag{5.16}$$

$$y^k_i - \sum_{z\in K_2} u^{kz}_i \le y^k_j + Q_k(1-x^k_{ij}) \qquad \forall i\in S^*, j\in\sigma^+_i, k\in K_1 \tag{5.17}$$

$$y^k_i = 0 \qquad \forall i\in S^*\cup\{o_2,o'_2\}, k\in K_2 \tag{5.18}$$

$$q_i \sum_{j\in\sigma^+_i} x^k_{ij} \le y^k_i \le Q_k \sum_{j\in\sigma^+_i} x^k_{ij} \qquad \forall i\in C_2, k\in K_2 \tag{5.19}$$

$$y^k_{o_k} \ge y^k_i - Q_k(1-x^k_{o_ki}) \qquad \forall i\in S^*, k\in K_2 \tag{5.20}$$

$$y^k_i + \sum_{z\in K_1} u^{zk}_i \ge y^k_j - Q_k(1-x^k_{ij}) \qquad \forall i\in S^*, j\in C_2, k\in K_2 \tag{5.21}$$

$$y^k_i - q_i x^k_{ij} \ge y^k_j - Q_k(1-x^k_{ij}) \qquad \forall i\in C_2, j\in\sigma^+_i, k\in K_2 \tag{5.22}$$

$$\sum_{k\in K_1} t^k_i = \sum_{k\in K_2} t^k_i \qquad \forall i\in S^* \tag{5.23}$$

$$\sum_{k\in K_1}\sum_{z\in K_2}\sum_{i\in S^*} u^{kz}_i = TD \tag{5.24}$$

Objective function (5.1) minimises the total fixed and variable travel costs of vehicles. Constraints (5.2) ensure that every vehicle leaves from its respective depot. Constraints (5.3) are flow conservation constraints. If a vehicle is not used, then the arc between the source and sink node of each depot $(o_k, o'_k) : k \in K$ is used. Constraints (5.4) state that each second-echelon customer is visited exactly once by a single city freighter. Constraints (5.5, 5.6) establish that the first θ *satellite*/meeting nodes have to be visited, and constraints (5.7, 5.8) state that the remaining nodes may or may not be visited by the urban and the city freighters, respectively. Constraints (5.9) ensure that, if a *satellite*/meeting node is used, then one vehicle of each type is required to be present. Constraints (5.10) establish the urban freighter starting time at the depot as 0. Note that, we do not define this constraint for city freighters as these may start their route at any time, so that they are perfectly synchronised with the urban freighter at their first *satellite*/meeting node. Constraints (5.11) establish the lower and upper bounds of the time elapsed as vehicles arrive at a given node. Different lower and upper bounds can be considered depending on the underlying graph structure of each problem, the type of vehicle and considered node. Constraints (5.12) are time elapsed constraints. Since t_i^k are unique for each node and always increasing, these constraints also serve as sub-tour elimination constraints. When considering the link between nodes in which $d_{ij} = 0$, as it is the case of arcs between satellite/meeting nodes, when active, these constraints will still serve as sub-tour elimination constraints as the service duration is always considered. Constraints (5.13) state that the urban freighter will always arrive empty at the depot, at the end of the day. Constraints (5.14) establish the lower and upper bounds for the load when the urban freighter arrives to a *satellite*/meeting node. The lower bound is set as the minimum demand of all second-echelon customers, and the upper bound as the capacity of the urban freighter. Constraints (5.15) establish the initial load with which the urban freighters are required to leave the depot, while constraints (5.16) are load conservation constraints at the source node, and constraints (5.17) are load conservation constraints at the *satellite*/meeting nodes. Constraints (5.18) establish that city freighters are empty when they start and end their working day, and that they are also empty when they arrive at *satellite*/meeting nodes. Constraints (5.19) set the lower and upper bounds for the load of city freighters as they arrive to second-echelon customers. The lower bound is set to the customer's demand, and the upper bound is the capacity of city freighters. Constraints (5.20) are load conservation constraints from the source node to a *satellite*/meeting node. Constraints (5.21) are load conservation constraints at *satellite*/meeting nodes. If a city freighter visits a *satellite*/meeting node, then the city freighter is loaded with the loads delivered by an urban freighter, represented by u_i^{kz}. Constraints (5.22) are load conservation constraints at second-echelon customers. Constraints (5.23) establish an exact time synchronisation between urban and city freighters at each *satellite*/meeting node. Finally, constraint (5.24) establishes that the total transferred load at *satellite*/meeting nodes is equal to the total demand of second-echelon customers TD.

5.1.1.1 Valid inequalities

To strengthen the model and address the inherent symmetry issues arising in this type of formulations, we consider a set of *valid inequalities* based on those proposed in the VRP literature (Sherali

& Smith, 2001; Baldacci et al., 2012; Adulyasak et al., 2013; Toth & Vigo, 2014; Lahyani et al., 2018). In this work, we propose a set of lexicographical-based symmetry breaking constraints (Lahyani et al., 2018) which aim to avoid the search of symmetrical solutions during the branch-and-bound procedure. Constraints (5.25) establish that a new city freighter may only be dispatched if the former vehicle in the ordered sequence has been already used. Additionally, constraints (5.26) address the route symmetry of dispatched vehicles. We also consider the so-called *rounded capacity constraints* establishing a lower bound on the number of vehicles to be used (Toth & Vigo, 2014). The minimum number of used urban freighters is established by (5.27), and as city freighters can perform multi-trips, the lower bound can only be set to 1 (5.28). Furthermore, given that we have an homogeneous fleet of vehicles at each echelon, and know the minimum number of vehicles to be used, we may include constraints (5.29) and (5.30) explicitly stating the use of the first k vehicles. The same reasoning can be used to derive *satellite* rounded capacity constraints (5.31, 5.32), thus establishing the minimum number of *satellite*/meeting nodes required to transfer all the demands of second-echelon customers, given the capacity of city freighters Q_2.

$$\sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} \leq \sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^{k-1}_{o_k j} \qquad \forall k \in K_2 \setminus \{1\} \tag{5.25}$$

$$\sum_{(i,j)\in A_k} d^k_{ij} x^k_{ij} \leq \sum_{(i,j)\in A_k} d^{k-1}_{ij} x^{k-1}_{ij} \qquad \forall k \in K_2 \setminus \{1\} \tag{5.26}$$

$$\sum_{k\in K_1} \sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} \geq \left\lceil \frac{\sum_{i\in C} q_i}{Q_1} \right\rceil \tag{5.27}$$

$$\sum_{k\in K_2} \sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} \geq 1 \tag{5.28}$$

$$\sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} = 1 \qquad \forall k = \{1, \ldots, \left\lceil \frac{\sum_{i\in C} q_i}{Q_1} \right\rceil\} : k \in K_1 \tag{5.29}$$

$$\sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} = 1 \qquad \forall k = 1 : k \in K_2 \tag{5.30}$$

$$\sum_{k\in K_1} \sum_{(i,j)\in A_1 : i\in S^*} x^k_{ij} \geq \left\lceil \frac{TD}{Q_2} \right\rceil \tag{5.31}$$

$$\sum_{k\in K_2} \sum_{(i,j)\in A_2 : i\in S^*} x^k_{ij} \geq \left\lceil \frac{TD}{Q_2} \right\rceil \tag{5.32}$$

5.1.2 Model extensions

The generic model proposed for T1 systems can be extended to address all other three types of 2E-MD. For these cases, we consider that the urban freighters fleet K_1 includes more than one vehicle and that there are multiple *satellites*. The model adaptations are performed in 3 dimensions, namely: the construction of the graph for urban freighters (G_1); the model constraints; and the valid inequalities that can be included.

5.1.2.1 Extension for T2 systems

In T2 systems, urban freighters may visit more than one *satellite* and do not perform direct deliveries to customers.

By considering more than one *satellite*, we no longer have an implicit ordering of the visits to *satellites*. Therefore, there must be arcs between all *satellite*/meeting nodes, and from all nodes to the sink node. Additionally, since the urban freighters fleet includes more than one vehicle, we add an arc from the source node to the sink node, that will be used by the urban freighters that are not used in the final solution. Then, the sub-graph for the urban freighters is now defined by $G_1 = (N_1, A_1)$, with $N_1 = \{o_1, o'_1\} \cup N^F$, $N^F = S^*$, and $A_1 = (o_1, o'_1) \cup \{(o_1, j) | j \in N^F\} \cup \{(i, j) | i, j \in N^F : i \neq j\} \cup \{(i, o'_1) | i \in N^F\}$.

Regarding the changes to the base model, the objective function (5.1) will also include both fixed and variable travel costs of urban freighters. As there is no implicit ordering of the *satellite*/meeting nodes, we remove constraints (5.5) and (5.6), and change constraints (5.7) and (5.8) to be applied to all S^*. As for the valid inequalities, those inequalities proposed for the generic model can all be used and, as the fleet of urban freighters includes more than one vehicle, both vehicle dispatching and route symmetry breaking constraints for the urban freighters (similar to constraints (5.25) and (5.26) for the city freighters) may also be considered.

5.1.2.2 Extension for T3 systems

In T3 systems, urban freighters can visit more than one *satellite* and can perform direct deliveries to a subset of customers, usually considered to be located outside the city centre area, and referred to as first-echelon customers. Then, the set of customers C now includes first-echelon customers C_1 (which can only be visited by urban freighters), and second-echelon customers C_2 (which can only be visited by city freighters), $C = C_1 \cup C_2$, $C_1 \cap C_2 = \emptyset$. Moreover, the set N^F is extended to include first-echelon customers, $N^F = S^* \cup C_1$. The graph G_1 can be defined in the same way as presented for T2 systems.

Regarding the changes to the base model, we perform the same changes as for T2 systems, as well as the following additional ones: i) add constraints establishing that each first-echelon customer is visited exactly once by a single urban freighter (similar to the constraints (5.4) for second-echelon customers); ii) for constraints (5.14), which now also exist for first-echelon customers, we set the lower bound for each customer node as its respective demand; iii) change constraint (5.15) establishing the load with which the urban freighter leaves the depot, by also including the loads to be delivered to first-echelon customers if visited; and iv) include the load conservation constraints for first-echelon customers (similar to the constraints (5.17)), where the term of loads to be transferred to city freighters is replaced by the demand of the customer. As for the valid inequalities, we can consider the same as for T2 systems. In Section 5.2 we present a more detailed analysis of the mathematical formulation for T3 type systems.

5.1.2.3 Extension for T4 systems

In T4 systems, urban freighters can visit more than one *satellite* a day, and can perform direct deliveries to both first- and second-echelon customers.

Therefore, the model now also includes the decision of establishing which type of vehicle (urban or city freighter) should deliver loads to second-echelon customers. The set of customers includes first-echelon customers that can only be visited by urban freighters, and second-echelon customers that can be visited by both urban and city freighters $C = C_1 \cup C_2$, $C_1 \cap C_2 = \emptyset$. The set N^F is extended to include both first- and second-echelon customers, $N^F = S^* \cup C_1 \cup C_2$. Then, the sub-graph G_1 can be defined as presented for T2 systems. The changes to the base model are the same we have presented for T2 systems, plus the following: i) add constraints establishing that each first-echelon customer is visited exactly once by a single urban freighter (as for constraint (5.4) in the base model); ii) change constraints (5.4) so that second echelon customers are visited only once by a single urban city freighter; iii) for constraints (5.14), we set the lower bound for each customer node to its respective demand; iv) change constraints (5.15) by including loads to be delivered to first- and second-echelon customers, if visited; and v) include load conservation constraints for first- and second-echelon customers (as for constraints (5.17)), where the term of the loads to be transferred to city freighters is replaced by the demand of the customer. As for the valid inequalities, we may consider both symmetry breaking constraints for urban and city freighters, and the rounded capacity constraints for urban freighters (5.27, 5.29). The rounded capacity constraints for city freighters (5.28, 5.30) and the satellite rounded capacity constraints (5.31, 5.32) cannot be included, as there can be solutions where only urban freighters are used.

5.1.3 Computational experiments

All tests were performed on a Intel(R) Core(TM) i7-6700HQ CPU at 2,6 GHz with 16 GB of RAM, and the maximum computation time was set to one hour. The model was implemented using the Java programming language, and the tests with the MIP models were performed using the commercial solver Gurobi v8.1.0, using the standard parameters settings and disabling the solver's presolve.

5.1.3.1 Test instances

To test the proposed formulation, we have adapted some Solomon's instances for the CVRPTW with 25 customers (C101, C201, R101, R201, RC101, RC201) as to take into account the characteristics of each system type. These instances were considered as the second echelon of the two-echelon network. The depot in the original instances was used as the city freighters' depot, the number of trucks became the available city freighters fleet, and the customers were set as the second-echelon customers. To complete the instance, we included a depot for the urban freighters, and for T1 systems we have established a single *satellite* with 16 possible *satellite*/meeting nodes. On the other hand, for T2, T3 and T4 systems, where more than one *satellite* is considered, we have included 8 *satellites* around second-echelon customers, each with two possible *satellite*/meeting nodes. For T3 and T4 systems, we have considered 12 first-echelon customers, of which 2 can also be used as *satellites*. These were randomly located between the urban freighters' depot and the *satellites*, with a demand taken from an uniform distribution $U[\alpha,\beta]$, such that $\alpha = \overline{q} - \sigma$ and $\beta = \overline{q} + \sigma$, where $\overline{q}$ is the average demand of second-echelon customers and σ its standard deviation. The number of urban freighters was set to half the number of city freighters rounded up (except for T1 where only one urban freighter was considered). The capacity of urban and city freighters Q was defined as 4 and 0,5 times the capacity of the vehicles in Solomon's instances, respectively. The fixed and variable costs of city freighters were set to 10 and 1, respectively. The costs of urban freighters were set as 3 times the costs of city freighters, and the maximum working times T were kept the same as in the original instances except for instances R101 and RC101, for which the maximum working time was set to 1000. The distances between location were set as the euclidean distances, and the service duration was set to 10, $st = 10 : i \in N^* \setminus \{O^*\}$.

The characteristics of the adapted instances are presented in Table 5.2. The instances are named according to their characteristics, including the type of system (T1, T2, T3 or T4), the name of the original Solomon instance, the number of first-echelon customers, the number of second-echelon customers, and the number of satellites ($systemType\_originalInstance\_|C_1|\_|C_2|\_|S|$).

Table 5.2: Characteristics of the adapted instances.

		Customers				Urban freighters		City freighters			
Type	Instance	$\|C_1\|$	$\sum_{i \in C_1} q_i$	$\|C_2\|$	$\sum_{i \in C_2} q_i$	$\|K_1\|$	Q_1	$\|K_2\|$	Q_2	$\|S^*\|$	T
T1	T1_C101_0_25_1	-	-	25	460	1	800	25	100	16	1236
	T1_C201_0_25_1	-	-	25	460	1	2800	25	350	16	3390
	T1_R101_0_25_1	-	-	25	332	1	800	25	100	16	1000[a]
	T1_R201_0_25_1	-	-	25	332	1	4000	25	500	16	1000
	T1_RC101_0_25_1	-	-	25	540	1	800	25	100	16	1000[a]
	T1_RC201_0_25_1	-	-	25	540	1	4000	25	500	16	960
T2	T2_C101_0_25_8	-	-	25	460	13	800	25	100	16	1236
	T2_C201_0_25_8	-	-	25	460	13	2800	25	350	16	3390
	T2_R101_0_25_8	-	-	25	332	13	800	25	100	16	1000[a]
	T2_R201_0_25_8	-	-	25	332	13	4000	25	500	16	1000
	T2_RC101_0_25_8	-	-	25	540	13	800	25	100	16	1000[a]
	T2_RC201_0_25_8	-	-	25	540	13	4000	25	500	16	960
T3	T3_C101_12_25_8	12	217	25	460	13	800	25	100	16	1236
	T3_C201_12_25_8	12	244	25	460	13	2800	25	350	16	3390
	T3_R101_12_25_8	12	149	25	332	13	800	25	100	16	1000[a]
	T3_R201_12_25_8	12	155	25	332	13	4000	25	500	16	1000
	T3_RC101_12_25_8	12	233	25	540	13	800	25	100	16	1000[a]
	T3_RC201_12_25_8	12	251	25	540	13	4000	25	500	16	960
T4	T4_C101_12_25_8	12	217	25	460	13	800	25	100	16	1236
	T4_C201_12_25_8	12	244	25	460	13	2800	25	350	16	3390
	T4_R101_12_25_8	12	149	25	332	13	800	25	100	16	1000[a]
	T4_R201_12_25_8	12	155	25	332	13	4000	25	500	16	1000
	T4_RC101_12_25_8	12	233	25	540	13	800	25	100	16	1000[a]
	T4_RC201_12_25_8	12	251	25	540	13	4000	25	500	16	960

[a] Value changed from the original instance

5.1.3.2 Computational results

In this section, we present the results of the MIP formulations for systems of type T1, T2, and T4. For the T3 distribution type systems, a more comprehensive analysis is presented in Section 5.2. We first present the results of using the MIP models without any valid inequalities, and then the results of including two combinations of valid inequalities, namely: i) using *vehicle rounded capacity* and *satellite rounded capacity* constraints; and ii) all of the proposed valid inequalities. We note that, as explained before, not all valid inequalities can be added when addressing some system types.

Table 5.3 presents the results when using the MIP model without any valid inequalities. We report the main indicators as produced by Gurobi, namely: the final value of the objective function; the MIP gap percentage (where "x" is used when no feasible solution was found by the solver during the allowed computation time); the total computational time ("-" represents the maximum computational time); the best lower bound (*BB*); the linear relaxation at the root node (*LR*); as well as the number of binary variables, continuous variables, and constraints of the model. Additionally, we present the number of urban freighters, city freighters, and *satellite*/meeting nodes used in the final solution.

Table 5.3: Results using the adapted MIP model for each problem type.

		MIP solver								Final solution		
Type	Instance	Obj.	Gap %	CPU(s)	*BB*	*LR*	Bin. var.	Cont. var.	Const.	$\|K_1\|$	$\|K_2\|$	$\|S^*\|$
T1	T1_C101_0_25_1	473,61	58,30	-	197,60	189,23	36078	2586	77183	1	3	5
	T1_C201_0_25_1	331,73	37,1	-	208,73	203,55	36081	2586	77189	1	2	2
	T1_R101_0_25_1	676,79	37,82	-	420,84	416,93	36079	2586	77185	1	3	4
	T1_R201_0_25_1	375,26	17,03	-	311,35	307,33	36082	2586	77191	1	1	1
	T1_RC101_0_25_1	1209,06	70,4	-	358,38	349,15	36077	2586	77181	1	4	7
	T1_RC201_0_25_1	319,59	47,05	-	169,21	165,34	36081	2586	77189	1	1	2
T2	T2_C101_0_25_8	1406,8	94,4	-	78,75	70,11	39599	7818	85269	1	4	7
	T2_C201_0_25_8	780,9	81,5	-	144,65	139,26	39599	7818	85269	1	1	2
	T2_R101_0_25_8	2029,91	85,4	-	296,01	277,62	39599	7818	85269	1	2	6
	T2_R201_0_25_8	679,17	58,3	-	283,34	277,62	39599	7818	85269	1	1	1
	T2_RC101_0_25_8	2755,64	96,5	-	96,76	92,98	39599	7818	85269	2	3	6
	T2_RC201_0_25_8	850,38	88,1	-	101,23	92,78	39599	7818	85269	1	1	2
T4	T4_C101_10_25_8	x	x	-	46,11	46,11	73269	8780	155026	x	x	x
	T4_C201_10_25_8	14102,12	100	-	22,02	22,02	73269	8780	155026	2	2	9
	T4_R101_10_25_8	x	x	-	60,27	60,27	73269	8780	155026	x	x	x
	T4_R201_10_25_8	x	x	-	11,32	11,32	73269	8780	155026	x	x	x
	T4_RC101_10_25_8	x	x	-	91,31	91,31	73269	8780	155026	x	x	x
	T4_RC201_10_25_8	x	x	-	10,20	10,20	73269	8780	155026	x	x	x

When using the MIP models alone, we were able to obtain feasible solutions of all 6 instances for all distribution systems except for T4 systems, where the solver was only able to find a feasible solution for one instance. This can be explained by the large increase in the number of binary variables and constraints, needed to model the decision of establishing if second-echelon customers should be visited by urban or city freighters. Despite the small size of the tested instances, the solver was unable to solve any of them to optimality during the allowed computation time, yielding large MIP gaps.

The MIP gaps for the T1 systems ranged from 17,03% to 70,4%. As for T2 systems, the MIP gaps were even larger and ranged from 58,3% to 96,5%. Finally, for T4 systems, the solver was only able to find a feasible solution for one of the six tested instances, namely instance

T4_C201_10_25_8, with a MIP gap of 100%. The difficulty in solving these instances is also evident when analysing the evolution of the best lower bound. After one hour, the best lower bound remained the same as the root linear relaxation.

The generic 3-index arc-based formulation, although flexible and able to consider alternative problem characteristics, has very weak root node linear relaxations. Furthermore, the average final gap % provided by the solver for each model type was: 44,62% for T1, 84,03% for T2, and 100% for the only feasible solution found for T4 type problem instances.

Impact of valid inequalities Two combinations of the proposed valid inequalities were tested, namely: i) using *vehicle and satellite rounded capacity constraints* (CR + SCR); and ii) all proposed valid inequalities (All), in order to evaluate the impacts of adding the symmetry breaking constraints. As previously explained in section 5.1.2, different sets of valid inequalities are able to be considered in each case. We present the results for T1 and T2 system. For T3 systems, a more comprehensive analysis is presented in Section 5.2, and no results are presented for T4 systems because, after including the valid inequalities, the solver was unable to find any feasible solution during the allowed computational time, further evidencing the complexity of the underlying problem and the inadequacy of the proposed exact formulation even to solve small instances.

Results for T1 instances are presented in Table 5.4, and the results for T2 instances are presented in Table 5.5. Each table includes information regarding: the final objective function value and the respective improvement percentage; the final MIP gap percentage as given by Gurobi; the root linear relaxation (RL) and its respective improvement percentage after including the set of valid inequalities when compared with the results without valid inequalities (RL imp %); the best lower bound (BB) and its respective improvement percentage after including the set of inequalities when compared with the results without valid inequalities (BB imp %); the number of binary and continuous variables, the number of constraints, as well as the number of urban freighters, city freighters and *satellite*/meeting nodes used in the final solution. At the bottom, the table presents the average improvement percentage in the final objective function value, linear root relaxation and best bound when using rounded capacity constraints (CR + SCR) and when further adding to these constraints, the *symmetry breaking* constraints (All). The tests in which the solver was able to prove that the solution was optimal are in bold.

Results for the T1 model adaptation For the T1 tests, results show that using the *rounded capacity* constraints (CR + SCR) has a positive impact in the root linear relaxation and in the best bound, with average improvements of 24,37% and 25,06%, respectively. However, we see that this does not always translate in an improvement of the final objective value, although yielding an average improvement of 1,43%. Despite the average improvement in the objective function value, adding the rounded capacity constraints only allowed solving a single instance to optimality, namely instance T1_R201_0_25_1 during the allowed computation time. Further adding the *symmetry breaking* constraints (SB1 and SB2) for city freighters, yielded the same linear root relaxation improvement as when considering only the *capacity rounded* constraints, and the best bound improvement was slightly worst than when solely using the rounded capacity constraints, with an average improvement of 21,96%. In part this can be explained because the addition of symmetry breaking constraints made it much harder for the solver to find a first feasible solution, thus wasting more time before starting the search procedure.

Table 5.4: Results for the T1 model adaptation.

		MIP model										Solution		
Instance	V.I.	Obj.	Obj imp. %	Gap%	RL	RL imp %	BB	BB imp. %	Bin var	Cont Var	Constraints	$\|K\_1\|$	$\|K\_2\|$	$\|S^*\|$
T1_C101_0_25_1	None	473,61	-	58,30	189,23	-	197,60	-	36078	2586	77183	1	3	5
	CR + SCR	450,03	4,98	42,90	247,78	30,94	256,81	29,96	-	-	77189	1	2	5
	All	x	x	x	247,78	30,94	247,78	25,39	-	-	77237	x	x	x
T1_C201_0_25_1	None	331,73	-	37,10	203,55	-	208,73	-	36081	2586	77189	1	2	2
	CR + SCR	283,21	14,63	7,84	252,34	23,97	261,00	25,04	-	-	77195	1	1	2
	All	282,58	14,82	8,73	252,34	23,97	257,90	23,55	-	-	77243	1	1	2
T1_R101_0_25_1	None	676,79	-	37,82	416,93	-	420,84	-	36079	2586	77185	1	3	4
	CR + SCR	679,63	-0,42	32,00	456,66	9,53	462,10	9,81	-	-	77191	1	3	4
	All	x	x	x	456,66	9,53	456,66	8,51	-	-	77239	x	x	x
T1_R201_0_25_1	None	375,26	-	17,03	307,33	-	311,35	-	36082	2586	77191	1	1	1
	CR + SCR	**374,81**	**0,12**	**0,00**	**352,92**	**14,83**	**374,81**	**20,38**	**-**	**-**	**77197**	**1**	**1**	**1**
	All	x	x	x	352,92	14,83	353,76	13,62	-	-	77245	x	x	x
T1_RC101_0_25_1	None	1209,06	-	70,40	349,15	-	358,38	-	36077	2586	77181	1	4	7
	CR + SCR	1040,09	13,98	59,22	417,84	19,67	424,14	18,35	-	-	77187	1	3	7
	All	x	x	x	417,84	19,67	417,84	16,59	-	-	77235	x	x	x
T1_RC201_0_25_1	None	319,59	-	47,05	165,34	-	169,21	-	36081	2586	77189	1	1	2
	CR + SCR	398,58	-24,72	37,68	243,54	47,30	248,39	46,79	-	-	77195	1	2	2
	All	x	x	x	243,54	47,30	243,77	44,06	-	-	77243	x	x	x
Avg. CR+ SCR imp. %			1,43			24,37		25,06						
Avg. All imp %			x			24,37		21,96						

Results for the T2 model adaptation Results show that for the T2 model adaptation, using *rounded capacity* constraints (CR + SCR) had a very positive impact in the root linear relaxation and in the best bound, with average improvements of 358,67% and 420,97%, respectively. The addition of these valid inequalities allowed for an improvement of all instances' objective function values, with an average improvement of 13,07% when compared with the MIP model alone, and allowed solving instance T2_R201_0_25_8 to optimality.

Further adding the *symmetry breaking* constraints for both urban and city freighters, yielded the same linear relaxation as when considering only the *capacity rounded* constraints, and the best bound improvement was slightly worst than when solely using the rounded capacity constraints, with an average improvement of 336,74%. An interesting result arises from adding the symmetry breaking constraints. Whenever these constraints were added, the solver took much longer to find a first feasible solution, a behaviour that has also been reported by Sherali & Smith (2001). For most instances, after adding these constraints, the solver was unable to find any feasible solution during the allowed computation time.

5.1.4 Discussion

We have proposed a generic 3-index arc-based mixed integer programming model for a two-echelon vehicle routing problem with synchronisation at the satellites and multi-trips at the second echelon, formulated for T1 systems, the most restrictive type of two-echelon distribution systems

Table 5.5: Results for the T2 model adaptation.

		MIP model										Solution		
Instance	V.I.	Obj.	Obj imp. %	Gap%	RL	RL imp %	BB	BB imp. %	Bin var	Cont Var	Constraints	$\|K\_1\|$	$\|K\_2\|$	$\|S^*\|$
T2_C101_0_25_8	None	1406,8	-	94,4	70,11	-	78,75	-	39599	7818	85269	1	4	7
	CR + SCR	1399,2	0,54	65,6	355,4	406,92	480,76	510,48	-	-	85275	2	2	6
	All	x	x	x	355,4	406,92	356,08	352,16	-	-	85347	x	x	x
T2_C201_0_25_8	None	780,9	-	81,5	139.26	-	144,65	-	39599	7818	85269	1	1	2
	CR + SCR	510,58	34,62	4,14	445,1	219,62	489,47	238,38	-	-	85275	1	1	2
	All	x	x	x	445,1	219,62	464,16	220,89	-	-	85347	x	x	x
T2_R101_0_25_8	None	2029,91	-	85,4	277,62	-	296,01	-	39599	7818	85269	1	2	6
	CR + SCR	1518,4	25,2	42,8	705,24	154,03	869,09	193,60	-	-	85275	2	2	4
	All	x	x	x	705,24	154,03	710,18	139,91	-	-	85347	x	x	x
T2_R201_0_25_8	None	679,17	-	58,3	277,62	-	283,34	-	39599	7818	85269	1	1	1
	CR + SCR	**674.81**	**0,64**	**0,00**	**652,92**	**135,18**	**674,81**	**138,16**	**-**	**-**	**85275**	**1**	**1**	**1**
	All	675,26	0,57	2,5	652,92	135,18	658,37	132,36	-	-	85347	1	1	1
T2_RC101_0_25_8	None	2755,64	-	96,5	92,98	-	96,76	-	39599	7818	85269	2	3	6
	CR + SCR	2352,97	14,61	58,3	724,99	681,41	981,41	913,92	-	-	85275	2	3	6
	All	x	x	x	724,99	681,41	747,58	672,61	-	-	85347	x	x	x
T2_RC201_0_25_8	None	850,38	-	88,1	92,78	-	101,23	-	39599	7818	85269	1	1	2
	CR + SCR	825,72	2,8	22,6	607,6	554,88	639,02	531,26	-	-	85275	1	2	2
	All	x	x	x	607,6	554,88	609,92	502,51	-	-	85347	x	x	x
Avg. CR+ SCR imp. %			13,07			358,67		420,97						
Avg. All imp %			x			358,67		336,74						

based on mobile depots. We have further explained how this generic base model can be extended to address the other three types of 2E-MD, by changing the underlying graph and the base model formulation.

Results show that the proposed generic formulation can be extended to account for the specific features of the different types of 2E-MD, such as visits to multiple satellites as well as direct deliveries from the depot to customers. Nevertheless, the resulting 3-index arc-based models present very weak root node linear relaxations, and are only able to address rather small problem instances.

For all types of problems, the MIP models alone were unable to obtain the optimal solution for most of the tested instances, ending with large MIP gaps. Furthermore, and as expected, the more complex the underlying problem, the higher the final MIP gap after the allowed computation time. Particularly, for T4 systems the MIP model is clearly unsuited to be used even for small instances, as it was not even able to find a feasible solution for 5 of the 6 tested instances during the allowed computation time.

Moreover, our computational results also show that the proposed valid inequalities have a positive impact in improving both the root node linear relaxation of the branch-and-bound, the best lower bounds, and ultimately the gaps. However, the addition of symmetry breaking constraints did not improve the linear relaxation, and largely increased the time for the solver to obtain a first feasible solution.

5.2 Exact solution method for a two-echelon vehicle routing problem, with synchronisation constraints, direct deliveries, transfers at customers, and multi-trips at the second echelon

In this section, we present a more comprehensive study of a MIP model for a two-echelon vehicle routing problem with synchronisation constraints, multi-trips at the second echelon, and direct deliveries (2E-MTVRP-SS-DD) arising in two-echelon distribution systems of type T3, where loads can be transferred between urban and city freighters at some first-echelon customers, i.e. they may also be used as satellites.

Given a depot (similar to the concept of urban consolidation centre) located in the periphery of the city, a set of satellites, and a set of customers, the 2E-MTVRP-SS-DD problem consists of distributing goods from the depot located in the periphery of the city to the customers, either directly or through the satellites, while respecting vehicles' capacity constraints and vehicle synchronisation constraints at the satellites. To perform the deliveries, two vehicle types are considered: a large capacity vehicle type (urban freighters) which operates at the first echelon; and a smaller capacity vehicle type (city freighters) operating at the second echelon. The urban freighters start and end their route at a depot located at the periphery of the city, from where all loads originate, and can deliver loads directly to first-echelon customers as well as transfer loads to city freighters at satellites. The city freighters are based at a depot located near or in the city centre and start their working day empty, therefore requiring to first receive loads from an urban freighter at a satellite before starting their delivery trips. Due to the smaller capacity of city freighters, and the high delivery density in city centres, we consider that they may perform more than one delivery trip during their working day. To this end, city freighters can reload multiple times at satellites after delivering all loads from their previous trip, but are not allowed to reload twice consecutively. After completing all their delivery trips, they are required to return empty to the depot before their maximum working time.

The customers are split into three different categories according to the types of vehicle that can visit them. First-echelon customers are those located outside the city centre and can only be visited by urban vehicles; second-echelon customers are those located in the city centre and can only be visited by city freighters; and lastly, the third category encompasses satellite-customers which are always served by urban freighters and may also be used as satellites. All customers have a given demand and must be served by a single urban or city freighter, depending on their type. Satellites have no storage capacity and serve only as transshipment locations. They can be visited more than once by both urban or city freighters or not visited at all. A simplified representation of this problem is presented in Figure 5.1.

This problem extends the basic variant of the 2E-VRP by considering that: i) urban freighters are able to perform direct deliveries to some customers instead of having all loads delivered through satellites (additionally, some customers required to be served by urban freighters may also be used as satellites); ii) the temporal dimension is considered as to jointly schedule vehicles operating at each echelon and enforce their synchronisation at satellites; iii) satellites do not have

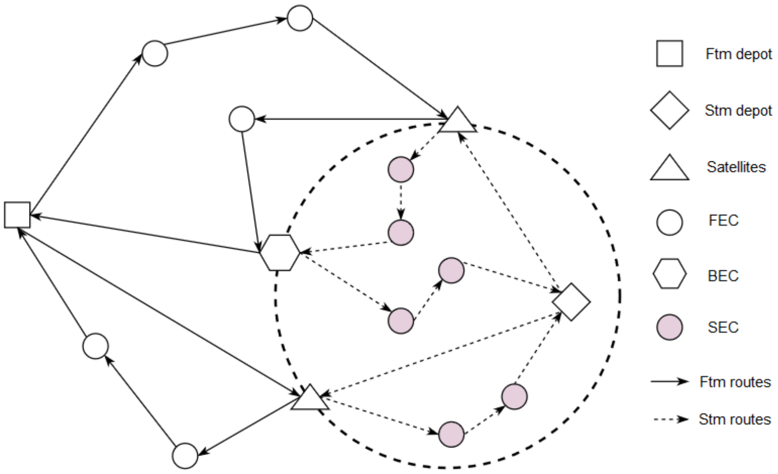


Figure 5.1: A two-echelon distribution system based on mobile depots and direct deliveries.

any storage capabilities, thus requiring space-time synchronisation between vehicles operating at both echelons (this also means that, unlike the basic 2E-CVRP, there is no consolidation of loads at satellites); iv) city freighters are allowed to perform multiple trips before ending their working day; and v) city freighters are not stationed at satellites, but instead they are based at a depot located near or in the city centre.

Despite being an operational level problem, our decisions concern the determination of the number of vehicles to use at each echelon, the joint routing and scheduling of both types of vehicles, the determination of where transfers must be performed, how much load is to be transferred and what are the vehicles involved, while respecting vehicle synchronisation, vehicles load capacity and maximum working times.

The objective is to minimise the total transportation costs, including the fixed costs of the used vehicle fleet, as well as the travel costs at both echelons.

5.2.1 Mathematical formulation

The problem is defined on a directed graph $G = (N, A)$, where N is the node set and A is the arc set. The node set N encompasses the depot nodes O, customer nodes C and satellite nodes S, $N = O \cup C \cup S$. As to define the proposed 3-index arc-based formulation the node set N is extended as explained next.

The depot set O encompasses the depots for vehicles operating at each echelon $e = \{1, 2\}$ with (o_1) as the urban freighters depot and (o_2) for the city freighters depot, $O = o_1 \cup o_2$. To model the departure and arrival times of vehicles at the depot, each depot node is duplicated into a source and a sink node o_e and $o'_e : e = \{1, 2\}$, respectively, yielding the extended depot node set $O^* = o_e \cup o'_e : e = \{1, 2\}$. Nonetheless, as to simplify the model formulation, we use the notation o_k and o'_k representing the depot of vehicle k which will use the depot corresponding to its echelon.

The set of customers C includes first-echelon customers C_1, which are only visited by urban freighters, and second-echelon customers C_2 which are visited only by city freighters, $C = C_1 \cup C_2$, $C_1 \cap C_2 = \emptyset$. The satellite-customers are first-echelon customers which can be used as satellites, and they will have their demand always satisfied by the urban freighters. To account for the possibility of being used as satellites, each satellite-customer is represented by a first-echelon customer node and a satellite node linked by an arc with distance equal to zero. Each customer has a demand $q_i : i \in C$ that must be fulfilled by the appropriate vehicle type.

The node set S represents the satellites but, since there might be more than one synchronised meeting between urban and city freighters at each satellite, it is necessary to uniquely identify these meetings. To accomplish this, we replicate each satellite node as many times as needed. The set of satellite replicas representing each possible meeting is denoted as S^*. The creation of these replicas depends on the type of formulation and on the considered assumptions. For example, some authors replicate each satellite as many times as there are customers' requests (Grangier et al., 2016; Anderluh et al., 2017, 2021). This modelling approach represents the worst-case scenario, in which every second-echelon customer's request could be individually transferred and delivered. This assumption seams to be unrealistic, and has the downfall of greatly increasing the size of the model. Therefore, we consider that each satellite is replicated according to a pre-established number of possible visits $m_s : s \in S$. This results in creating $\sum_{s \in S} m_s$ satellite/meetings replicas instead of $|S| \times |C_2|$. This modelling decision is similar to how capacity at satellites is established in the basic variant of the 2E-CVRP, where a maximum number of vehicles that can leave a given satellite is established beforehand.

Given the extended set of nodes $N^* = O^* \cup C \cup S^*$, we have an extended graph $G^* = (N^*, A)$, which can be understood as two sub-graphs $G^* = G_1 \cup G_2$, one for the first echelon G_1 and another for the second echelon G_2, connected by the satellite replicas nodes S^*, i.e. $G_1 \cap G_2 = S^*$.

Arc set A also reflects the two-echelon distribution system by defining specific networks for each echelon. The first-echelon graph is defined by $G_1 = (N_1, A_1)$, with $N_1 = \{o_1, o_1'\} \cup N^F, N^F = C_1 \cup S^*$, and $A_1 = (o_1, o_1') \cup \{(o_1, j) | j \in N^F\} \cup \{(i, j) | i, j \in N^F : i \neq j\} \cup \{(i, o_1') | i \in N^F\}$. The second-echelon graph is defined by $G_2 = (N_2, A_2)$, with $N_2 = \{o_2, o_2'\} \cup N^H, N^H = C_2 \cup S^*$, and the arc set can be defined as $A_2 = (o_2, o_2') \cup \{(o_2, S^*)\} \cup \{(i, j) | i \in S^*, j \in C_2\} \cup \{(i, j) | i \in C_2, j \in S^*\} \cup \{(i, j) | i, j \in C_2 : i \neq j\} \cup \{(i, o_2') | i \in C_2\}$. As shown in the arc set definition for city freighters, they will always leave the depot towards a satellite/meeting node in order to load, they do not load from two satellites in a row, and will always arrive to the depot coming from a C_2 customer. Each arc $(i, j) \in A$ has a travel time d_{ij}, and each node $i \in C_1 \cup C_2 \cup S^*$ has an associated service time st_i. For the sake of simplicity, we consider that the service time at these nodes is constant and does not depend on the location, the type of operation (delivering or transferring loads) or the transferred amounts. Furthermore, we consider that that $st_i = 0 : i \in O^*$.

Table 5.6: Sets, parameters and decision variables.

Sets	
O/O^*	set / extended set of depot nodes
C	set of customers
C_1	set of first-echelon customers
C_2	set of second-echelon customers
S	set of satellites
S^*	set of satellite replicas representing satellite/meetings
N^F	set of customers and satellite/meeting nodes able to be visited by urban freighters
N^H	set of customers and satellite/meeting nodes able to be visited by city freighters
K	fleet of all vehicles
K_1	fleet of urban freighters
K_2	fleet of city freighters
Parameters	
f_k	fixed cost of using vehicle $k \in K$
c_{ij}^k	cost of vehicle $k \in K$ for traversing arc $(i,j) \in A$
q_i	demand of customer $i \in C$
d_{ij}	time to transverse arc $(i,j) \in A$
st	service time
Q_k	maximum capacity of vehicle $k \in K$
T	maximum working time
TD	total demand of second-echelon customers C_2
σ_i^+	set of nodes that succeed node i
σ_i^-	set of nodes that precede node i
Variables	
x_{ij}^k	binary variable equal to 1 if vehicle $k \in K$ uses arc $(i,j) \in A$, and 0 otherwise
t_i^k	elapsed time as a vehicle $k \in K$ arrives at node i
y_i^k	load of vehicle $k \in K$ as it arrives to node i
u_i^{kz}	load transferred from $k \in K_1$ to $z \in K_2$, at transfer point $i \in S^*$

The set of available vehicles K encompasses a set of urban freighters K_1 and a set of city freighters K_2, $K = K_1 \cup K_2$. Each vehicle type fleet is homogeneous with fixed cost $f_k : k \in K$, travel costs c_{ij}^k, and capacity $Q_k : k \in K$, where the fixed costs, travel costs and capacity of urban freighters is always greater than those of city freighters i.e., $f_k > f_z$, $c_{ij}^k > c_{ij}^z$,and $Q_k > Q_z : k \in K_1, z \in K_2$. All vehicles have the same maximum working time T before which they must return to their respective depot.

For modelling purposes, we define the constant TD as the total demand of second-echelon customers $TD = \sum_{i \in C_2} q_i$, σ_i^+ as the set of nodes that succeed node i, and σ_i^- as the set of nodes that precede node i in their respective graph, such that $i \in N^*$. Additionally, we define the following decision variables:

- x_{ij}^k - binary variable equal to 1 if vehicle $k \in K$ travels from node i to node j, and 0 otherwise
- t_i^k - elapsed time as vehicle $k \in K$ arrives at node $i \in N$
- y_i^k - load of the vehicle $k \in K$ as it arrives to node $i \in N$
- u_i^{kz} - load transferred at satellite/meeting node $i \in S^*$ between urban freighters $k \in K_1$ and city freighters $z \in K_2$

A list of the used sets, parameters and decision variables is presented in Table 5.6. Given these definitions, we propose the following three index arc-based MIP model for the 2E-MTVRP-SS-DD.

$$min \quad Z = \sum_{k\in K} \sum_{j\in\sigma^{+}_{o_k}\setminus\{o'_k\}} f_k x^{k}_{o_k j} + \sum_{k\in K} \sum_{(i,j)\in A_k} c^{k}_{ij}(d_{ij} x^{k}_{ij}) \tag{5.33}$$

Our objective (5.33) is to minimise the fixed costs of the fleet and the total travel cost at both echelons.

Routing constraints

$$\sum_{j\in\sigma^{+}_{o_k}} x^{k}_{o_k j} = 1 \qquad \forall k\in K \tag{5.34}$$

$$\sum_{j\in\sigma^{+}_{o_k}} x^{k}_{o_k j} - \sum_{j\in\sigma^{-}_{o'_k}} x^{k}_{j o'_k} = 0 \qquad \forall k\in K \tag{5.35}$$

$$\sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} - \sum_{j\in\sigma^{-}_{i}} x^{k}_{ji} = 0 \qquad \forall i\in N^{F}, k\in K_1 \tag{5.36}$$

$$\sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} - \sum_{j\in\sigma^{-}_{i}} x^{k}_{ji} = 0 \qquad \forall i\in N^{H}, k\in K_2 \tag{5.37}$$

$$\sum_{k\in K_1} \sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} = 1 \qquad \forall i\in C_1 \tag{5.38}$$

$$\sum_{k\in K_2} \sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} = 1 \qquad \forall i\in C_2 \tag{5.39}$$

$$\sum_{k\in K_1} \sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} \leq 1 \qquad \forall i\in S^{*} \tag{5.40}$$

$$\sum_{k\in K_2} \sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} \leq 1 \qquad \forall i\in S^{*} \tag{5.41}$$

$$\sum_{k\in K_1} \sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} = \sum_{k\in K_2} \sum_{j\in\sigma^{+}_{i}} x^{k}_{ij} \qquad \forall i\in S^{*} \tag{5.42}$$

Constraints (5.34) ensure that every vehicle leaves its respective source node. Constraints (5.35) establish that every vehicle leaving a source node also arrives to their respective sink node. Given these first two types of constraints, if a vehicle is not used, then the arc between the source and the sink node of the depot $(o_k, o'_k) : k\in K$ is used. Constraints (5.36) and (5.37) are flow conservation constraints for the urban and city freighters, respectively, stating that if a vehicle arrives at a customer or satellite/meeting node then it must also leave. Constraint (5.38) states that each first-echelon customer is visited exactly once by a single urban freighter, and constraints (5.39) state that each second-echelon customer is visited exactly once by a single city freighter. Constraints (5.40) and (5.41) state that each satellite/meeting node is visited at most once by one urban and one city freighter, respectively, or not at all. Constraints (5.42) ensure that if a satellite/meeting node is used, then one vehicle of each type is required to be present.

Scheduling constraints

$$t_{o_k}^k = 0 \qquad \forall k \in K_1 \tag{5.43}$$

$$\tau_{is}^k \sum_{j \in \sigma_i^+} x_{ij}^k \leq t_i^k \leq \hat{T}_{is}^k \sum_{j \in \sigma_i^+} x_{ij}^k \qquad \forall i \in N^* \setminus \{O^*\}, k \in K \tag{5.44}$$

Constraints (5.43) establish the starting time of urban freighters at the depot as 0. Note that, we do not define this constraint for city freighters as these may start their route at any time, so that they are perfectly synchronised with urban freighters at their first satellite/meeting node. Constraints (5.44) establish the lower and upper bounds of the elapsed time as vehicles arrive at a given node. These are not time windows *per se*, and should be understood as a sort of valid inequalities. Given the characteristics of the problem, we are able to calculate lower and upper bounds as presented in equations (5.45) and (5.46), respectively.

$$\tau_{is}^k = \begin{cases} d_{o_k i} & \text{if } i \in N_1, k \in K_1 \\ d_{o_k i} & \text{if } i \in S^*, k \in K_2 \\ \min_{s \in S^*}\{d_{o_k s} + st_s + d_{si}\} & \text{if } i \in C_2, k \in K_2 \end{cases} \tag{5.45}$$

$$\hat{T}_{is}^k = \begin{cases} T - (st_i + d_{io'_k}) & \text{if } i \in N_1, k \in K_1 \\ T - \min_{s \in C_2}\{d_{is} + d_{so'_k} + st_i + st_s\} & \text{if } i \in S^*, k \in K_2 \\ T - (st_i + d_{io'_k}) & \text{if } i \in C_2, k \in K_2 \end{cases} \tag{5.46}$$

Regarding the time elapsed lower bounds (Equation 5.45), for the first echelon they are set as the time it takes from the depot (source node) to the node. For the second echelon, lower bounds are computed differently for satellite/meeting or customer nodes. As city freighters leave the depot empty, they will always go directly towards a satellite/meeting node to load. Therefore, for each satellites/meeting node the lower bound is set as the time it takes to reach it from the depot. On the other hand, for the second-echelon customers, the lower bound is computed as the minimum time it takes to go from the depot (source node) to a satellite/meeting node, plus the service time, and the time it takes to go from that satellite/meeting node to the second-echelon customer.

The time elapsed upper bounds (Eq.5.46) are computed so that these values are minimum, while still being possible to reach the depot respecting the maximum working time. For the first echelon, the upper bounds are computed as the difference between the maximum working time and the time it takes to perform a service, plus the time it takes to travel from that node to the depot (sink node). For the second echelon, the upper bound is computed differently for customer and satellite/meeting nodes. For customers, it is computed as the difference between the maximum working time and the service time at that node, plus the time it takes to go from that node to the depot (sink node). On the other hand, the upper bounds for satellite/meeting nodes are computed as the difference between the maximum working time and the minimum time it takes to go from the satellite/meeting node to a customer, from a customer to the depot (sink node) and the service times at both the satellite/meeting node and the customer.

$$\gamma_{is}^{k} \sum_{j\in\sigma^{+}_{o_k}\setminus\{o'_k\}} x^{k}_{o_k j} \leq t^{k}_{o'_k} \leq T \sum_{j\in\sigma^{+}_{o_k}\setminus\{o'_k\}} x^{k}_{o_k j} \qquad \forall k \in K \tag{5.47}$$

Constraints (5.47) establish the lower and upper bounds for the arrival times at the depot (sink node) of vehicles used. The upper bound is set to the maximum working time, and the lower bounds are computed differently for urban and city freighters, and are calculated as shown in Eq. (5.48).

$$\gamma_{is}^{k} = \begin{cases} \min_{i\in N^F}\{2d_{o_k i} + st_i\} & \text{if } k \in K_1 \\ \min_{i\in S^*, s\in C_2}\{d_{o_k i} + d_{is} + d_{so'_k} + st_i + st_s\} & \text{if } k \in K_2 \end{cases} \tag{5.48}$$

The lower bound for urban freighters is computed as the minimum time it takes to reach a node, perform a service and return to the depot. As for the lower bound for the city freighters, it is computed as the minimum time it takes to reach a satellite/meeting node, from there go to a customer, and then return to the depot, plus the service time at each location.

$$t^{k}_{i} + (d_{ij} + st_i)x^{k}_{ij} \leq t^{k}_{j} + \hat{T}^{k}_{is}(1 - x^{k}_{ij}) \qquad \forall (i,j) \in A_k, k \in K \tag{5.49}$$

Constraints (5.49) are time elapsed constraints. Since t^k_i are unique for each node and always increasing, these constraints also serve as sub-tour elimination constraints. When considering the link between a first-echelon customer node and a satellite/meeting node at the same location where $d_{ij} = 0$, these constraints still serve as sub-tour elimination constraints since a service time is always considered. As for the *"Big M"*, we use the upper bounds for elapsed time as previously presented in Eq. (5.46), depending on the type of vehicle $k \in K$, and the type of node $i \in N^* \setminus \{O^*\}$.

Load conservation constraints For a clearer representation of load conservation constraints, we have split them into two groups, one for each echelon. The first group of constraints apply to urban freighters, and the second to the city freighters.

$$y^k_{o'_k} = 0 \qquad \forall k \in K_1 \tag{5.50}$$

$$\bar{q}_i \sum_{j \in \sigma_i^+} x^k_{ij} \leq y^k_i \leq Q_k \sum_{j \in \sigma_i^+} x^k_{ij} \qquad \forall i \in N^F, k \in K_1 \tag{5.51}$$

$$y^k_{o_k} = \sum_{i \in C_1} \sum_{j \in \sigma_i^+} q_i x^k_{ij} + \sum_{z \in K_2} \sum_{i \in S^*} u^{kz}_i \qquad \forall k \in K_1 \tag{5.52}$$

$$y^k_{o_k} \leq y^k_i + Q_k(1 - x^k_{o_k i}) \qquad \forall i \in N^F \cup o'_k, k \in K_1 \tag{5.53}$$

$$y^k_i - q_i x^k_{ij} \leq y^k_j + Q_k(1 - x^k_{ij}) \qquad \forall i \in C_1, j \in \sigma_i^+, k \in K_1 \tag{5.54}$$

$$y^k_i - \sum_{z \in K_2} u^{kz}_i \leq y^k_j + Q_k(1 - x^k_{ij}) \qquad \forall i \in S^*, j \in \sigma_i^+, k \in K_1 \tag{5.55}$$

Constraints (5.50) state that urban freighters will always arrive empty at the depot. Constraints (5.51) establish the lower and upper bounds for the load when an urban freighter arrives to a first-echelon customer or to a satellite/meeting node. The upper bound is the same regardless of the type of node and it is set as the capacity of urban freighters. As for the the lower bound, its value is different, depending if the node is a customer or a satellite/meeting node. For customer nodes the lower bound is set as that customer's demand, $\bar{q}_i = q_i : i \in C_1$, and for the satellite/meeting nodes, the lower bound is set as the minimum demand of all second echelon customers $\bar{q}_i = \min_{s \in C_2}\{q_s\} : i \in S^*$. Constraints (5.52) establish the initial load with which each urban freighter is required to leave the depot. This amount encompasses the loads to be delivered to first-echelon customers C_1 and all loads to be transferred to city freighters at satellite/meeting nodes S^*. Constraints (5.53) are load conservation constraints, when leaving the source node. Together with constraints (5.50), they also set the load of unused vehicles at the source node to zero. Constraints (5.54) are load conservation constraints for the first-echelon customers C_1, and constraints (5.55) are load conservation constraints for the satellite/meeting nodes, where transferred loads to city freighters act as the demand at those locations.

$$y^k_i = 0 \qquad \forall i \in S^* \cup \{o_2, o'_2\}, k \in K_2 \tag{5.56}$$

$$q_i \sum_{j \in \sigma_i^+} x^k_{ij} \leq y^k_i \leq Q_k \sum_{j \in \sigma_i^+} x^k_{ij} \qquad \forall i \in C_2, k \in K_2 \tag{5.57}$$

$$y^k_{o_k} \geq y^k_i - Q_k(1 - x^k_{o_k i}) \qquad \forall i \in S^*, k \in K_2 \tag{5.58}$$

$$y^k_i + \sum_{z \in K_1} u^{zk}_i \geq y^k_j - Q_k(1 - x^k_{ij}) \qquad \forall i \in S^*, j \in C_2, k \in K_2 \tag{5.59}$$

$$y^k_i - q_i x^k_{ij} \geq y^k_j - Q_k(1 - x^k_{ij}) \qquad \forall i \in C_2, j \in \sigma_i^+, k \in K_2 \tag{5.60}$$

The load conservation constraints for city freighters have been inspired by the formulation presented in Bard et al. (1998) for the VRP with satellite facilities. Constraints (5.56) establish that city freighters start and end their working day empty, and that they arrive at satellite/meeting nodes empty as well. Constraints (5.57) establish the lower and upper bounds for the load of city freighters as they arrive to second-echelon customers. The lower bound is set to the demand of the customer and the upper bound is the capacity of city freighters. Constraints (5.58) are load conservation constraints from the source node to a satellite/meeting node. Constraints (5.59) are load conservation constraints at satellite/meeting nodes. If a city freighter visits a *satellite*/meeting node, then it will be loaded with the amount provided by an urban freighter, represented by u_i^{kz}. Constraints (5.60) are load conservation constraints, when arriving at a second-echelon customers.

Linking constraints These constraints allow us to model exact space-time synchronisation and load synchronisation between both types of vehicles.

$$\sum_{k\in K_1} t_i^k = \sum_{k\in K_2} t_i^k \qquad \forall i \in S^* \tag{5.61}$$

$$\sum_{k\in K_1}\sum_{z\in K_2}\sum_{i\in S^*} u_i^{kz} = TD \tag{5.62}$$

Constraints (5.61) define an exact time synchronisation between urban and city freighters at satellite/meeting nodes. This means that both types of vehicle may have waiting times at the previous node so that these constraints are satisfied. Constraint (5.62) establishes that the total transferred load at satellite/meeting nodes is equal to the total demand of second-echelon customers (TD).

$$x_{ij}^k \in \{0,1\} \qquad \forall (i,j) \in A, k \in K \tag{5.63}$$

$$0 \le t_i^k \le T \qquad i \in N, k \in K \tag{5.64}$$

$$0 \le y_i^k \le Q_k \qquad i \in N, k \in K \tag{5.65}$$

$$0 \le u_i^{kz} \le Q_z \qquad i \in S^*, k \in K_1, z \in K_2 \tag{5.66}$$

Constraints (5.63), (5.64), (5.65), and (5.66) set the domain of the variables.

5.2.2 Valid inequalities

3-index MIP arc-based formulations for problems of the VRP family, particularly where the decision on the number of vehicles to deploy is also taken into account, usually have very weak linear relaxations, yielding very poor lower bounds, and commonly suffer from an inherent symmetry problem, resulting in intractable MIP based approaches (Toth & Vigo, 2014). In this work, we propose a set of valid inequalities based on those proposed in the VRP literature and adapted to our problem, aiming to improve the lower bound provided by the linear relaxation of the proposed model, address the symmetry problem, and ultimately speed-up the branch-and-bound procedure.

Symmetry breaking constraints The proposed 3-index arc-based formulation suffers from a symmetry problem, due to the vehicles index k in the decision variables and to the fact that vehicles are considered to be homogeneous at each echelon. Let $\bar{K}_1$ and $\bar{K}_2$ represent the number of dispatched urban and city freighters, respectively. Therefore, there are $\binom{K_1}{\bar{K}_1}$ and $\binom{K_2}{\bar{K}_2}$ different alternatives for dispatching urban and city freighters, respectively. Additionally, among the selected vehicles, there are $\bar{K}_1!$ and $\bar{K}_2!$ alternatives to swap the routes assigned to each dispatched vehicle. Therefore, due to these two types of symmetry, we can have $\binom{K_1}{\bar{K}_1} \times \bar{K}_1! \times \binom{K_2}{\bar{K}_2} \times \bar{K}_2!$ equivalent solutions (they can also be seen as the product of each echelon $\bar{K}$-permutations of the respective total available fleet, $P^{K_1}_{\bar{K}_1} \times P^{K_2}_{\bar{K}_2}$). These issues can significantly slow down the branch-and-bound procedure, due to the duplication of solutions in the search tree (Sherali & Smith, 2001). To address such issues, we include two sets of symmetry-breaking constraints, one for vehicle dispatching (SB1) and one for vehicles' routes (SB2), inspired by Sherali & Smith (2001), Adulyasak et al. (2013), and Lahyani et al. (2018).

We start by lexicographically ordering vehicles at each echelon, such that $K_1 = \{1, 2, ..., |K_1|\}$ and $K_2 = \{1, 2, ..., |K_2|\}$. Then, we address the vehicle dispatching symmetry issue by including constraints (5.67) and (5.68) (SB1) which enforce that whenever a new vehicle is required, the previous vehicle in the order must have been used already.

$$\text{(SB1)} \quad \sum_{j \in \sigma^+_{o_k} \setminus \{o'_k\}} x^k_{o_k j} \leq \sum_{j \in \sigma^+_{o_k} \setminus \{o'_k\}} x^{k-1}_{o_k j} \qquad \forall k \in K_1 \setminus \{1\} \tag{5.67}$$

$$\sum_{j \in \sigma^+_{o_k} \setminus \{o'_k\}} x^k_{o_k j} \leq \sum_{j \in \sigma^+_{o_k} \setminus \{o'_k\}} x^{k-1}_{o_k j} \qquad \forall k \in K_2 \setminus \{1\} \tag{5.68}$$

To address the used vehicles' routing symmetry, we include constraints (5.69) and (5.70) (SB2), which order the used routes according to their total route time.

$$\text{(SB2)} \quad \sum_{(i,j) \in A_k} d^k_{ij} x^k_{ij} \leq \sum_{(i,j) \in A_k} d^{k-1}_{ij} x^{k-1}_{ij} \qquad \forall k \in K_1 \setminus \{1\} \tag{5.69}$$

$$\sum_{(i,j) \in A_k} d^k_{ij} x^k_{ij} \leq \sum_{(i,j) \in A_k} d^{k-1}_{ij} x^{k-1}_{ij} \qquad \forall k \in K_2 \setminus \{1\} \tag{5.70}$$

Vehicles rounded capacity constraints Aside from symmetry breaking constraints, we have also considered valid inequalities based on the capacity of vehicles (RC). Constraints (5.71), commonly known as *rounded capacity constraints* (Baldacci et al., 2012; Toth & Vigo, 2014), establish a lower bound for the number of urban freighters needed to transport all customer's loads, including both first- and second-echelon customers. Note that, these constraints can only be used for urban freighters as city freighters can replenish at satellites throughout their working day. Nonetheless, we include constraint (5.72) as at least one city freighter will be required to deliver loads to second-echelon customers. Furthermore, given the symmetry breaking constraints (5.67) and (5.68), and the rounded capacity constraints (5.71) and (5.72), we are able to state that the first needed vehicles of each type will be used, and thus include constraints (5.73) and (5.73) for urban and city freighters, respectively.

$$\text{(RC)} \quad \sum_{k\in K_1} \sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} \geq \left\lceil \frac{\sum_{i\in C} q_i}{Q_1} \right\rceil \tag{5.71}$$

$$\sum_{k\in K_2} \sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} \geq 1 \tag{5.72}$$

$$\sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} = 1 \qquad \forall k = \{1, ..., \left\lceil \frac{\sum_{i\in C} q_i}{Q_1} \right\rceil\} : k \in K_1 \tag{5.73}$$

$$\sum_{j\in\sigma^+_{o_k}\setminus\{o'_k\}} x^k_{o_k j} = 1 \qquad \forall k = 1 : k \in K_2 \tag{5.74}$$

Satellites rounded capacity constraints The idea behind the capacity rounding constraints can also be applied to compute the lower bound for the number of satellite/meeting nodes required to be visited by urban and city freighters as to serve second-echelon customers. Given that only a single vehicle of each type may visit a satellite/meeting node, the lower bound of the number of satellite/meeting nodes visited by urban and city freighters is computed as the ceiling of the total demand of second-echelon customers divided by the capacity of city freighters, as given by constraints (5.75) and (5.76) (SCR).

$$\text{(SCR)} \quad \sum_{k\in K_1} \sum_{(i,j)\in A_1 : i\in S^*} x^k_{ij} \geq \left\lceil \frac{TD}{Q_2} \right\rceil \tag{5.75}$$

$$\sum_{k\in K_2} \sum_{(i,j)\in A_2 : i\in S^*} x^k_{ij} \geq \left\lceil \frac{TD}{Q_2} \right\rceil \tag{5.76}$$

5.2.3 Computational experiments

In this section, we analyse the behaviour of the model and the impact of the proposed valid inequalities. We start by describing the adaptation of some VRPTW instances to the 2E-MTVRP-SS-DD, with which all computational experiments were performed. The details regarding the construction of the instances are discussed in Section 5.2.3.1. In Section 5.2.4.1, we present the results obtained by our MIP model, without and with the proposed valid inequalities.

5.2.3.1 Benchmark instances

To test the proposed MIP formulation and the impact of valid inequalities, we have adapted Solomon's CVRPTW instances (Solomon, 1987) with 25 customers (Networking & emerging optimization Research Group, 7 January 2013), as to account for the characteristics of our problem. We have used instances C101, C201, R101, R201, RC101, RC201, where "C" stands for clustered customers, "R" is for randomly located customers and "RC" for a combination of both. We have considered only the first two instances of each type, as the only difference from the remaining instances are the time windows at customers, which we do not take into account.

We have considered the Solomon's instances as the second echelon of our network. The depot is used as the city freighters depot, the number of vehicles in the original instances became the number of available city freighters, and customers became second-echelon customers.

We set the number of available urban freighters to half of the number of city freighters, rounded up. The capacity of the vehicles is established as 4 and 0,5 times the capacity of the vehicles in Solomon's instances for urban and city freighters, respectively. Regarding vehicles' costs, we set the fixed and variable costs of urban and city freighters as $f_k = 30$ and $c_{ij}^k = 3 : i \in K_1$, $f_k = 10$ and $c_{ij}^k = 1 : i \in K_2$. For the maximum arrival time of vehicles at the depot we consider the latest time of arrival at the depot in Solomon's instances, except for instance R101 and RC101 for which we established the maximum working time to 1000, instead of the original 230 and 240, respectively. Additionally, we have included the urban freighters depot, first-echelon customers and the satellites as explained in the next subsection. For all instances, the distance matrix is calculated as the Euclidean distance rounded up to the second decimal place, and service times were set to 10, $s_i = 10 : i \in N^* \setminus \{O^*\}$.

Instances construction In this subsection we describe in detail how we have adapted the original Solomon's instances to account for the requirements of our problem, including the urban freighters' depot, satellites and first-echelon customers.

Urban freighters depot According to Crainic et al. (2010), the 2E-CVRP gets its most benefit when compared to the VRP alternative when the urban freighters depot is located outside the city centre zone where second-echelon customers are located, due to savings in travel times to reach and return from customers. Taking this into account, we add the urban freighters depot in the following manner. Let x_{min}, y_{min} and x_{max}, y_{max} represent the minimum and maximum x and y coordinates of all second-echelon customers. Given this, we consider customers' zone to be the geometric figure formed by points (x_{min}, y_{min}), (x_{min}, y_{max}), (x_{max}, y_{min}), (x_{max}, y_{max}), referred from this point on as ε, and locate the urban freighters' depot at $(\frac{x_{max} - x_{min}}{2}, 2y_{max} - y_{min})$.

Satellites We have considered a set of 8 satellites for all instances. The location of the satellites is calculated based on ε. To compute the location of the satellites we first compute the length and height of ε as $l = x_{max} - x_{min}$ and $h = y_{max} - y_{min}$, respectively. With this information we compute the location of the 8 satellites so that all satellites are located outside ε, as shown in Figure 5.2. To perform all computational tests we have limited the number of possible visits to each satellite to 2, as the replication of satellite nodes into dummy satellite/meeting nodes greatly increases the size of the model, sometimes make it intractable even for smaller instances.

$$\begin{array}{lll}
s_1(x_{min} - \frac{l}{4}, y_{max} + \frac{h}{4}) & s_4(\frac{x_{max} + x_{min}}{2}, y_{max} + \frac{h}{4}) & s_6(x_{max} + \frac{l}{4}, y_{max} + \frac{h}{4}) \\
s_2(x_{min} - \frac{l}{4}, \frac{y_{max} + y_{min}}{2}) & & s_7(x_{max} + \frac{l}{4}, \frac{y_{max} + y_{min}}{2}) \\
s_3(x_{min} - \frac{l}{4}, y_{min} - \frac{h}{4}) & s_5(\frac{x_{max} + x_{min}}{2}, y_{min} - \frac{h}{4}) & s_8(x_{max} + \frac{l}{4}, y_{min} - \frac{h}{4})
\end{array}$$

Figure 5.2: Geometrical layout of satellites.

First-echelon customers We include 10 first-echelon customers randomly located based the location of the satellites and of the urban freighters depot. Given the position of the satellites, let α and β be their minimum and maximum x coordinates, and δ, ρ be their minimum and maximum y coordinates. Consider also that y^* represents the y coordinates of the urban freighters depot. Therefore, we compute the x and y coordinates of customers such that $\alpha - \frac{l}{2} \leq x_i \leq \alpha \wedge \beta \leq x_i \leq \beta + \frac{l}{2}$, and $\delta - \frac{h}{2} \leq y_i \leq \delta \wedge \rho \leq y_i \leq y^*$. Note that, all limits are rounded up to the next integer. Additionally, we randomly choose 2 of the generated satellites become satellite-customers, representing those where loads may be transferred between both types of vehicles. The demand of first-echelon customers and of satellite-customers is taken from an uniform distribution $U[\alpha, \beta]$, such that $\alpha = \overline{q} - \sigma$ and $\beta = \overline{q} + \sigma$, where $\overline{q}$ is the average demand of second-echelon customers and σ its standard deviation.

Total set of instances The total set of instances is formed by two sets. Set (S1) contains the larger instances based on the original Solomon's instances with 25 customers, and the second set (S2) are smaller instances based on (S1) where we have removed some first-echelon customers, second-echelon customers, and some vehicles of each type. As to account for the reduction of customers, we have also reduced the capacity of vehicles to half the capacity of those in S1, and set the maximum working time to 500. These instances were used to show the performance of the proposed valid inequalities. The instances are named according to their characteristics, including the name of the original Solomon instance, number of first-echelon customers, number of second-echelon customers and number of satellites ($originalInstance\_|C_1|\_|C_2|\_|S|$). The complete list of used instances is presented in Table 5.7.

5.2.4 Results

In this section, we present the results of using the MIP model presented in section 5.2.1, and an assessment of the impacts of considering the proposed valid inequalities to solve the problem. First, we present the results of using the MIP model to solve both sets of instances, without any valid inequalities. Next, we present the results when using several combinations of the proposed

Table 5.7: Characteristics of instances.

		Customers				K_1		K_2			
Set	Instance	$\|C_1\|$	$\sum_{i\in C_1} q_i$	$\|C_2\|$	$\sum_{i\in C_2} q_i$	$\|K_1\|$	Q_1	$\|K_2\|$	Q_2	$\|S^*\|$	T
S1	C101_12_25_8	12	217	25	460	13	800	25	100	16	1236
	C201_12_25_8	12	244	25	460	13	2800	25	350	16	3390
	R101_12_25_8	12	149	25	332	13	800	25	100	16	1000[a]
	R201_12_25_8	12	155	25	332	13	4000	25	500	16	1000
	RC101_12_25_8	12	233	25	540	13	800	25	100	16	1000[a]
	RC201_12_25_8	12	251	25	540	13	4000	25	500	16	960
S2	C101_4_6_8	4	85	6	90	5	400	10	50	16	500
	C201_4_6_8	4	87	6	90	5	1400	10	175	16	500
	R101_4_6_8	4	43	6	78	5	400	10	50	16	500
	R201_4_6_8	4	43	6	78	5	2000	10	250	16	500
	RC101_4_6_8	4	84	6	140	5	400	10	50	16	500
	RC201_4_6_8	4	77	6	140	5	2000	10	250	16	500

[a] Value changed from the original instance

valid inequalities to solve the set of smaller instances S2, and then to solve the larger set of instances S1. Finally, we present the results of applying a more restricted set of combinations of valid inequalities to set S1, after using a MIP *warm-start* procedure.

All tests were performed on a Intel(R) Core(TM) i7-6700HQ CPU at 2,6 GHz with 16 GB of RAM. The model was implemented using the Java programming language and all tests with the MIP model and valid inequalities were performed using the commercial solver Gurobi v8.1.0, using the standard parameters' settings and disabling the solver's *presolve*. All tests without *warm-starting* the MIP model were performed establishing a maximum computation time of one hour. For the tests using the *warm-start*, we established a maximum computation time of two hours.

5.2.4.1 Performance of the MIP model

Table 5.8 summarises the main results when using the proposed 3-index mathematical formulation to solve all 12 instances. We report the main indicators as produced by Gurobi, namely: the final value of the objective function, the MIP gap percentage, the total computation time ("-" represents the maximum computational time), the best lower bound (*BB*), the linear relaxation at the root node (*LR*), as well as the number of binary variables, continuous variables, and of constraints of the model. Additionally, we present the number of urban freighters, city freighters and satellite/meeting nodes used in the final solution. In bold, we indicate the tests in which the solver was able to prove that the solution was optimal.

The solver was unable to prove the optimality of all best solutions for the instances of set S1, yielding large final MIP gaps that ranged from 26,92% to 80,64%. As for the smaller instances of set S2, the solver was able to prove the optimality of the final solution for 2 out of 6 instances, while the others ended with MIP gaps that ranged from 6,66% to 29,8%. For each of the instance types (C, R or RC), in both large and small instances, the best results were obtained in the ones where vehicles had more capacity, and consequently where less satellite/meetings were needed in the final solution, evidencing the added complexity of considering the exact synchronisation

Table 5.8: Results using the base MIP model.

		MIP solver								Final solution		
Set	Instance	Obj.	Gap %	CPU(s)	*BB*	*LR*	Bin. var.	Cont. var.	Const.	$\|K_1\|$	$\|K_2\|$	$\|S^*\|$
S1	C101_12_25_8	1492,07	55,83	-	659,06	485,80	46619	8130	100101	1	4	7
	C201_12_25_8	1343,22	26,92	-	981,51	650,37	46619	8130	100101	1	1	2
	R101_12_25_8	2808,20	54,83	-	1268,06	977,94	46619	8130	100101	2	2	6
	R201_12_25_8	2643,02	33,69	-	1751,65	1388,62	46619	8130	100101	2	1	2
	RC101_12_25_8	5526,89	80,64	-	1070,02	819,57	46619	8130	100101	4	5	11
	RC201_12_25_8	2481,47	46,97	-	1315,92	1071,10	46619	8130	100101	2	2	2
S2	C101_4_6_8	439,73	29,80	-	308,67	213,54	4555	1500	10710	1	1	2
	C201_4_6_8	**802,32**	**0,00**	**1235**	**802,32**	**250,71**	**4555**	**1500**	**10710**	**1**	**1**	**1**
	R101_4_6_8	791,50	11,05	-	703,97	388,76	4555	1500	10710	1	1	2
	R201_4_6_8	**1257,24**	**0,00**	**3495**	**1257,24**	**472,39**	**4555**	**1500**	**10710**	**1**	**1**	**1**
	RC101_4_6_8	1061,76	11,09	-	943,48	297,13	4555	1500	10710	1	1	3
	RC201_4_6_8	1211,33	6,66	-	1130,60	493,00	4555	1500	10710	1	1	1

between both vehicles at satellites. For the instances of set S2, we later proved, when using the proposed valid inequalities (see Section 5.2.4.2), that all the best solutions found using solely the proposed formulation were, in fact, optimal. The solver was unable to prove their optimality during the allowed computation time, indicating that the main difficulty was the long time the branch-and-bound procedure took to converge, reflecting the combinatorial nature of the problem as well as the impacts of the inherent solution symmetry.

5.2.4.2 The impact of valid inequalities

To evaluate the effectiveness of the proposed valid inequalities, we conducted additional computational tests where different combinations of the proposed valid inequalities were added to the proposed MIP model, in a static way. First, we present the results for the set of smaller instances S2, and follow with the analysis for the set of larger instances S1.

S2 instances Table 5.9 presents an assessment of including different combinations of the valid inequalities, to solve the set of smaller instances S2. The table includes the number of S2 instances for which the final solution was proven optimal (*OS*), the improvement percentage in the root linear relaxation (*LR*), in the best bound (*BB*), and in the computational time to prove the solutions were optimal, as well as the time to obtain a first feasible solution (in seconds) (FF). These tests showed that the final solutions obtained without any of the valid inequalities (see Table 5.8) were in fact the optimal solutions, and therefore we do not present the improvements in the final solutions. The results regarding the improvement percentage of the root linear relaxation and of the best bound have the MIP model without valid inequalities as the baseline. Additionally, the table also presents the improvement percentage in the best bound for a single combination of valid inequalities with which the final solutions were optimal (SB1 + SB2), as all others would have the same values. As for the improvement percentage in CPU time, the results obtained using the combination (SB1 + SB2) are used as the baseline, as that was the combination with which all instances' solutions were proven optimal with the highest average computation time.

The results show that, by adding only one of the two sets of symmetry breaking constraints, SB1 or SB2, the solver was able to prove the solutions optimality for more instances than using

Table 5.9: Main indicators after using valid inequalities in set S2.

		LR improvement %			*BB* improvement %			CPU time improvement %			$FF(s)$		
Valid inequalities	*OS*	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
SB1	3	0,00	0,00	0,00	2,93	8,53	14,82	-	-	-	2	32,83	136
SB2	5	0,00	0,00	0,00	7,14	15,57	30,23	-	-	-	12	38,67	63
SB1 + SB2	6	0,00	0,00	0,00	7,14	18,63	42,46	-	-	-	12	16,67	28
RC	6	3,06	33,05	57,14	-	-	-	-43,64	34,39	97,29	0	1,67	6
RC + SRC	6	3,06	38,20	57,14	-	-	-	17,65	75,03	99,18	0	1,33	4
All	6	3,06	38,20	57,14	-	-	-	47,06	81,93	99,39	2	12,17	23

solely the MIP model (although still unable to do so for all 6 instances). When added to the model alone, the SB2 constraints led to better results than SB1, solving more instances to optimality and yielding an average improvement of the best lower bound of 15,57%. When both SB1 and SB2 are added, all 6 instances were solved to optimality, and the solver was able to find a first feasible solution faster than when using SB1 or SB2 alone. The root linear relaxation was unaffected by adding any symmetry breaking constraints, but these constraints had a positive impact in the best lower bound, particularly when both SB1 and SB2 were added.

When adding only the rounded capacity constraints (RC), all instances were solved to optimality. Adding these inequalities allowed for an average improvement of the root linear relaxation of 33,05%. When compared with the simultaneous use of SB1 and SB2, not only was the solver able to find a first feasible solution faster, but the average computational time to prove optimality also improved by 34,39%. By further adding the satellite rounding capacity constraints (SRC) to the RC, the root linear relaxation improved from 33,05% to 38,2%, showing a small positive effect of including the SRC constraints. We note that this positive impact only existed when the minimum number of required satellite/meetings was higher than 1, and that the impact was greater as the number of required satellite/meetings increases. Moreover, the solver was slightly faster in finding a first feasible solution, and the time to prove optimality improved considerably, with the average improvement rising from 43,39% using only RC, to 75,03%.

When all sets of valid inequalities were added to the MIP model, this is, both sets of symmetry breaking constraints (SB1 and SB2) as well as vehicle and satellite rounded capacity constraints (RC and SRC), the improvement in the root linear relaxation was the same as when using only the RC and SRC constraints. Furthermore, there was an increase in the average time for the solver to obtain a first feasible solution, from 1,33 to 12,17 seconds.However, further adding both symmetry breaking constraints yielded the highest improvements regarding the computation time required to prove the solution optimality.

In conclusion, the results for S2 instances show that the symmetry breaking constraints (SB1 and SB2) had no impact in the root linear relaxation, but they resulted in a improvement of the best lower bound. We note that the addition of these constraints increased the time required for the solver to find a first feasible solution, although together with RC and SRC they allowed for faster computational times, indicating a positive impact on the reduction of explored nodes during the branch-and-bound procedure. Both RC and SRC constraints had a positive impact in improving the root linear relaxation, although the RC constraints were more relevant. The best results were achieved when all proposed valid inequalities were added, as they allowed solving all instances to optimality in the least computational time.

S1 instances Table 5.10 shows some indicators on the effectiveness of including different combinations of the valid inequalities to solve the set of larger instances (S1). The main indicators considered are the improvement percentage of the root linear relaxation, of the best lower bound, and of the final objective function value (upper bound).

Table 5.10: Main indicators after using valid inequalities in set S1.

	LR improvement %			*BB* improvement %			Obj. improvement %		
Valid inequalities	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
SB1	0,00	0,00	0,00	1,23	6,43	13,16	-	-	-
SB2	0,00	0,00	0,00	-12,69	-8,78	-3,63	-	-	-
SB1 + SB2	0,00	0,00	0,00	-1,19	1,69	6,62	-	-	-
RC	8,67	16,09	24,11	6,01	11,03	16,66	-95,45	-9,82	44,96
RC + SRC	8,76	20,24	36,75	7,20	15,05	28,49	-3,99	13,69	34,08
All	8,76	20,24	36,75	2,66	10,75	25,06	-	-	-

In what concerns the symmetry breaking constraints, the results show that the root linear relaxation was not affected by their inclusion. Regarding the improvements in the best lower bound, adding only SB1 provided the best results, with an average improvement of 6,43%, while adding only SB2 had a negative impact, with an average of 8,78%. Moreover, when adding both SB1 and SB2, the positive impact on the best lower bound obtained when adding only SB1 was worsened with the inclusion of SB2, with a reduction of the average improvement from 6,43% to 1,69%.

The rounded capacity constraints (RC) had a positive impact in the root linear relaxation and in the best lower bound, with average improvements of 16,09% and 11,03%, respectively. These positive impacts did not always led to an improvement of the objective function value (upper bound), yielding widely variable results, with an average deterioration of 9,82%. By further including the satellite rounded capacity constraints (SRC), this wide variability in the improvement percentage of the objective function value was significantly reduced, and the average improvement percentage increased from -9,82% to 13,69%. Further adding both SB1 and SB2, represented, on average, to a deterioration of the best lower bound, when compared with only using RC and SRC, resulting in a decrease from 15,05% to 10,75%.

Note that, whenever the symmetry breaking constraints were added, the solver was unable to find a first feasible solution during the allowed computational time. This means that the increase in the required computation time to find a first feasible solution (observed when solving the smaller instances of S2) became even more evident when larger instances were considered. Similar results have also been reported by Sherali & Smith (2001), when studying the effects of using lexicographical-based hierarchical constraints to break the inherent symmetry of several mathematical formulations.

Given these results, we decided to perform an alternative evaluation by *warm-starting* the MIP model with a first feasible solution. This exercise aimed not only to solve the S1 instances, but also to further evaluating the impacts of adding the proposed symmetry breaking constraints on the objective function value, and ultimately on the gap.

5.2.4.3 Application of a warm-start procedure

Aiming to better grasp the impacts of the proposed valid inequalities, and in an attempt to solve the larger instances of set S1, additional tests were performed by *warm-starting* the MIP model using the first feasible solution obtained when running the MIP model without any valid inequalities, and setting the number of available vehicles of each fleet to the number of used vehicles in that solution. Additionally, we considered a maximum computation time of two hours as to better assess the evolution of the branch-and-bound procedure. Table 5.11 presents the information of the first feasible solution of each instance used to *warm-start* the MIP model. We present the objective function value, the MIP gap % and the time taken to find the solution, and the number of urban freighters (K_1), city freighters (K_2), and satellite/meetings (S^*) used in the solution.

Table 5.11: Information of first feasible solution used in the warm-start.

	MIP model			Final solution		
Instance	Objective function	Gap %	CPU (s)	$\lvert K_1\rvert$	$\lvert K_2\rvert$	$\lvert S^*\rvert$
C101_12_25_8	1706,97	71,50	252	1	4	9
C201_12_25_8	2190,6	70,3	162	1	3	5
R101_12_25_8	3101,79	68,5	238	2	4	7
R201_12_25_8	4076,04	65,9	138	4	3	3
RC101_12_25_8	6718,37	84,2	2489	4	6	13
RC201_12_25_8	3948,89	72,9	134	5	2	4

To establish a new baseline with which to assess the impacts of adding the proposed valid inequalities, we first ran the MIP model without any valid inequalities again, after performing the *warm-start*. Additionally, given the results obtained with the set of smaller instances S2, we tested only the two best combinations of valid inequalities, namely: i) using vehicles and satellites rounded capacity constraints (CR + SRC); and ii) all proposed valid inequalities, thus allowing for the evaluation of the impacts of adding the symmetry breaking constraints (SB1 and SB2).

Table 5.12 presents the results of solving all 6 instances of set S1 after warm-starting the MIP model, reducing the available fleet, and establishing a maximum computation time of two hours. The table presents the used combinations of valid inequalities (V.I), the final objective function value (Obj.) and their resulting improvement percentage, the final MIP gap percentage as given by the solver, the computation time (in seconds) in which the final solution was proven to be optimal (CPU(s)), the best lower bound (BB) and its resulting improvement percentage, the number of binary variables, continuous variables, and constraints of the model, as well as the number of urban and city freighters, and the number of satellite/meeting nodes used in the final solution. The tests in which the solutions were proven optimal are indicated in bold.

Table 5.12: Main indicators for set S1, using valid inequalities after warm-start.

		MIP model									Solution		
Instance	V.I.	Obj.	Obj imp. %	Gap%	CPU (s)	BB	BB imp. %	Bin var	Cont Var	Constraints	$\lvert K\_1\rvert$	$\lvert K\_2\rvert$	$\lvert S^*\rvert$
C101_12_25_8	None	1176,04	-	37,10	-	739,94	-	6581	468	14187	1	2	5
	RC + SRC	1224,75	-4,14	27,40	-	889,06	20,15	-	-	14193	1	3	7
	All	1333,03	-13,35	33,70	-	883,69	19,43	-	-	14199	1	3	5
C201_12_25_8	None	1247,65	-	9,40	-	1130,39	-	5139	366	11109	1	1	2
	RC + SRC	**1225,17**	**1,80**	**0,00**	**5127**	**1225,17**	**8,39**	-	-	**11115**	**1**	**1**	**2**
	All	**1225,17**	**1,80**	**0,00**	**3005**	**1225,17**	**8,39**	-	-	**11119**	**1**	**1**	**2**
R101_12_25_8	None	2037,31	-	27,50	-	1477,97	-	7394	592	15960	1	3	4
	RC + SRC	1790,28	12,13	9,34	-	1623,07	9,82	-	-	15966	1	1	4
	All	2003,1	1,68	19,00	-	1622,99	9,81	-	-	15974	2	1	4
R201_12_25_8	None	2070,63	-	3,26	-	2003,05	-	7578	690	16428	1	1	1
	RC + SRC	**2070,63**	**0,00**	**0,00**	**155**	**2070,63**	**3,37**	-	-	**16434**	**1**	**1**	**1**
	All	**2070,63**	**0,00**	**0,00**	**195**	**2070,63**	**3,37**	-	-	**16444**	**1**	**1**	**1**
RC101_12_25_8	None	2447,56	-	51,30	-	1191,33	-	11904	1140	25662	2	2	6
	RC + SRC	2056,24	15,99	29,80	-	1443,20	21,14	-	-	25668	1	3	6
	All	3522,81	-43,93	60,10	-	1406,82	18,09	-	-	25684	2	2	7
RC201_12_25_8	None	1936,55	-	11,50	-	1713,52	-	6949	632	15123	1	1	2
	RC + SRC	1897,71	2,01	2,80	-	1844,60	7,65	-	-	15129	1	1	2
	All	1900,47	1,86	3,01	-	1843,18	7,57	-	-	15139	1	1	2
Avg. imp. % RC + SRC			4,63				11,75						
Avg. imp. % All			-8,66				11,11						

Results show that despite warm-starting the MIP model, reducing the available fleet and increasing the computation time to two hours, the solver was unable to solve any instance to optimality when using the MIP model without any valid inequalities. Nevertheless, for instance R201_12_25_8, the solver was able to reach the optimal solution but was unable to prove its optimality. On the other hand, by adding the proposed valid inequalities, the solver was able to solve 2 of the 6 instances to optimality or improve the final MIP gap percentages.

Regarding the impact of the proposed valid inequalities, results show that the combination (RC+SRC) yielded the best results, with an average improvement of the objective function of 4,63% and an average improvement of the best lower bound of 11,75%. Furthermore, their inclusion allowed for a significant improvement in the GAP percentage in every instance.

Further adding SB1 and SB2 to (RC+ SCR) resulted in a slight decrease in the average improvement of the best lower bound when compared with using only the (RC + SRC) combination. Moreover, the addition of SB1 and SB2 made it harder for the solver to improve upon the best objective function value (upper bound), with a degradating percentage of 8,66% when compared with solving the MIP model without any valid inequalities. The addition of both symmetry breaking constraints made it increasingly harder for the solver to improve the objective function value, as well as the MIP gap percentages during the allowed computation time, mostly because adding symmetry breaking constraints increases the complexity of the model, and increases time to find a first feasible solution. The positive impact of adding the symmetry breaking constraints is only noticeable as the enumeration of the branch and bound proceeds towards the end of the process. Only when solving instance C201_12_25_8 is this characteristic evident. When looking to instance R201_12_25_8 on the other hand, we note that even when using the MIP model without any valid inequalities the solver can find the optimal solution, although not being able to prove its optimality.

Furthermore, including both rounded capacity constraints immediately provided the solution to the problem as it forced the use of one urban freighter, one city freighter and one satellite/meeting node. We can, therefore, conclude that adding the symmetry breaking constraints only added complexity to the model and increased the time to find a first feasible solution, which in turn led to longer computation time to prove the solutions optimality, when compared to only using the rounded capacity constraints.

In conclusion, the results show that the proposed 3-index arc-based MIP formulation is only able to tackle very small instances even when applying a *warm-start* procedure, and that the impact of the proposed inequalities is limited and instance dependent, although they provide an overall improvement in the root linear relaxation and best bounds. Adding both vehicle and satellite rounded capacity constraints (RC + SRC) was the combination with which average best results were obtained, particularly when addressing larger instances. These constraints strengthen the MIP formulation, yielding better root linear relaxations, and allow for the improvement of both lower and upper bounds. Symmetry breaking constraints, did not have any impact in the model's root linear relaxation and in general increased the difficulty for the solver to obtain a first feasible solution, especially in larger instances.

Adding the symmetry breaking constraints improved the computation time required to solve the instances to optimality, by reducing the number of explored nodes in the search tree. This benefit was not evident when addressing larger instances during the allowed computation time. Nonetheless when there was enough time to prove the optimality of the solution, and there was an improvement in the upper bound, the addition of the symmetry breaking constraints allowed for a faster convergence of the branch-and-bound. This is in line with the observations in Sherali & Smith (2001), who state that the relative advantages of adding this type of lexicographical-based symmetry breaking constraints become more evident as the enumeration in the branch-and-bound proceeds.

5.2.4.4 Additional model extensions

The mathematical formulation presented in Section 5.2.1 can be further extended to consider other operational rules not considered in this work. Besides the proposed extensions to the 2E-CVRP, mainly based on the accessibility and mobility of first echelon transport modes, it is possible to adapt the proposed based model to consider, for example, the use of subcontracted second-echelon vehicles, which may have a preferred working area and time intervals to operate. When considering subcontracted second-echelon vehicles, one usually does not have to consider neither their exit from or return to the depot at the end of the working day, which is usually the case with many external outsourced carriers. Therefore, one would simply establish the satellite where the vehicle should start their working day and the last customer where they would finish their working day, yielding an Open Vehicle Routing (OVRP) problem with multi-trips. Considering the proposed mathematical formulation, since the planning of operations would not take into account the initial starting time or the latest time of arrival of second-echelon vehicles to the depot, this alternative can be modelled by simply setting for this type of vehicles, distances and travel times of arcs from the depot to satellites and from second-echelon customers to the depot to 0.

Furthermore, aside from the temporal issues of vehicle synchronisation at satellites, it is possible to extend the model to also account for time windows at customers and at satellites, establishing the earliest and latest time in which these locations must be visited.

In terms of the objective function, it is possible to further consider other types of costs, including distance based costs (possibly expressed in fuel costs or associated polluting emissions), as well as fixed and/or variable costs of each transshipment at satellites.

5.3 Chapter summary

The literature on two-echelon vehicle routing problems has mostly focused on the basic version of the problem, while variants concerning temporal synchronisation, particularly the exact space-time synchronisation between vehicles at satellites required for direct transshipments, have been seldom addressed.

We have, therefore, proposed a generic 3-index arc-based formulation for 2E-VRP with vehicle synchronisation at satellites and multi-trips at the second echelon, formulated for the most restrictive type of two-echelon distribution system (T1), according to the classification proposed in Section 3.3, that could be adapted to model all other three types. Additionally, we proposed some valid inequalities adapted from those usually accounted for in the VRP literature, to strengthen the formulation. These valid inequalities encompass both vehicle and satellite capacity rounded constraints, as well as symmetry breaking constraints used to tackle the inherent solution symmetry problem arising in arc-based VRP-based formulations, where decision variables have the vehicle index, and the fleet of vehicles is homogeneous.

We described how the generic model and the proposed valid inequalities can be adapted/used to address the other three types of distribution systems, and presented a more comprehensive analysis of the mathematical formulation for T3 type systems, where we analyse the impacts of including the proposed valid inequalities, and tested solving the problem using a warm-start procedure.

Results have shown that the proposed generic model is flexible and that it can be adapted to address all four two-echelon distribution systems, with vehicle synchronisation at satellites and multi-trips at the second echelon, as given by the classification scheme proposed in this work. Nonetheless, given the complexity of the underlying problems, the proposed formulations and the use of the exact solution methods proved unfit to solve large instances of these types of problems, particularly when the complexity of the problem increases. This became ever more evident given the impossibility to even find a first feasible solution during the allowed computation time for T4 type system problems, the most complex of the four types. The linear relaxation of the proposed formulation is very weak, and the inclusion of the proposed valid inequalities has a very limited impact in improving the capabilities of the proposed model to solve these types of problems in viable computation time. Regarding the proposed valid inequalities, the best results were obtained by adding both vehicle and satellite rounding constraints. An interesting result was the evidence that the use of symmetry breaking constraints did not improve the root linear relaxation of the model, and greatly increased the required time for the solver to find a first feasible solution.

Chapter 6

Heuristic approach

As shown in Chapter 5, exact solution methods are only able to tackle small instances of the two-echelon distribution problems encompassing complicating characteristics such as exact synchronisation between vehicles at satellites and multi-trips at the second echelon. For real life applications, where the size of the problem can be quite large, it is usually desirable to use heuristics to obtain a reasonably good solution in viable computation time.

In this chapter, we present a heuristic solution method for a two-echelon vehicle routing problem with synchronisation at satellites and multi-trips at the second echelon that extends the problem addressed in Chapter 5 by further considering a heterogeneous fleet of city freighters.

First, in Section 6.1, we describe the two-echelon vehicle routing problem variant to be solved, putting it into context within the 2E-CVRP literature.

In Section 6.2, we propose a heuristic approach based on a hybrid VNS-based heuristic guided by a *simulated annealing* (SA) acceptance criterion scheme.

In Section 6.3, we describe a set of auxiliary evaluation metrics aiming to support the decision making process. These metrics reflect the efficiency of the fleet, its impact on road and kerbside occupancy and a qualitative metric regarding the fitness of using a given type of city freighter in a given city centre zone.

In Section 6.4, we present our experimental setup. First, we describe the new instances used to test the proposed solution method (Section 6.4.1), and discuss the use of different best insertion rules (Section 6.4.2), and the parameter settings of the improvement phase (Section 6.4.3). In Section 6.4.4, we present our computational results. We evaluate different best insertion rules used during the greedy best insertion heuristic, the impacts of time windows, and the consideration of an heterogeneous fleet of city freighters. Additionally, we evaluate and compare different distribution policies against two alternative distribution systems, namely: i) using only urban freighters to deliver loads, representing the business-as-usual (BAU); and ii) considering storage capabilities at satellites, representing distribution systems where micro-consolidation centres/lockers are used to store freight for short periods of time, before being picked up by city freighters. In this latter case, exact space-time synchronisation is no longer necessary, and only precedence between urban and city freighters visits at satellites is required.

Finally, we briefly discuss some problem alternatives and algorithm improvements in Section 6.5, and in Section 6.6 we present our conclusions and suggest some improvements of the proposed solution method.

6.1 Problem description

The problem addressed in this section extends the two-echelon vehicle routing problem presented in Section 5.2, by further considering a heterogeneous fleet of city freighters, as well as additional city and vehicle characteristics. The problem can be defined as a *Fleet Size and Mix 2E-CVRP with Fixed Costs and Vehicle-Dependent Routing Costs* with time windows, synchronisation at satellites, direct deliveries, transfers at customers, and multiple trips at the second echelon.

We consider a city divided in two major areas: the periphery, and the city centre. Additionally, the city centre is split into different zones which, depending on their characteristics, will have a preestablished "zone suitability" profile. This profile is characterised by a set of indices, based on a 5 points Likert-type scale, representing the decision maker’s perceived adequacy of using each city freighter type to deliver to customers located in that particular zone.

Two main types of vehicles are considered, namely: urban freighters (trucks) operating at the first echelon; and smaller more environmentally friendly vehicles, such as small electric vans, cargo cycles or walking porters, here called city freighters, operating at the second echelon. The set of available vehicles K encompasses: i) an unlimited fleet of urban freighters (K_1); and ii) an unlimited heterogeneous fleet of city freighters (K_2), $K = K_1 \cup K_2$.

The customers are split into three different categories, $C = C_1 \cup C_2 \cup C_3$. First-echelon customers (C_1) are located outside the city centre, and can only be serviced by urban freighters. Second-echelon customers (C_2) are located inside the city centre area, and can only be served by city freighters. Each second-echelon customer has a set of suitability indices ($\sigma_i^a : i \in C_2, a \in K_2$) representing the suitability of it being served by each city freighter type, given by the zone suitability profile where it is located. Finally, the third category (C_3) represents the set of satellite-customers, i.e. customers located inside the city centre which, due to their consignment characteristics (such as volume or weight), are deemed unfit to be served by city freighters, and therefore must be served by urban freighters. As these customers are located in the city centre, we consider that they may also be used as transshipment locations, where urban and city freighters can meet to transfer loads.

Each customer can only be visited once by one vehicle of the appropriate type. In the case of C_3 customers, whenever they are used as a transshipment point, we consider that the load transfers to city freighters and the delivery to the customer occur simultaneously. Each customer $i \in C$ has a demand q_i, a delivery service duration st_i, and a time window $[e_i, l_i]$, where e_i and l_i represent the earliest start service time and the latest start service time, respectively. If a vehicle arrives before a customer’s earliest start service time, then it will have to wait, and the customer will be served at e_i.

Vehicles fleet A homogeneous fleet of urban freighters (K_1) is parked at the depot located in the periphery of the city (O_1), from where all loads originate. These vehicles make direct deliveries to C_1 and C_3 customers. Additionally, urban freighters also transport the loads to be transferred to city freighters at satellites (S) or satellite-customers (C_3).

We consider an unlimited heterogeneous fleet of city freighters $K_2 = K_2^1 \cup K_2^2 \cup K_2^3$, representing three different types of transport modes: small e-vans K_2^1, cargo-cycles K_2^2, and walking porters K_2^3. The fleet of types K_2^1 and of K_2^2 start and end their route at a depot in the city centre (O_2), which is considered unfit to be used as a transshipment location (satellite). As for the fleet of K_2^3, we do not account for their leaving and arriving to a depot. Instead, they start their working day at a satellite and end their working day at a customer, yielding an open vehicle routing problem (OVRP), commonly arising when subcontracted transport services are considered (Li et al., 2007; Atefi et al., 2018). All city freighters start and end their working day empty. Therefore, they are required to first visit a transshipment point and meet with an urban freighter to load, before starting their delivery trips. Given the small capacity of city freighters, we consider that they may perform multiple delivery trips throughout a working day, i.e., they may return to satellites to reload after delivering all loads from their previous trip, but are not allowed to perform two reloads consecutively.

Each type of vehicle is characterised by its capacity Q, and speed s, used to compute the travel time between nodes in their respective network. Regarding the cost structure, each type of vehicle has an associated usage fixed cost f, and a distance unit cost c. All types of vehicles have different capacities, speeds as well as fixed and distance unit costs, where $Q_k > Q_w > Q_r > Q_p$; $s_k > s_w > s_r > s_p$; $f_k > f_w > f_r > f_p$; $c_k > c_w > c_r > c_p : k \in K_1, w \in K_2^1, r \in K_2^2, p \in K_2^3$.

All vehicles have the same maximum working time T. For the smaller city freighter type (K_2^3), the maximum working time represents the maximum time to finish the last delivery service, while for the other three types of vehicle (K_1, K_2^1, K_2^2) it is associated with the latest time they are required to arrive at their respective depot.

Satellites Satellites are transshipment locations where urban freighters and city freighters can meet to directly transfer loads between them. These locations can be off-street/on-street parking spaces, or nearby delivery areas located near the city centre. Additionally, we take advantage of the fact that urban freighters are required to serve some satellite-customers inside the city centre, and allow transfers to be performed at these locations as well. There are no storage capabilities at the transshipment locations, thus requiring exact space-time synchronisation between urban and city freighters, as to transfer loads directly between them. Satellites may be visited more than once by different vehicles, and at each vehicle meeting, it is possible for urban vehicles to transfer loads to more than one city freighter at the same time. At satellite-customers, if any load transfers are to be performed, they are assumed to occur at the same time as the delivery. Each transshipment is assumed to have a constant service duration, regardless of the location, the type of vehicles involved in the transshipment, and the transshipped amount.

Our decisions concern the determination of: i) the fleet size and mix of urban and city freighters; ii) the joint routing and scheduling of urban and city freighters; iii) the definition of where load transfers are performed, how much load is to be transferred, and what are the vehicles involved.

Our objective is to minimise the total transportation costs, that include the fixed costs of the vehicles and the distance-based travel costs at both echelons.

6.1.1 Related work

The problem at hand can be positioned in the literature as a fleet-mix two-echelon capacitated vehicle routing problem with time-windows, synchronisation at satellites, multi-trips at the second echelon, and direct deliveries including customers that may be used as satellites. Table 6.1 shows the problem features considered in works most resembling our problem.

Table 6.1: Summary of related 2E-CVRP variants.

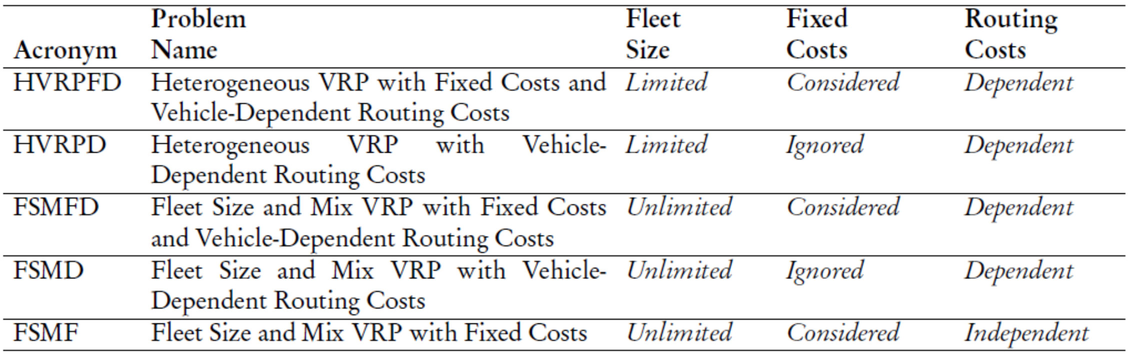
Reference	Time windows	Synchronisation	Multi-trips	Direct deliveries	Transfers at customers	Heterogeneous fleet	Solution method
Crainic et al. (2009)	✓	✓	✓				Hierarchical decomposition
Crainic, Errico, et al. (2015b)	✓	✓	✓				Hierarchical decomposition
Grangier et al. (2016)	✓	✓	✓				ALNS
Anderluh et al. (2017)		✓	✓	✓			GRASP + path-relinking
Anderluh et al. (2021)		✓	✓	✓			LNS
Our problem	✓	✓	✓	✓	✓	✓	Hybrid VNS

Particularly, when regarding heterogeneous fleets, to our knowledge, the only reference to two-echelon vehicle routing problems with heterogeneous fleets is by Bevilaqua et al. (2019), where the authors address a *Two-Echelon VRP* where a limited heterogeneous fleet of both urban and city freighters is considered. To solve the problem, the authors use a Parallel Island Based Memetic Algorithm with Lin-Kernighan Local Search.

On the other hand, several variants of VRP with heterogeneous fleets have been addressed in the literature. According to the classification proposed by Baldacci et al. (2008), VRP variants with heterogeneous fleets may differ in terms of: i) the fleet may be limited or unlimited; 2) the fixed costs may be considered or ignored; 3) the routing costs on arcs may be vehicle dependent or independent (Figure 6.1).

Usually the fleet size and mix problem is considered to be a more strategic/tactical problem as it is related to the fleet dimensioning, i.e, the assessment of how many of which type of vehicles should be purchased (Toth & Vigo, 2014). The magnitude of the fixed costs strongly depends on the type of vehicles, and if the fleet is owned by the decision maker or if it is subcontracted. As for the variable arc-based costs, these can be vehicle type dependent independent. The relative magnitude between fixed and variable costs is quite important as fleet size minimisation and routing cost minimisation are conflicting objectives, although being, in general, aggregated in the objective function (Toth & Vigo, 2014).

Our problem accounts for unlimited vehicle fleets for all types, and considers both fixed and variable type dependent costs. Therefore, and according to the classification in Figure 6.1, our



Acronym	Problem Name	Fleet Size	Fixed Costs	Routing Costs
HVRPFD	Heterogeneous VRP with Fixed Costs and Vehicle-Dependent Routing Costs	*Limited*	*Considered*	*Dependent*
HVRPD	Heterogeneous VRP with Vehicle-Dependent Routing Costs	*Limited*	*Ignored*	*Dependent*
FSMFD	Fleet Size and Mix VRP with Fixed Costs and Vehicle-Dependent Routing Costs	*Unlimited*	*Considered*	*Dependent*
FSMD	Fleet Size and Mix VRP with Vehicle-Dependent Routing Costs	*Unlimited*	*Ignored*	*Dependent*
FSMF	Fleet Size and Mix VRP with Fixed Costs	*Unlimited*	*Considered*	*Independent*

Figure 6.1: Heterogeneous VRP variants (Baldacci et al., 2008).

problem can be defined as a *Fleet size and mix two-echelon capacitated vehicle routing problem* variant, with time-windows, synchronisation at satellites, multi-trips at the second echelon, direct deliveries, transshipments at some customers, and an *Open VRP* (OVRP), for one of the city freighter types, i.e., they may start at any satellite and end at any customer, instead of having to start and end at a given depot.

We have considered unlimited fleets of all city freighter types, fixed costs and vehicle dependent variable arc-based routing costs. Nonetheless, the heuristic has been developed so that we can relax these assumptions.

6.2 Solution framework

As referred, the results presented in Chapter 5 show that the proposed exact solution method is unfit to solve large instances of two-echelon vehicle problem variants with complicating characteristics, such as exact synchronisation between vehicles and multiple trips at the second echelon. Exact algorithms are usually computationally expensive for large scale combinatorial optimisation problems, so heuristics to obtain reasonably good solutions in viable computational time are usually adopted in practice.

Therefore, we address our *fleet size and mix two-echelon vehicle routing problem with time windows, synchronisation at satellites, multi-trips at the second echelon, and direct deliveries* problem with a *VNS-based heuristic* guided by a *Simulated Annealing* (SA) acceptance scheme. The general heuristic framework is presented in Algorithm 2.

The heuristic starts by constructing a first feasible solution s_{init}. This solution then undergoes through a solution improvement phase based on a VNS-based heuristic, guided by a *Simulated Annealing* (SA) acceptance scheme. At each SA iteration, we compute a new solution s' belonging to the neighbourhood of the incumbent solution $N(s)$.

To address the *interdependence* problem arising from the synchronisation between city freighters and urban freighter schedules (Drexl, 2012), the original two-echelon (2E) vehicle routing problem

s is decomposed into two subproblems, one for each echelon. The solution of the original two-echelon vehicle routing problem (s) is obtained by solving these two subproblems sequentially (Algorithm 1). The city freighters routes s_A are calculated first, given the set of second-echelon customers requests R_A, and will establish the time and location of transshipments, as well as the amounts to be transferred. This information is used to update the set of of urban freighters requests R'_B, and then used to construct the urban freighter routes s_B. The solution for the original two-echelon vehicle routing problem s is given by the solutions $s = s_A \cup s_B$ of both echelons.

Algorithm 1: Problem decomposition

```
Result: $s$ - Solution for the original 2E problem
$s_A \leftarrow$ cityFreighters_route_construction ($R_A$);
$R_B \leftarrow$ create_ urbanFreighters_requestList ($s_A$);
$s_B \leftarrow$ urbanFreighters_route_construction ($R_B$);
$s \leftarrow s_A \cup s_B$
```

Algorithm 2: Simulated annealing framework

```
Result: $s^*$
Initialisation: $s \leftarrow s_{init}$ , $s^* \leftarrow s_{init}$, $T \leftarrow T_0$, $it_{temp}$, $\alpha$ ;
while Stoppage criterion not met do
    while $i < it_{temp}$ do
        compute neighbour solution $s' \in N(s)$;
        $\Delta \leftarrow f(s') - f(s)$;
        if $\Delta < 0$ then
            $s \leftarrow s'$;
            if $f(s') < f(s^*)$ then
                $s^* \leftarrow s'$;
            end
        else
            $x \leftarrow random[0;1]$;
            if $x < e^{\frac{-\Delta}{T}}$ then
                $s \leftarrow s'$;
            end
        end
        $i = i + 1$;
    end
    $T \leftarrow \alpha T$;
    $i \leftarrow 0$;
end
```

The search process is guided by a simulated annealing (SA) acceptance criterion scheme (Kirkpatrick et al., 1983; Suman & Kumar, 2006) (see Algorithm 2). The SA algorithm provides a strategy for accepting non-improving solutions under certain conditions, which allows for a diversified search of the solution space, and as a way to escape local optima.

Improving solutions are always accepted, while non-improving solutions are accepted with a probability given by $exp(\frac{-\Delta}{T})$, where $\Delta = f(s') - f(s)$ is the difference between the cost of the new solution $f(s')$ and the cost of the incumbent solution $f(s)$, and T is the *temperature* parameter (see Algorithm 2, line 13). The acceptance probability of non-improving solutions depends on Δ and on T, and will approach zero for low *temperatures*. Throughout the process, the *temperature* decreases according to a *cooling scheme* that may take many forms including linear, proportional, logarithmic and adaptive forms. In this work, we have considered a proportional *cooling scheme* where the *temperature* parameter T is reduced by a cooling factor α such that $T_{i+1} = \alpha T_i : 0 < \alpha < 1$ (see Algorithm 2, line 19). Furthermore, at each *temperature* "level", we run it_{temp} iterations before updating T (see Algorithm 2, line 3).

Regarding the stopping criterion, several alternatives can be considered, such as establishing a minimum temperature, a maximum number of iterations (*temperature* levels), or a maximum number of iterations without any solution improvement. In this work, we have established a maximum number of iterations as the stopping criterion (See Algorithm 2, line 2).

VNS-based heuristic VNS is a metaheuristic for solving combinatorial and global optimisation problems proposed by (Mladenović & Hansen, 1997; Hansen & Mladenović, 2001). It is based on the systematic change of neighbourhoods during both a descent phase to find local optima, and a perturbation phase to escape the corresponding solution valleys. VNS has been applied to a wide range of combinatorial problems, and has been successfully used to tackle several VRP variants, including VRP with time windows (Bräysy, 2003), heterogeneous VRP (Imran et al., 2009), multi-depot VRP (Stenger et al., 2013), periodic VRP (Hemmelmayr et al., 2009), dial-a-ride (DARP) (Parragh et al., 2010).

At each iteration, a new neighbour solution $s' \in N(s)$ (see Algorithm 2, line 4) is obtained by sequentially applying a VNS-based heuristic to each echelon's routing problem following the sequential order as presented in Algorithm 1. The VNS algorithm used to construct the city freighters' routes s_A and urban freighters routes s_B is the same (see Algorithm 3). For each echelon's routing and scheduling problem, the VNS algorithm starts with an initial solution x and a pre-selected set k_{max} of neighbourhood structures N_k (Algorithm 3, line 1). Note that, when applying the VNS heuristic to determine city freighters routes, the initial solution x will correspond to the city freighter routes of the incumbent solution, while for the urban freighters problem, the initial solution for the VNS is constructed given the update requests by the newly constructed city freighter routes as shown in Algorithm 1.

The main solution procedure of VNS consists in applying a *shaking* procedure followed by a *local search* step. Given the incumbent solution x, a *shaking* procedure is performed, randomly generating a neighbour solution $x' \in N_k(x)$ belonging to the k^{th} neighbourhood structure (Algorithm 3, line 4).

Algorithm 3: VNS-based heuristic

```
1 Set the initial solution $x$; Select the set of neighbourhood structures $N_k, k = 1,...,k_{max}$, that
    will be used in the search;
2 (1) set $k \leftarrow 1$;
3 (2) until $k = k_{max}$, repeat the following steps;
4     (a) Shaking. generate a point $x'$ at random from the $k^{th}$ neighbourhood of $x$
        ($x' \in N_k(x)$);
5     (b) Local search. Apply some local search method with $x'$ as the initial solution.
        Denote as $x''$ the so obtained local optima. If this local optima $x''$ is better than
        neighbour solution $x'$ then $x' \leftarrow x''$. Otherwise $x'$ remains unaltered. Set $x \leftarrow x'$ and
        $k \leftarrow k+1$
```

After performing the *shaking* step, a *local search* is performed to determine a local optimum $x'' \in N_k(x')$. The basic VNS usually considers a *steepest descent* heuristic, but this can be very time consuming (Hansen & Mladenović, 2018). As an alternative, instead of exploring the entire neighbourhood, we have considered a *first descent* heuristic, i.e. the local search will stop as soon as a better solution is found, or until a maximum number of iterations without improvement have passed it_{local}. If the new solution x'' improves the neighbour solution x', then x'' replaces x', otherwise x' remains unaltered. In the basic VNS heuristic, after improving upon the incumbent solution, the process resumes at the first neighbourhood structure and continues. In our case, we follow a nested neighbourhood strategy (Hansen & Mladenović, 2018), i.e. the neighbourhood structures are explored sequentially, and the *shaking* step for neighbourhood structure $k+1$ is applied over the best solution x' of the previous neighbourhood k. The proposed neighbourhood operators and their sequence are described in section 6.2.2.

6.2.1 Initial solution

The initial solution s_{init} is constructed following a sequential three-phase constructive heuristic (see Algorithm 1). The two-echelon distribution problem is decomposed into a routing and a scheduling subproblems, for each echelon. The heuristic starts by constructing city freighters' routes sequentially, one route at a time, using a *greedy best insertion* heuristic. Then, a preprocessing method is used to establish the list of requests R_B to be performed by the urban freighters. This list will include the first-echelon customers' requests, as well as the satellite-customers' updated requests and the transshipment requests at satellites, as given by the previously constructed city freighter routes. Given the request list R_B, urban freighters' routes are constructed, one route at a time, using a *greedy best insertion*, as when constructing city freighters routes. Finally, the initial solution s_{init} is given by the solutions of both city freighter and urban freighters routing problems. A more detailed explanation of each phase of the algorithm is presented next.

Construction of city freighters routes City freighters routes are constructed sequentially, one route at a time, while there are still second echelon customers' requests R_A to be assigned. Each new city freighter route is initialised by first selecting the type of city freighter that will perform the route. The selected type of city freighter will be the one with the largest capacity still with available fleet (in the case of unlimited fleet of city freighters, every route in the initial solution is performed by the largest city freighter type in the fleet).

Routes are then constructed using a *greedy best insertion heuristic*. At each insertion step, we attempt to insert a customer's request, or a transshipment-point/request pair, whenever a reload is required. As city freighters start their route empty, the first insertion will be the best feasible transshipment point/request pair. Then, we determine the next best feasible request insertion in terms of time windows, and we sequentially check for feasibility regarding capacity and maximum route duration constraints. If these constraints are respected, the request is inserted in the route. If not, two situations may occur. If the capacity constraint is respected but the maximum route duration constraint is violated, we cannot insert any other request, and and we simply add the depot to the end of the route, completing it. On the other hand, if the capacity constraint is violated, i.e. a reload would be necessary, we determine the next best feasible (given time windows) transshipment-point/customer request pair insertion, and check for feasibility regarding the maximum route duration constraint. If the maximum route duration constraint is respected, we add the transshipment and customer request to the route. Otherwise, as there would not be enough time for a reload and delivery, we simply add the depot to the route completing it. The process continues until there are no more second echelon customers' requests to be assigned.

Urban freighters' requests update The city freighters routes establish the time and location of transfers, as well as the amount to be transferred. This information is used to create the urban freighters request list R_B, which includes the first-echelon customers' requests, as well as the updated satellite-customers requests and the transshipment requests, as given by the city freighters routes. The total load at each city freighter transshipment request is calculated by summing up the demand of the second-echelon customers of each trip originating at that transshipment location. In the case when a transshipment occurs at a satellite-customer, that customer's request is updated by summing the amount to be transferred to its demand.

City freighters' transshipment requests occurring at the same location can be bundled based on the time they are due to occur. To ensure the exact synchronisation between urban and city freighters at all transshipment services, only transshipments occurring at the same place at exactly the same time can be bundled. We note that, although this may rarely occur throughout the day, it is particularly useful to bundle the very first load transshipments of the day at a given satellite.

Alternatively, it is possible to consider several bundling time windows, i.e. city freighters transshipment requests can be bundled if they occur at the same location, within the same time window. However, in this case, we no longer have exact synchronisation between urban and city freighters. Instead, it is only necessary to guarantee the precedence of urban freighters visits at the transshipment point. This is accomplished by setting the earliest service start time of the urban freighter transshipment requests as the minimum service start time of the bundled city freighters transshipments. In this case, we assume that loads can be stored for some period of time before being picked up by city freighters. In this work, we use this alternative when evaluating a scenario where satellites have storage capabilities, by considering a single bundling time window, representing the entire day, for each transshipment location (see Section 6.4.4). Nonetheless, it is possible to consider several time windows for each transshipment point, which may be used to model transshipment locations located in zones with access time windows, for example.

Whenever the sum of the bundled city freighters' transshipped loads at a satellite-meeting (β) is greater than the capacity of the urban freighters Q_1, we create $n = \left\lceil \frac{\beta}{Q_1} \right\rceil$ transshipment requests with the same earliest starting time, in which $n-1$ are satellite-meetings requests with total demand of Q_1, and the last request with the remaining load to be transferred. Since we do not account for multiple-trips at the first echelon, this implies that each satellite-meeting i with total load to be transshipped $d_i = Q_1$ will be the sole delivery of a urban freighter for that day.

Construction of urban freighters routes After constructing the city freighters routes and performing the urban freighters' requests list update, we construct the urban freighters routes. The urban freighters' set of requests encompass those of first-echelon customers, satellite-customers (which include their demand and, if used as a transshipment point, the load to be transferred to city freighters), and the transshipment requests as given by the request updating method. All urban freighters routes start and end at the depot located at the periphery of the city, and are constructed sequentially route by route while there are requests yet to be assigned, using a *greedy best insertion heuristic* similar to that used for the construction of the city freighters routes.

6.2.2 Improvement phase

After computing the initial solution, the heuristic follows with an VNS-based improvement phase (see Algorithm 3). The VNS-based heuristic requires the establishment of the neighbourhood structures N_k for the *shaking* step and a method for the *local search* phase.

Shaking We have considered 3 neighbourhood structures for the *shaking* step $k_{max} = 3$ (see Algorithm 3 line 4). The operators used to explore each neighbourhood $N_k : k = \{1, 2, 3\}$ are used sequentially, in order, and are always applied within routes of the same echelon. The first operator attempts to change the city freighter type used to perform a route, the second attempts to move one customer from one route to another, and the third attempts to swap customers between routes.

1. ***Vehicle change() operator.*** The *vehicle change()* operator is used to address the fleet mix and size problem arising from having an heterogeneous fleet of city freighters. First, this operator destroys a random city freighter route from the list of routes in the current solution. Then, new city freighters routes are constructed while there are still unassigned customers using the *greedy best insertion heuristic* as used during the computation of the the initial solution. The type of city freighter used to perform each new route is chosen randomly, from the set of vehicle types that are different from the one originally used, and still with an available fleet (when limited fleets are considered).

2. ***Relocate() operator.*** The relocate operator is used to move a customer from one route to another. First, a random route is selected from the current list of routes and we select a random customer to be relocated. Then, we select the route in which to insert the selected customer, as well as the position where the customer is to be inserted. The route in which the customer is to be relocated is the one with the earliest finishing time at the depot, as to increase the chance that the new route will be feasible in terms of the maximum arrival time at the depot. The position in which the customer is to be inserted in the selected route will be the one that, being feasible in terms of time windows, yields the smallest increase in total route distance. After determining the route and position where to insert the relocated customer, we reconstruct the new route starting from the position where the relocated customer has been inserted, always checking for feasibility in terms of capacity, time windows and maximum working time. If the route in which we would insert the customer is not feasible, we discard the infeasible route and return the original list of city freighter routes. During this process, if a route ends up without any customers, it is simply destroyed.

3. ***Inter-route swap() operator.*** The *inter-route swap ()* operator exchanges one customer between two routes. We start by selecting two random routes, and from each a random customer. Both routes are reconstructed starting from the newly inserted customer position, always checking for feasibility in terms of capacity, time windows and maximum working time. If one of the resulting routes is infeasible we return the original routes.

Local search The solution obtained through the *shaking* step undergoes through local search step (see Algorithm 3 line 5) in an attempt to find a local optimum. To preform the local search we use an *intra-route swap* operator which attempts to exchange the position of two customers belonging to the same route. We start by randomly selecting a route from which we randomly select two customers to be swapped. To guarantee that capacity, time windows, and maximum working time constraints are still respected after the customers swap, first the route is destroyed from the position of the earliest selected customer request. Then, the algorithm attempts to insert the unassigned requests into the partial route following the new customers visiting order. At each insertion, we check for capacity, time windows and maximum arrival time constraints. Note that, for urban freighters routes the capacity constraints will always hold. Therefore, the verification of the capacity constraints is only considered for the city freighters, and includes checking if and when a transshipment/delivery request pair insertion is required. If the new solution is feasible, then it becomes the new incumbent solution, otherwise, the original route is kept. The *local search* follows a *first descent* strategy, and ends as soon as a new better solution is found or after a number of iterations without improvement have passed.

6.3 Auxiliary evaluation metrics

Besides the objective of minimising the total transportation costs, we propose a set of additional auxiliary evaluation metrics, aiming to provide further insights on the: i) the overall efficiency of used vehicles; ii) the effects on road and kerbside space occupancy of the used fleet; and iii) the suitability of using different city freighter types when serving customers located in a given city centre zone, according to the decision makers' assessment. Next, we describe each of these metrics in more detail.

6.3.1 Global Aggregated Vehicle Performance (*GAVP*) metric

To assess the overall efficiency of the used vehicle fleet in the final solution, we propose the *Global Aggregated Vehicle Performance* (*GAVP*) metric, inspired by the concept of *Overall Vehicle Effectiveness* (*OVE*) proposed by Simons et al. (2004), a single operational measure in turn based on the *Overall Equipment Effectiveness* (*OEE*), encompassing three main transport efficiency elements, namely: performance, quality, and availability. Since not all elements considered in *OVE* can be computed considering the characteristics and information of our problem, the *GAVP* accounts only for vehicle performance elements.

The GAVP metric is computed considering 3 elements of vehicles efficiency, namely: i) productive working time; ii) productive travelled distanced; and iii) load capacity utilisation. Much like the *OVE*, the *GAVP* is a single value operational metric calculated by multiplying the ratios of the three efficiency elements (Eq. 6.1). This single value metric should be accompanied by a more detailed inspection of its elements, as it is the result of the product of three factors.

$$GAVP = PTR \times LTDR \times LCUR \tag{6.1}$$

Productive Time Ratio (*PTR*) The *Productive time ratio* (PTR) is computed as the ratio between the total productive time over the total available working time. The vehicles' total available working time T_{max} is split into productive and unproductive working times. Following the approach by Simons et al. (2004), we consider loading and unloading as value-adding activities in road freight transport, therefore they are considered as productive working time. We account for two sources of time utilisation inefficiencies, namely: i) the unused available working time, which is a result of vehicles finishing their working day before the maximum available working time, and; ii) the waiting times at customers and satellites. This decomposition of the total available working time is presented in Figure 6.2.

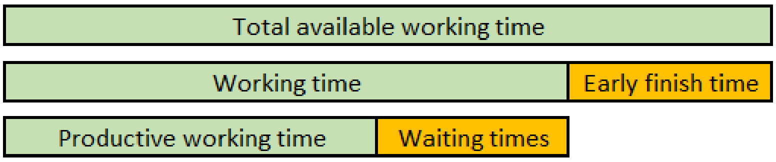


Figure 6.2: Total available working time utilisation decomposition.

Let R represent the set of all urban and city freighters' routes in the final solution. Given this, we compute the PTR as the ratio between the total used fleet productive times divided by the total available working time (Eq. 6.2).

$$PTR = \frac{\sum_{i \in R} productive\_times_i}{|R| * T_{max}} \tag{6.2}$$

Loaded Travelled Distance Ratio (*LTDR*) Regarding travelled distances, empty running, i.e. the travelled distance while empty, is considered as an inefficiency (European Environment Agency, 2017).

Urban freighters leave the depot already loaded and perform a single trip throughout a working day, therefore they will only travel empty from the last service to the depot. As for the city freighters' routes, since city freighters are assumed to start their working day empty and are able to re-load multiple times, for each city freighter route the empty running distance is the sum all distances from a depot or customer towards its next transshipment point plus the distance from the last customer to the depot. Note that in the case of city freighters of type 3 (K_2^3), for which we do not account for a starting or ending depot, there will be no empty runs related to having to reach the first transshipment location neither the distance after completing its last service.

Given this, the distance travelled while loaded is simply computed as the difference between the total travelled distance and the total empty travelling distances. Let R represent the set of all routes in the final solution. Given this, we compute the distribution system's $LTDR$ as the ratio between the total laden distance (productive travelled distance) of all routes divided by the total travelled distance, as given by Eq. 6.3

$$LTDR = \frac{\sum_{i \in R} Laden\_distance_i}{\sum_{i \in R} total\_travelled\_distance_i} \tag{6.3}$$

Load Capacity Utilisation Ratio (LCUR) Vehicles should be used to their maximum capacity (whatever the most restrictive capacity unit, may it be weight or volume). Therefore, a source of inefficiency occurs when vehicles' capacity is not used to its fullest.

For urban freighters, the only vehicle loading operation is performed at the depot at the beginning of the day. As for city freighters, given that they start their working day empty and are able to perform multiple trips throughout the day, these loading operations encompass all loading operation at transshipment locations (satellites and satellite-customers), including the one at the beginning of the day, and all other subsequent reloads that may occur.

Let J represent the set of loading operations, $\bar{K}$ be the set of used vehicles in the final solution, d_j^k be the load of vehicle $k \in \bar{K}$ after loading operation $j \in J$, and cap_k the capacity of vehicle $k \in \bar{K}$. Given this, we compute the $LCUR$ as the average load capacity utilisation ratio after each loading operation, as given by Eq. 6.4.

$$LCUR = \frac{\sum_{k \in \bar{K}} \sum_{j \in J} (\frac{d_j^k}{cap_k})}{|J|} \tag{6.4}$$

6.3.2 Road and kerbside occupancy metrics

As different types of vehicles have different sizes (lengths and widths), they will occupy different amounts of road and kerbside space in the city, which in turn will influence road traffic conditions. To assess the effects on road and kerbside space requirements in the city when using different mixes of vehicle types to perform the deliveries, we compute a metric for road and one for kerbside space occupancy inspired by those presented in Browne et al. (2011).

The *road occupancy* metric is calculated by multiplying the travel time of vehicles by their area in m^2. In turn, the *kerbside occupancy* metric is calculated by multiplying the length of the vehicle by the total amount of time spent waiting, performing transshipments, and delivering orders to customers.

6.3.3 Vehicle suitability metric

The *vehicle suitability* metric is a qualitative metric reflecting the planner's perceived adequacy of using a given city freighters fleet mix to deliver freight to customers in the city centre area. This metric may include considerations such as the lack of parking space for larger vehicles, lack of accessibility infrastructure (such as appropriate bike lanes) or even the topology of the area, as hilly locations may be more difficult to access by bike or walking.

Given the vehicle suitability profiles established *a priori* by the planner for each city centre zone, the *vehicle suitability* metric is calculated as the ratio between the total vehicle suitability of a solution, calculated as the sum of the suitability indices of second-echelon customers given by the type of city freighter planned to visit each second-echelon customer in the final solution, over the maximum vehicle suitability metric if every customer was visited by the most suitable city freighter type.

6.4 Computational experiments

In this section, we present the computational experiments conducted to evaluate the proposed solution method.

First, in Section 6.4.1 we describe the set of newly constructed instances, encompassing all problems characteristics, used to test and evaluate the proposed solution method.

In Section 6.4.2, we follow with an evaluation of two alternative *best insertion* rules used during the construction of the initial solution.

Then, in Section 6.4.3, we present the results on the parameters calibration tests used to determine the most suited solution method's parameters combination with which to conduct the computational tests.

Finally, in Section 6.4.4 the final results of the tests are presented.

6.4.1 Test instances

Due to the lack of benchmark instances encompassing all the characteristics of our problem, we have implemented an instance generator to create random instances of the problem given the set of input parameters presented in Table 6.2.

Table 6.2: Instance generator input parameters.

City related parameters
Width and height of the city (m)
Width and height of the city centre (m)
Distance between the depot at the periphery of the city and the edge of the city centre (m)
The number of each type of customer (unit)
For each type of vehicle
Number of vehicles in the fleet (unit)
Load capacity (unit)
Speed (km/h)
Fixed utilisation costs (monetary unit/vehicle)
Variable distance related costs (monetary unit/m)
Length (m)
Width (m)
For each city centre zone
Zone profiles encompassing the suitability indexes for visiting a customer with a given type of city freighter
Operational parameters
Maximum working time (minutes)
Service duration (minutes)

The city The test instances were generated on a Cartesian plane representing a city with a total area of 100 km^2 (10 $km\times$ 10 km), and distances were calculated as the Euclidean distance between locations and are expressed in meters. The maximum working time was set to 300 minutes (5 hours), and the service duration to 5 minutes, regardless of the location, the amount of load delivered/transshipped, or type of service to be performed. As distance was expressed in meters and time in minutes, travel times were computed using the vehicles' speed expressed in $m/minute$. For all instances, the urban vehicles' depots is located at the top edge of the city at half the city width, and the city freighters depot is located directly under it, at the centre of the city centre area, as defined by the satellites' location. The number of satellites is set to 12, and they are located following a similar principle for satellite spatial distribution as proposed by Grangier et al. (2016) and Anderluh et al. (2017, 2021). The rectangle formed by the satellites establishes the boundary between the periphery and the city centre, and its closest point to the urban vehicles' depot was set to 4 km. Additionally, the position of the satellites is used to define 9 zones within the city centre area (see Figure 6.3), for which a pre-established suitability profile is attributed. A zone's suitability profile determines the set of suitability indices of customers located in that zone. Each suitability profile encompasses a set of 3 suitability indexes based on a Likert-type scale, expressing the decision maker's relative preference of using each type of city freighter to visit a customer in a given zone. We have considered 4 different suitability profiles distributed by the city centre zones as presented in Figure 6.4.

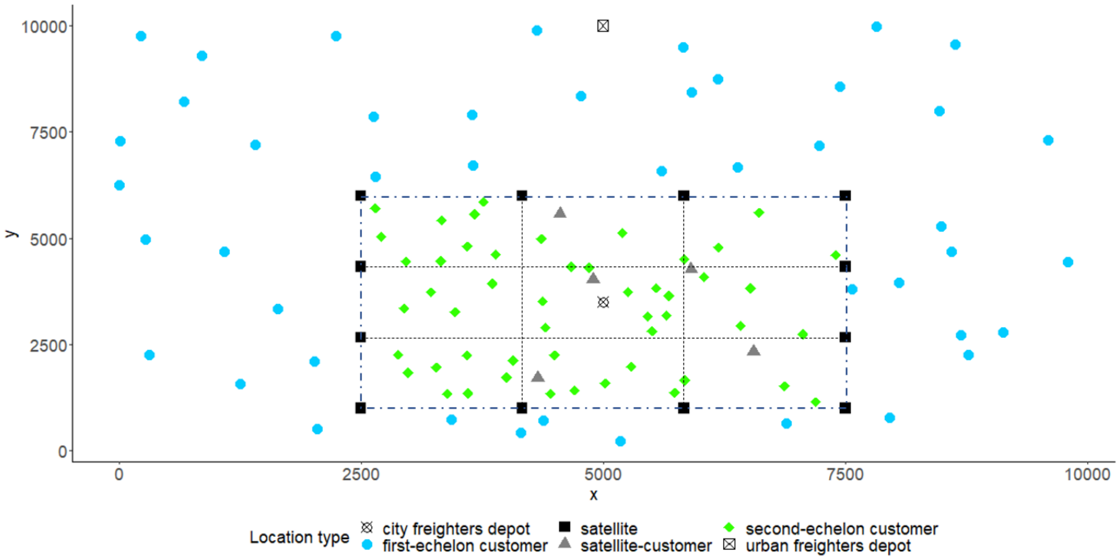
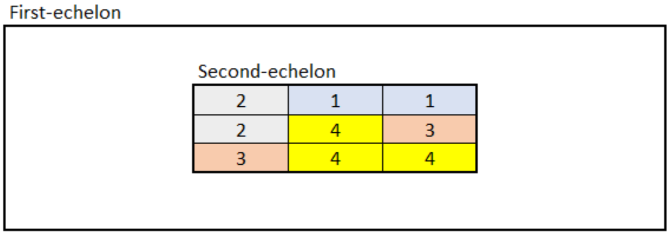


Figure 6.3: Instance example, evidencing the the 9 city centre zones defined by the satellites' position.

Customers The total number of customers is set to 100, and they are randomly located either inside or outside the city centre depending on their type. Second-echelon customers' demand is taken from an uniform distribution $U(1, min\{Q_k\}) : k \in K_2$, as to ensure that every city



(a) Suitability profiles spatial distribution

	Suitability indices		
Profile	K_2^1	K_2^2	K_2^3
1	5	3	1
2	3	4	2
3	2	5	3
4	1	3	5

(b) Suitability profiles

Figure 6.4: Zones' suitability profiles and their spatial distribution.

freighter type is able to perform the delivery. As for customers required to be served by urban freighters, namely first-echelon customers and satellite-customers, their demand is calculated as $2 \times U(1, min\{Q_k\}) : k \in K_2$. Second-echelon customers' suitability indices are set according to the suitability profile of the city centre zone where they are located (see Figure 6.4). Regarding customers' time windows, we have considered three different time windows spans, namely: i) narrow time windows of 60 minutes ($0 \leq l_i \leq 200$ and $u_i = l_i + 60$); ii) wider time window spans of 120 minutes ($0 \leq l_i \leq 100$ and $u_i = l_i + 120$); and, "no" time windows ($l_i = 0$ and $u_i = maxTime = 280$).

Vehicles' characteristics The vehicle types' characteristics have been set according to the real values whenever possible, but information regarding their cost structures and capacity were seldom available and widely variable, therefore proxy values have been considered. Furthermore, since requested amounts were not set using real life information, we established the capacity of these vehicles to proxy values as well, while keeping some sense of proportionality. Given this, the the vehicle's capacity Q, fixed cost f, and distance unit cost c where set after some preliminary test to approximate proxy values, so that $Q_k > Q_w > Q_r > Q_p$; $f_k > f_w > f_r > f_p$; $c_k > c_w > c_r > c_p$ $: k \in K_1, w \in K_2^1, r \in K_2^2, p \in K_2^3$. As for the speed, we have considered a free flow average speed of 35 km/h for the urban vehicle (both in the periphery and in the city centre), 25 km/h for the small e-vans, 15 km/h for the cargo-cycles, and a walking speed of 4 km/h. As for each vehicle type dimensions, the urban vehicles' dimensions are those of a Ford Transit 350L3H3, and those of small e-vans and cargo cycles were taken from Browne et al. (2011). Lastly, all vehicle types start and end their working day at their respective depot except for walking porters (K_2^3), which start their working day at a transshipment location (satellite or satellite-customer) and end their route at a second-echelon customer. The set of vehicle types' parameters is presented in Table 6.3.

Sets of instances We have generated 27 instances considering different settings for: i) city centre area size; ii) number of customers of each type; and iii) time window spans. Regarding the size of the city centre, we consider 3 alternatives $S = \{A, B, C\}$, representing city centre areas with 25 km^2 ($5km \times 5km$), 15 km^2 ($5km \times 3km$), and 9 km^2 ($3km \times 3km$), respectively. Regarding the number of customers of each type, we consider 3 different customer distribution alternatives $D = \{a, b, c\}$. Let $d = (x, y, z) : d \in D$ be a customer distribution alternative with x first-echelon customers, y

Table 6.3: Vehicles parameters.

Type	K_1	K_2^1	K_2^2	K_2^3
Vehicle	Truck	E-van	Cargo-cycle	Walking porter
Fixed cost ($m.u./vehicle$)	40000	30000	20000	10000
Variable cost ($m.u./m$)	4	3	2	1
Capacity ($un.$)	50	20	10	5
Speed (km/h)	35	25	15	4
Length (m)	5,98	3,32	2,35	1
Width (m)	2,47	1,49	1,03	1
Start/End point	O_1/O_1	O_2/O_2	O_2/O_2	$(S \cup C_3)/C_2$

second-echelon customers, and z satellite-customers. Given this, alternative (a) considers a balanced distribution of customers at each echelon, $a = (45, 50, 5)$. Alternative (b) considers a larger percentage of second-echelon customers, $b = (15, 80, 5)$, and alternative (c) considers that most customers are located at the first echelon, $c = (75, 20, 5)$. The combination of S and D yields a total of 9 test instances with the naming convention SD. Details about the generated S_D instances are presented in Table 6.4. Additionally, for each SD instance, we have considered 3 different customers' time window spans, $T = \{0, 1, 2\}$, where: (0) stands for narrow time windows spans of 60 minutes; (1) stands for wider time windows spans of 120 minutes; and (2) stands for *no* time windows. This yields a total of 27 instances, with the naming convention S_D_T, where $S = \{A, B, C\}$, $D = \{a, b, c\}$, and $T = \{0, 1, 2\}$.

Table 6.4: Instances characteristics.

Instance	City centre area (km^2)	$\lvert C_1 \rvert$	$\lvert C_2 \rvert$	$\lvert C_3 \rvert$	$\sum_{i \in C_1} d_i$	$\sum_{i \in C_2} d_i$	$\sum_{i \in C_3} d_i$	Total demand
A_a	25	45	50	5	198	114	30	342
A_b	25	15	80	5	88	202	30	320
A_c	25	75	20	5	410	51	22	483
B_a	15	45	50	5	244	129	22	395
B_b	15	15	80	5	84	198	30	312
B_c	15	75	20	5	344	57	20	421
C_a	9	45	50	5	226	138	22	386
C_b	9	15	80	5	84	199	22	305
C_c	9	75	20	5	404	56	28	488

6.4.2 Initial solution best insertion criteria

The initial solution is constructed using a *greedy best insertion heuristic*. The criteria used to establish the next *best* insertion can greatly influence the quality of the initial solution (Jiang et al., 2014). Several criteria can be used to determine the next best insertion, for example:

1. *Shortest distance*: Select next feasible insertion with the shortest distance, also known as the nearest neighbour;
2. *Longest distance*: Select next feasible insertion with the longest distance to the depot;

3. *Earliest start service time*: Select next feasible insertion with the earliest start service time;

4. *Tightest time window*: Select next feasible insertion with the tightest time window;

In this work, we have tested two alternatives namely, the shortest distance and the earliest start service time criteria. The average results of the initial solution of all 27 instances are presented in Figure 6.5.

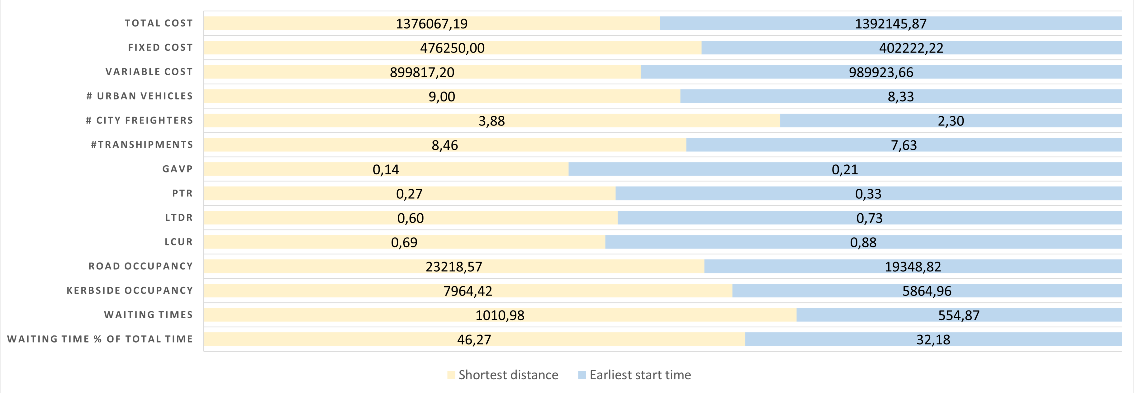


Figure 6.5: Greedy insertion criteria average results.

Results show that both criteria yield similar results in terms of average total cost. Nonetheless, there is a trade-off between the minimisation of the used vehicle fleet and the total travelled distance, a result that has been noted by Toth & Vigo (2014). When the shortest distance criteria is used, the variable distance-based costs are smaller but the fixed costs are higher due to the higher number of used vehicles. This occurs because, although the next *best* insertion is the closest, vehicles may have to wait if they arrive before the earliest start service time. These wasteful waiting times result in less time to visit more customers during a working day, thus requiring the use of additional vehicles. On the other hand, when considering the earliest start time, the waiting times are reduced, the used fleet is smaller but the order in which the customers are visited yields longer routes. By using less vehicles, the fleet is used more efficiently, as given by the $GAVP$ metric, and the roadside and kerbside occupation is reduced. Given these results, all subsequent tests were performed using the earliest start time criteria during the constructing of the initial solutions.

6.4.3 Improvement phase parameter settings

The proposed solution method requires setting the parameters for the SA acceptance criterion scheme (see Algorithm 2), and for the VNS-based heuristic used at each echelon during the improvement phase (see Algorithm 3). The parameters to be set are: i) the initial temperature T_0; ii) the cooling rate α; iii) the maximum number of iterations of the simulated annealing process $maxIt$; and, iv) the maximum number of iterations of the local search method during the VNS it_{max}.

The initial temperature T_0 was set such that the first non-improving solution would be accepted with a probability P_0, and it is computed as $T_0 = \frac{-\Delta}{ln(P_0)}$. We have considered $P_0 = \{0,3;0,5;0,7\}$, $\alpha = \{0.90;0.95;0.99\}$, $maxIt = \{500;1000;2000\}$, and $it_{temp} = \{20,50,70\}$ The maximum number of iterations of the local search step was not tested, and was simply set to 20. The solution method parameters were determined based on pretests of the 81 parameter combinations, using the 9 instances with larger city centre areas (A_*_* instances), and taking the average total cost and computational time over 5 runs.

Results show that, as expected, there is a trade-off between the computation time and quality of the solution. The best solutions are obtained when starting with lower acceptance probabilities such as 0.3 and 0,5, slow cooling rates of 0,99, and more iterations at each temperature level. This indicates that a more thorough evaluation of the search space with lower acceptance probabilities of non-improving solutions is the preferable search strategy. Furthermore, although the best results were obtained setting a larger number of iterations of the SA algorithm, the required computation time was much higher, therefore we decided to set the number of iterations to a smaller number $maxIt = 1000$. Given these results, all remaining tests were performed using the parameter settings presented in Table 6.5.

Table 6.5: Parameter settings.

Initial acceptance probability (P_0) [1]	0,3
Cooling rate (α)	0,99
# SA iterations ($maxIt$)	1000
# iterations per temperature "level" (it_{temp})	70
# iterations in VNS local search (it_{local})	20

[1] Used to set the initial temperature T_0 given the first non-improving solution as explained in Section 6.4.3

6.4.4 Results

The proposed solution method has been coded using the Java programming language, and all tests were performed on a Intel(R) Core(TM) i7-6700HQ CPU at 2,6 GHz with 16 GB of RAM. The have tested the impacts on the solution given different time window spans, the benefits of using an heterogeneous versus an homogeneous fleet of city freighters, as well as an assessment of two alternative distribution policies including two-echelon distribution systems with storage capabilities at satellites, thus requiring only precedence between urban freighter and city freighters at satellites, and the business-as-usual (BAU) representing a single echelon distribution system using only urban freighters. We ran each instance 10 times and kept the best solution for each instance. These "best" solutions were then used to compute the average results presented in Tables 6.6, 6.8, 6.9.

Impacts of instances characteristics time windows Results show that, as expected, more restrictive the time windows result in higher total costs. Additionally, instances with tighter time windows tended to use more walking porters and consequently require more transshipments. Furthermore, we note that the reduction of the $GAVP$ metric as the time windows get less restrictive is mostly influenced by the decrease of the PTR (see Section 6.3.1). The PTR is greatly influenced by the end time of vehicles' routes. Since the number of urban vehicles is bounded by capacity (all solutions used the lower bound of urban vehicles in terms of capacity), the less restrictive problem without time windows, allows vehicles to end their working day earlier, therefore "wasting" available working time. Since the unused total time is considered as an inefficiency, we end up with smaller PTR, which in turn reduces the the final $GAVP$ value. Table 6.6 presents the average results regarding the total cost, $GAVP$, roadside occupancy metric α, kerbside occupancy β, suitability ratio γ, the used fleet and the number of transfers τ. Results were obtained using the 9 instances' best solutions for each time window type ($*\_*\_T : T \in \{0,1,2\}$).

Table 6.6: Average results for each time-windows type.

T	Total cost	GAVP	α	β	γ	$\lvert K_1\rvert$	$\lvert K_2^1\rvert$	$\lvert K_2^2\rvert$	$\lvert K_2^3\rvert$	τ
0	1374664,79	0,24	21975,07	7041,77	0,68	8,11	0,33	1,56	4,00	18,33
1	1235626,81	0,22	16465,18	5026,74	0,62	8,11	1,11	1,11	1,67	13,00
2	1072659,02	0,22	17416,36	5595,71	0,59	8,11	0,78	0,22	2,00	14,56

Used fleet mix In all instances the final number of used urban vehicles was always the lower bound, given their capacity. As for the mix of used city freighters, sometimes final solutions presented very different fleet mixes with very similar total costs, as shown in the example presented in Table 6.7.

Table 6.7: Example of a solutions subset of instance A_b_0.

Instance	Total cost	GAVP	α	β	γ	$\lvert K_1\rvert$	$\lvert K_2^1\rvert$	$\lvert K_2^2\rvert$	$\lvert K_2^3\rvert$	τ
A_b_0	1343353,25	0,25	22091,77	7671,51	0,52	7	3	1	0	13
A_b_0	1349618,63	0,23	22080,76	7745,89	0,72	7	0	4	5	27
A_b_0	1363064,50	0,22	23673,57	8162,29	0,62	7	1	2	6	26
A_b_0	1372402,00	0,25	22826,06	7827,77	0,58	7	2	2	2	19

The alternative city freighters mixes are quite balanced in terms of the total costs despite having very different vehicle compositions. This fleet mix cost similarity is highly dependent on the considered vehicle types' characteristics, including cost structure, capacity and speed, which greatly increases the difficulty of the problem, and shows that any consideration should be taken into account for each particular use case, as the relative characteristics of vehicles can greatly influence the end results. As no fleet mix is clearly superior in terms of costs, the procedure is required to explore more of the solution space in regards to alternative fleet compositions.

Comparison with homogeneous city freighter fleets We evaluate the benefit of using an heterogeneous fleet against using a homogeneous fleet of each city freighter type. The instances with homogeneous city freighters fleets are solved using the proposed solution method, and because there is only one city freighter type, the *vehicle change* operator is not used used during the city freighters VNS procedure. Table 6.8 presents the average of the best solution of the 21 instances for each city freighters fleet type alternative: heterogeneous, homogeneous fleet of K_2^1, K_2^2, and K_2^3.

Table 6.8: Average results for each second-echelon vehicle type fleet.

Fleet	Total cost	GAVP	α	β	γ	$\lvert K_1 \rvert$	$\lvert K_2^1 \rvert$	$\lvert K_2^2 \rvert$	$\lvert K_2^3 \rvert$	τ
Hetero.	1227650,21	0,23	18618,87	5888,07	0,63	8,11	0,74	0,96	2,56	15,30
K_2^1	1271647,75	0,22	17691,01	5510,87	0,52	8,11	2,30	-	-	7,11
K_2^2	1247106,22	0,24	18265,99	5790,55	0,78	8,11	-	2,89	-	14,30
K_2^3	1301849,13	0,26	19755,49	5819,19	0,63	8,11	-	-	7,22	30,30

Results show that, on average, the total costs are smaller when an heterogeneous fleet is considered. Despite this, it presents one of the smallest GAVP, and the roadside and kerbside impacts are somewhat high. When homogeneous fleets are considered, the least expensive alternatives were the cargo cycles, followed by the e-vans, and lastly the walking porters. The high number of walking porters and the consequent increased number of transfers, with its inefficiencies in regards to vehicle synchronisation, make this alternative the most expensive. Nonetheless, the use of walking porters is the solution yielding the higher GAVP. Using more walking porters, which follow an open vehicle routing problem, allows for more of the available working time to be used productively, i.e., by having less waiting times and finishing their working day closer to the maximum available working time. On the other hand, the use of walking porters yields on average lower $LTDR$ due to the high number of empty trips towards the next transshipment.

Comparison between different distribution policies We compare the solutions obtained for the proposed two-echelon distribution system with exact synchronisation at satellites against 2 alternative distribution policies.

For the first alternative, we assume that satellites have storage space, representing distribution systems based on micro-depots/lockers akin to the systems presented in Section 3.2. In this case, exact synchronisation between vehicles at satellites is no longer necessary, and only precedence between urban and city freighters at satellites is required, guaranteeing that urban freighters have already supplied the satellite before the city freighters reloads. To consider this problem characteristic, the transshipments merging method needs to be adapted (see Algorithm 1 line 2). Instead of summing only the loads of transshipments occurring at the same satellite at the same time, we sum all loads of transshipments occurring at the same satellite during the day. Furthermore, as to guarantee that an urban freighter will precede all city freighters' transshipment requests at each satellite, we set the latest time of arrival of the new merged transshipment request of urban freighters as the earliest start service time of all city freighters' visits to that satellite.

The second alternative represent the current BAU, i.e. a single echelon distribution system where urban freighters (trucks) are used to perform all deliveries. In this case the problem becomes a CVRP-TW. To test this alternative we adapted the original instances by labelling all customers as first-echelon customers and, in order to account for the speed reduction in the city centres due to congestion, we set the speed of the urban freighters to the speed of the fastest city freighter type. These problem were solved using the proposed solution method but applied only to the urban freighters routing problem.

Table 6.9: Average results for each distribution type.

Policy	Total cost	$GAVP$	α	β	γ	K_1	$\lvert K_2^1\rvert$	$\lvert K_2^2\rvert$	$\lvert K_2^3\rvert$	τ
Exact synch.	1227650,21	0,23	18618,87	5888,07	0,63	8,11	0,74	0,96	2,56	15,30
Precedence	1179125,77	0,21	15152,85	4473,32	0,65	8,11	0,07	0,67	5,93	26,30
BAU	1166149,19	0,29	18069,73	4311,59	-	8,22	-	-	-	-

Results show that, on average, the BAU is not only less expensive than any of the other two-echelon alternatives, but it is also the most efficient as given by the $GAVP$. The distribution system based on exact synchronisation is, on average, the most expensive and results in a much higher percentage of waiting times. This is to be expected given the difficulty to synchronise transshipment operations between vehicles operating at both echelons. In the case of systems with storage capabilities at satellites (with precedence), solutions use more walking porters, which in turn also increases the number of city freighters reloads. Note that, the number of transshipments presented in Table 6.9 correspond to reloads by the city freighters. As these requests are bundled as previously explained, the number of transshipments of urban vehicles is much smaller. When compared with exact synchronisation, the precedence-based distribution system yields less waiting times, but the total distance and the total empty running distance is higher, which greatly reduces the $LTDR$ and consequently the final GAVP. This can be attributed to the small capacity of walking porters and the consequent need to return more times to transshipment locations to replenish.

6.5 Alternative considerations and algorithm improvements

Besides the aspects taken into account throughout the previous section, the proposed solution method can be adapted to accommodate some alternative considerations:

- The cost function can be extended to include, for example: travel time-based variable costs, fixed and load-based variable costs associated with each transshipment, and variable costs associated with the waiting times at transshipment locations. Furthermore, it is possible to consider capacity constraints at each transshipment location, and a maximum waiting time at each location.
- The transshipment merge operator (see Algorithm 1) can be adapted to merge transshipments which occur at the same satellite within different time windows.

- It is possible to consider multi-trips at the first echelon by establishing route construction methods similar to those used for city freighters.
- Regarding the use of the neighbourhood structures, one can apply a random or adaptive selection mechanism.
- A more efficient time feasibility test in the insertion procedure can be implemented, based on the constant-time forward time slack (FTS) test algorithm similar to that proposed by Grangier et al. (2016); Gschwind & Drexl (2019).

6.6 Chapter summary

In this chapter, we have proposed a heuristic solution method to solve a variant of the basic 2E-CVRP that considers: i) a heterogeneous fleet of city freighters, where one of these types follows an OVRP; ii) time windows at customers; iii) exact synchronisation at transshipment locations between vehicles operating at each echelon; iv) multiple-trips for city freighters; and v) the possibility of performing transshipments at some customer locations.

The proposed solution method is a VNS-based heuristic guided by a simulation annealing acceptance scheme. To address the interdependence between the schedules of vehicles operating at different echelons, the main problem is decomposed into two routing ad scheduling problems, one for each echelon, which are solved sequentially.

Due to the lack of a real case study data, we have developed an instance generator, used to generate 21 instances encompassing all the characteristics of our problem with which all evaluation and validation tests of the solution method were conducted.

We present the results of using two alternative *best insertion* criteria for the construction of the initial solution, namely the shortest distance and earliest start service time criteria. Results show that using each of these alternatives have different impacts in the quality of the initial solution and entail trade-offs which should be taken into account when deciding which one to use. Additionally, we have tested several solution method parameters with which the rest of the tests were conducted. Results show that, the best results where obtained when considering a lower acceptance probability of non-improving solutions, slow cooling rates and higher number of iteration within each temperature level in the simulated annealing algorithm framework.

We evaluated the impacts of different time windows, of using an heterogeneous fleet at the second echelon against using an homogeneous fleet of each of the considered city freighter types, and compared the proposed distribution system with exact synchronisation with two alternative distribution policies namely: i) two-echelon distribution systems where loads can be stored at transshipment locations thus requiring only precedence between vehicles instead of exact synchronisation needed for direct transshipment of loads; and, ii) the business as usual, where a single echelon is considered and first echelon vehicles are used to deliver to all customers. Results show that, as expected, the more restrictive the time windows the higher the distribution costs. Additionally, results show that there were cost benefits in considering an heterogeneous fleet of city freighters in opposition to using homogeneous fleets of any of the considered vehicle types. Lastly, results show that using the BAU distribution system was less expensive and more efficient, given the proposed GAVP metric, than any of the distribution alternatives based on two-echelons. Furthermore, when considering two-echelon systems, results show that requiring exact space-time synchronisation between vehicles operating at each echelon is more expensive than considering systems with storage capabilities at transshipment locations.

We note that, the presented results were obtained using the generated proxy instances. Therefore, the presented results and the subsequent conclusions should be considered only in the context of these tests. The relative fixed and variable costs, speeds, and capacities between vehicle types, together with the relative location of satellites, customers and depots will determine the best size and mix to be used in each real life context.

The proposed solution method is flexible and can be adapted, to solve problems with an homogeneous and/or limited fleet, and to be used to solve the vehicle routing problems arising from alternative distribution policies, such as considering storage capabilities at transshipment points or single echelon distribution systems (BAU). Furthermore, other extensions such as additional vehicles' time- ,distance- or satellite-based fixed/variable costs could also be accounted for, as well as additional problem characteristics such as bundling time windows, maximum waiting times or storage capacity at transshipment locations.

Chapter 7

A prototype for a decision support system

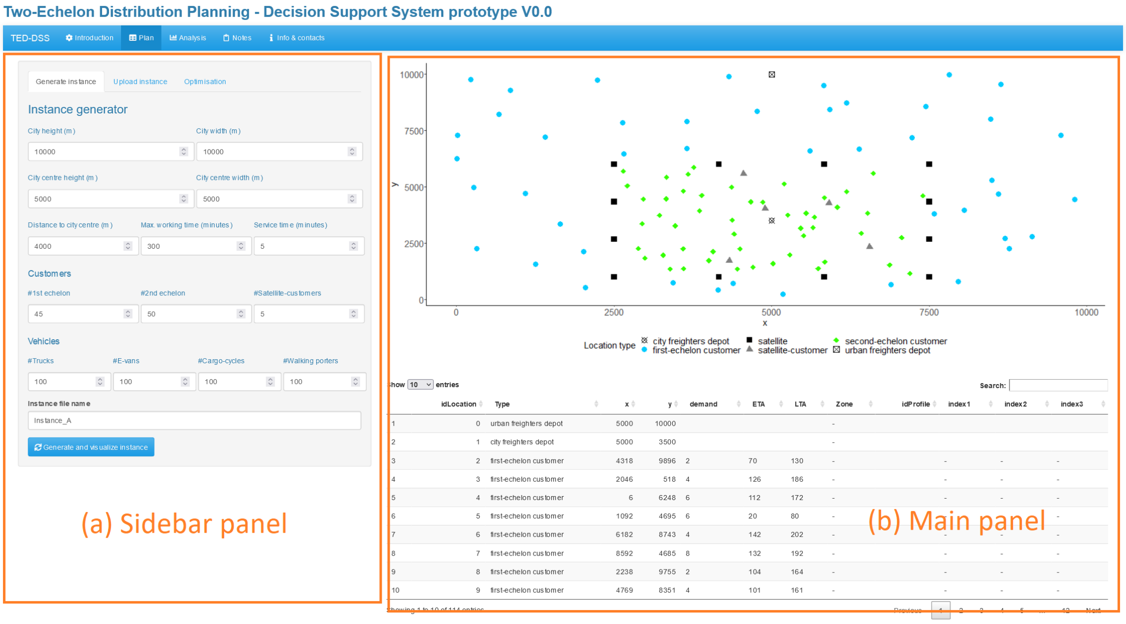
In this chapter, we present the prototype of a *Decision Support System* (DSS) for the planning and evaluation of two-echelon distribution systems. We start by describing the DSS prototype (Section 7.1) , and follow with some future improvement suggestions (Section 7.2). The main goal of this prototype is to show how the work developed in this dissertation can be applied in practice.

7.1 System description

The DSS prototype described here aims to illustrate how a software tool could allow decision makers to plan and evaluate two-echelon distribution systems with exact synchronisation at the satellites, and compare them with two alternative distribution systems namely two-echelon systems with storage capabilities at satellites, and the single-echelon *business-as-usual* (BAU). The DSS prototype is composed by an optimisation engine and the DSS graphic user interface (GUI).

The optimisation engine was developed using the Java programming language and encompasses the heuristic solution method presented in Section 6.2. It is used to solve the heterogeneous fleet two-echelon vehicle routing problem with synchronisation at satellites and multi-trips at the second echelon, as well as two alternative distribution policies, namely two-echelon distribution systems with storage capacity at satellites and the single-echelon BAU.

The system's GUI was developed using R (R Core Team, 2020) and R-shiny (Chang et al., 2020), a package used to build interactive web apps/dashboards using the R language. The GUI dashboard is split into a *planning* section and an *analysis* section. Additionally, each section is split into a *sidebar* and a *main* panel (Figure 7.1).



Two-Echelon Distribution Planning - Decision Support System prototype V0.0

Instance generator

City height (m): 10000
City width (m): 10000
City centre height (m): 5000
City centre width (m): 5000
Distance to city centre (m): 4000
Max. working time (minutes): 300
Service time (minutes): 5

Customers

#1st echelon: 45
#2nd echelon: 50
#Satellite-customers: 5

Vehicles

#Trucks: 100
#E-vans: 100
#Cargo-cycles: 100
#Walking porters: 100

Instance file name: Instance_A

Show 10 entries

	idLocation	Type	x	y	demand	ETA	LTA	Zone	idProfile	index1	index2	index3
1	0	urban freighters depot	5000	10000				-				
2	1	city freighters depot	5000	3500				-				
3	2	first-echelon customer	4318	9896	2	70	130	-		-	-	-
4	3	first-echelon customer	2046	518	4	126	186	-		-	-	-
5	4	first-echelon customer	6	6248	6	112	172	-		-	-	-
6	5	first-echelon customer	1092	4695	6	20	80	-		-	-	-
7	6	first-echelon customer	6182	8743	4	142	202	-		-	-	-
8	7	first-echelon customer	8592	4685	8	132	192	-		-	-	-
9	8	first-echelon customer	2238	9755	2	104	164	-		-	-	-
10	9	first-echelon customer	4769	8351	4	101	161	-		-	-	-

Showing 1 to 10 of 114 entries

Figure 7.1: Planning section.

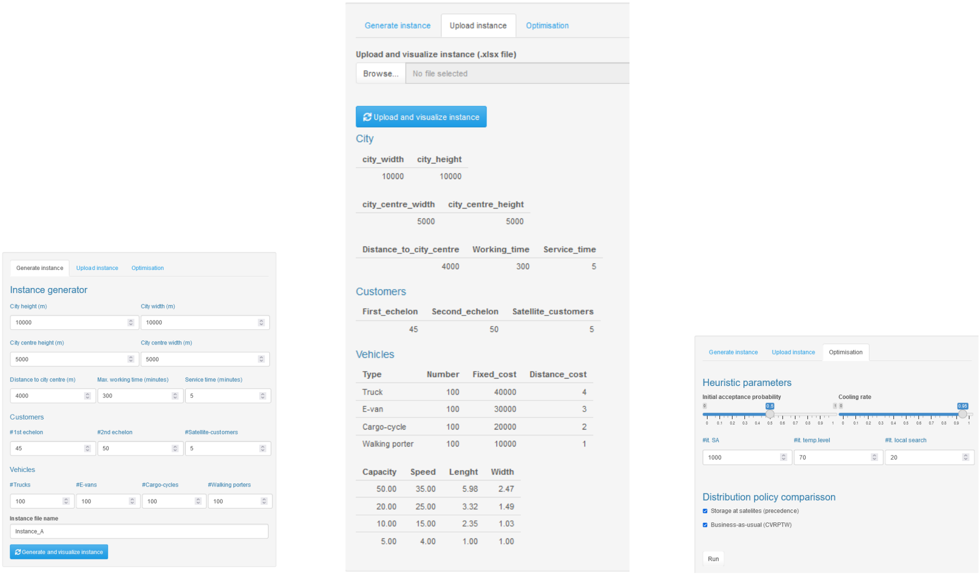
7.1.1 Planning section

In the planning section (Figure 7.1), the sidebar allows users to generate a new instance, based on some inputs and/or upload an existing instance, inspect its characteristics, set the input parameters for the heuristic solution method, and select what alternative distribution systems should be considered in the distribution alternatives comparison. Each of these functionalities is depicted in Figure 7.2 and described next.

- **Generate instance** (Figure 7.2a). To generate a new instance of the two-echelon vehicle routing problem variant with heterogeneous fleet and exact synchronisation at satellites (as presented in Section 6.4.1), the user must specify: the dimensions of the city and city centre; the distance between the depot located at the periphery of the city and the edge of the city centre; the service duration of deliveries; the number of customers of each type; and the number of vehicles of each type. The customers spatial distribution and demand values, as well as the vehicles characteristics, are currently generated according to the same process used to generate the test instances (see Section 6.4.1). For example, in the example of the figure, the user is generating an instance file named *Instance_A* with: a city of 10,000 meters height and 10,000 meters width; a city centre with a 5,000 meters height and 5,000 meters width; a distance from the city centre edge to the periphery depot of 4,000 meters; a maximum working time of 300 minutes; a service duration of 5 minutes; 45 first-echelon customers; 50 second-echelon customers; 5 satellite-customers; and 100 vehicles of each type.

- **Upload instance** (Figure 7.2b). Users can upload an instance file (currently only available in excel format) and inspect its characteristics, including the city and city centre dimensions, as well as information regarding the characteristics of customers and of the fleets of the different vehicle types.

- **Optimisation options** (Figure 7.2c). Users can set the parameters for the simulated annealing including: the initial acceptance probability, the cooling rate, the number of overall simulated annealing iterations, and the number of iterations at each "temperature level". For the VNS, the user can set the number of iterations of the local search used during the procedure (see Section 6.2). Besides solving the two-echelon distribution problem with exact synchronisation between vehicles at satellites, the user may also chose to evaluate two alternative distribution policies, namely: considering that the satellites have storage capabilities, i.e. there is only precedence between vehicles at satellites; and the BAU, where only urban freighters are used to perform the deliveries. The routing and scheduling problems arising from these alternative distribution policies are also solved using the optimisation engine with the proposed heuristic approach, which is adapted to take into account their characteristics, as explained in Section 6.4.4.



Instance generator

City height (m) 10000
City width (m) 10000
City centre height (m) 5000
City centre width (m) 5000
Distance to city centre (m) 4000
Max. working time (minutes) 300
Service time (minutes) 5

Customers

#1st echelon 45
#2nd echelon 50
#Satellite-customers 5

Vehicles

#Trucks 100
#E-vans 100
#Cargo-cycles 100
#Walking porters 100
Instance file name Instance_A

Upload and visualize instance (.xlsx file)
No file selected

City

city_width	city_height
10000	10000

city_centre_width	city_centre_height
5000	5000

Distance_to_city_centre	Working_time	Service_time
4000	300	5

Customers

First_echelon	Second_echelon	Satellite_customers
45	50	5

Vehicles

Type	Number	Fixed_cost	Distance_cost
Truck	100	40000	4
E-van	100	30000	3
Cargo-cycle	100	20000	2
Walking porter	100	10000	1

Capacity	Speed	Lenght	Width
50.00	35.00	5.98	2.47
20.00	25.00	3.32	1.49
10.00	15.00	2.35	1.03
5.00	4.00	1.00	1.00

Heuristic parameters

Initial acceptance probability 0.5
Cooling rate 0.95
#it. SA 1000
#it. temp.level 70
#It. local search 20

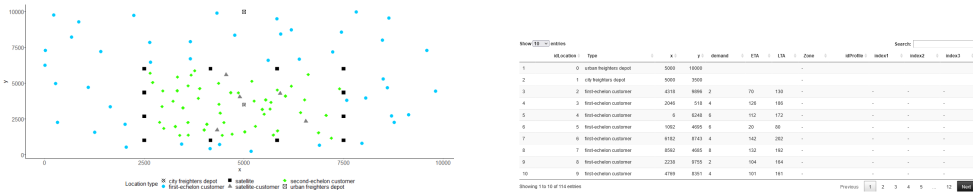
Distribution policy comparisson

☑ Storage at satelites (precedence)
☑ Business-as-usual (CVRPTW)

(a) Generate instance (b) Upload instance (c) Optimisation options

Figure 7.2: Planning section sidebar panel.

After generating or uploading an instance, the main panel will display a graphic representation of the instance in the cartesian plane (Figure 7.3a), as well as a table with the list of locations (depots, customers and satellites) and their characteristics, including: their coordinates in the plane; the demand; time windows lower and upper bounds; the city centre zone where customers are located; the suitability profile associated with that zone; and the corresponding suitability indics for each vehicle type (Figure 7.3b).



(a) Instance graphic representation

Show 10 entries

Search:

	idLocation	Type	x	y	demand	ETA	LTA	Zone	idProfile	index1	index2	index3
1	0	urban freighters depot	5000	10000				-				
2	1	city freighters depot	5000	3500				-				
3	2	first-echelon customer	4318	9896	2	70	130	-		-	-	-
4	3	first-echelon customer	2046	518	4	126	186	-		-	-	-
5	4	first-echelon customer	6	6248	6	112	172	-		-	-	-
6	5	first-echelon customer	1092	4695	6	20	80	-		-	-	-
7	6	first-echelon customer	6182	8743	4	142	202	-		-	-	-
8	7	first-echelon customer	8592	4685	8	132	192	-		-	-	-
9	8	first-echelon customer	2238	9755	2	104	164	-		-	-	-
10	9	first-echelon customer	4769	8351	4	101	161	-		-	-	-

Showing 1 to 10 of 114 entries

(b) Locations information table

Figure 7.3: Planning section main panel.

7.1.2 Analysis section

The analysis section of the DSS is designed around a dashboard with information about the final results and the associated plans.

The sidebar panel (Figure 7.4) provides information about the final solution for the two-echelon distribution system variant with heterogeneous fleet and exact space-time synchronisation at satellites. This information encompasses the number of used vehicles of each type, the number of transshipments, the total cost of the plan, the auxiliary evaluation metrics (see Section 6.3). It also includes some additional support metrics, namely: i) the total travelled distance, the empty running distance and the corresponding proportion of the total distance travelled while empty; ii) the total travel time, the waiting time and its corresponding proportion of the total travel time; and, iii) the average of both urban and city freighters' load factors.

The main panel has three tabs with further information for the evaluation of the final solution. The two first tabs are dedicated to the display of urban and city freighters' routes in the final solution (Figures 7.5a and 7.5b, respectively). In each case, a graphical representation of the route is displayed, along with a table with the vehicle's route schedule, presenting each service start time, location, the expected waiting/buffer time before starting the service, the amount to deliver and/or transship, and the vehicle's load as it finishes the service.

The third tab allows a comparative analysis between alternative distribution systems (Figure 7.6). The exact synchronisation distribution system is compared with the alternative distribution systems selected by the user (in the optimisation options tab in the sidebar panel of the plan section) (see Figure 7.2).

At the upper area of the main panel, there is a table with information about each distribution policy, including the number and type of vehicles used, and the number of transshipments performed by urban and city freighters in each distribution policy. In the bottom area, there are a set of charts comparing the different distribution systems in terms of total costs, auxiliary evaluation metrics (see Section 6.3) and additional support (in)efficiency metrics, including the proportion of

Fleet

Trucks	E_vans	Cargo_cycles	Walking_porters	Transhipments
7	0	2	4	17

Metrics

Total_cost	GAVP	PTR	LTDR	LCUR
1383624.25	0.30	0.43	0.77	0.93

Roadside_occupancy	Kerbside_occupancy	Suitability_ratio
19475.41	5799.54	0.70

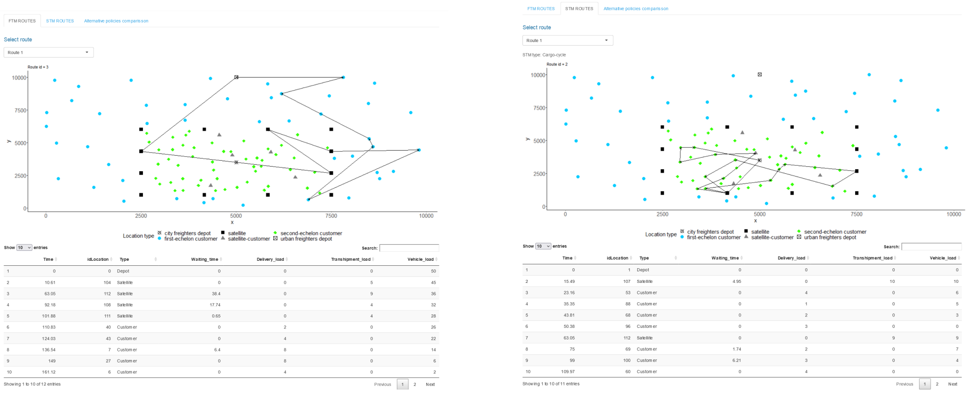
Details

Total_distance	Empty_distance	percent_total_distance
305061.91	71294.66	23.37

Total_time	Waiting_time	percent_total_time
2497.08	822.80	32.95

Average_FTM_load_factor	Average_STM_load_factor
0.98	0.92

Figure 7.4: Solution analysis sidebar panel.



(a) Urban freighters route display

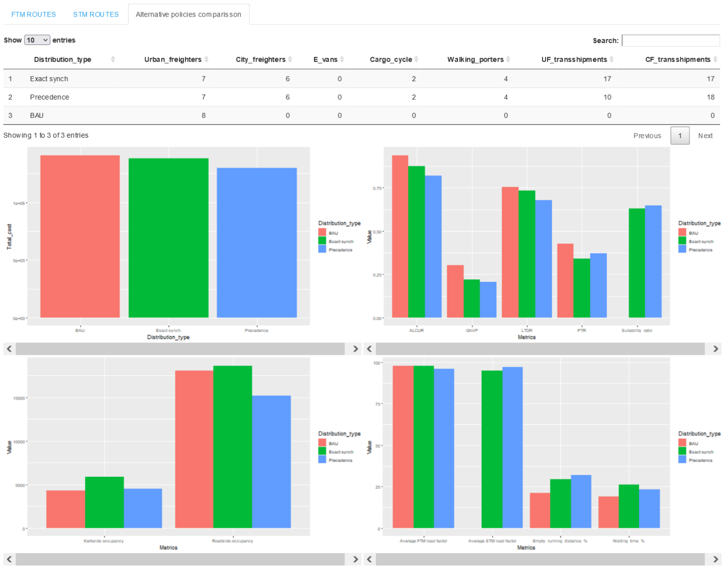
(b) City freighters routes display

Figure 7.5: Solution analysis section main panel: routes display.

the total travelled distance while empty, the proportion of the total time spent waiting, and the average of the urban and city freighters' load factors are displayed. This graphical representation aims to allow for an intuitive identification of the potential trade-offs between alternative distribution systems, and possible sources of inefficiencies.

7.2 Future developments

As referred above, the proposed DSS prototype is still under development. At the current stage, the prototype is prepared to accept only proxy instances, represented over the Cartesian plane, as used



	Distribution_type	Urban_freighters	City_freighters	E_vans	Cargo_cycle	Walking_porters	UF_transshipments	CF_transshipments
1	Exact synch	7	6	0	2	4	17	17
2	Precedence	7	6	0	2	4	10	18
3	BAU	8	0	0	0	0	0	0

Showing 1 to 3 of 3 entries

Figure 7.6: Policies comparison tab.

during the computational experiments of the heuristic solution method. A natural extension of the research is the use of real geodata and real distances between locations. The visual representation of the location of customers, satellites and of the solution routes may also be performed over a map, using, for example, Leaflet (Agafonkin, 2020), and the distances and travelled times could be retrieved from real life data, collected from *OpenStreetMap* (OpenStreetMap Foundation, 2020), for example.

Regarding the generation of instances, some additional functionalities could be implemented, for example: allowing the user to establish the catchment area to be analysed; further provide the user with the ability to add, remove and edit customers, satellites, vehicle types and their characteristics; and establish suitability zones and suitability profiles.

Regarding the optimisation options tab, a possible improvement would be to include additional parameter inputs to be set by the user. For example, in a multi-objective framework, it would be interesting to allow the user to select the objectives, and their priorities.

Finally, the support information provided to the user in the analysis section should be adapted to match the needs and requirements of specific decision makers.

7.3 Chapter summary

In order to support and improve the decision making process associated with the planning of two-echelon distribution systems, we have developed a DSS prototype, encompassing two main components, namely: i) an optimisation engine implementing the heuristic solution method proposed in this work, and developed using the Java programming language; ii) and, a web-app GUI developed using the R shiny package.

This prototype can be used to generate, upload, and solve instances for the two-echelon vehicle routing problem addressed in Chapter 6. Furthermore, it allows the user to compare the results of considering the aforementioned two-echelon distribution variant with two alternative systems, namely two-echelon distribution with storage at satellites, and the BAU where a single-echelon is considered.

The DSS provides the user with a simple and direct access to important cost and system efficiency related information of the final plan. Furthermore, it provides a graphical representation and detailed schedule of each vehicle route, along with comparative graphs and plots between the alternative distribution policies. The DSS concept has therefore been validated, thus showing its application potential, but the prototype is still being developed, being therefore still open to further improvements.

Chapter 8

Conclusions

8.1 Main contributions of the thesis

The first goal of this work was to understand and characterise two-echelon distribution systems in the context of city logistics (Chapter 2). In particular, focus was given to the study of systems based on mobile depots, for which a review of the state of practice was performed (Chapter 3). Following the findings of this review, we proposed a classification of these systems, according to the degree of mobility and accessibility to customers by the urban vehicles.

Having set the context of two-echelon distribution systems used in city logistics and the associated planning problems, the next steps entailed the review of the relevant literature on operations research applied to solving two-echelon vehicle routing problems (Chapter 4), as well as to develop and test exact solution methods for variants of the basic two-echelon (capacitated) vehicle routing problem (2E-CVRP) encompassing synchronisation constraints and multiple trips at the second echelon, arising from the different types distribution systems, as given by the proposed classification (Chapter 5). To this end, we have proposed a generic MIP formulation for two-echelon vehicle routing problems with exact space-time synchronisation constraints, modelled for the most restrictive two-echelon distribution system (type T1, where feeder vehicles only visit a single transfer location and do not visit any customers), able to be extended to address the other three types of systems. We then focused our analysis on the study of T3 type systems (where the feeder vehicle is able to visit more than one transfer location but can only visit some customers), and performed an in-depth analysis of the impacts of adding valid inequalities, and a solution method based on a warm-start procedure.

As the exact solution methods cannot solve large real-life instances of the problem, the next step was to develop and test a heuristic solution method able to find satisfactory solutions in a reasonable computational time (Chapter 6). Furthermore, as multiple types of city freighters can be used to perform last mile deliveries, we developed a solution method for a variant of the problem with a heterogeneous fleet of city freighters. We proposed a hybrid heuristic based on the *variable neighbourhood search* (VNS) guided by a *simulated annealing* (SA) acceptance criteria. The heuristic proved to be flexible, as it can be used to solve problems with various characteristics including, but not limited to, problems with: time windows; exact synchronisation between vehicles at transshipment locations; storage at the satellites (where only precedence and not synchronisation is required); direct deliveries; single-echelon routing (the BAU); open routing (as with the case of the walking porters); heterogeneous vehicles; and multi-trips at the second echelon.

Additionally, to improve the assessment and comparison of alternative urban distribution systems, we proposed a set of auxiliar performance metrics, reflecting the efficiency of the used fleet, the impacts on road and kerbside occupation, and the overall vehicle suitability as established by the decision maker (Section 6.3). These metrics provide a broader assessment of the quality of the solutions, and can be used as alternative objectives in a multiobjective solution framework.

Finally, we propose a DSS concept to plan and evaluate two-echelon distribution systems with exact synchronisation at the satellites, and to compare them with two alternative distribution systems, namely two-echelon systems with storage capabilities at satellites, and the single-tier BAU (Chapter 7). A first prototype of the DSS was developed to illustrate its functionalities.

The main contributions of this dissertation are the following:

- a review of the state-of-practice and a classification of two-echelon distribution systems based on mobile depots, in the context of urban freight transport;
- a review of the literature on two-echelon vehicle routing problems;
- A generic MIP formulation for two-echelon vehicle routing problems with synchronisation constraints and multi-trips at the second echelon, able to represent the 4 previously identified types of two-echelon distribution systems based on mobile depots previously identified;
- a comprehensive study on the impacts of adding valid inequalities to the MIP formulation, and the benefits of solving the problem by using a *warm-up* procedure;
- a heuristic solution method for the two-echelon vehicle routing problem, with a heterogeneous fleet at the second-echelon, time windows, exact space-time synchronisation between vehicles at satellites, direct deliveries and with the possibility of making load transfers at customers - the proposed heuristic is flexible, as it can also be used to solve alternative distribution policies including the BAU (single-echelon distribution systems) and two-echelon systems where transshipment locations have storage capabilities, thus requiring only precedence between urban and city freighters. instead of exact synchronisation;
- a set of auxiliary evaluation metrics aimed to better assess the impacts of different urban freight distribution systems, and assist in the process of decision making;
- a first prototype of a Decision Support System integrating the proposed heuristic solution method, to illustrate how decision makers might evaluate, and compare alternative urban distribution systems, and assess their trade-offs.

8.2 Future research opportunities

A limitation of this study lies in the fact that our results are based solely on the presented synthetic instances. As the heuristic is yet to be tested using real life data, we note that different vehicles' characteristics such as capacity, speed, fixed and variable costs, as well as different city structures and customer distributions can yield different results which must be analysed in their own context.

These limitations are a result of the lack of meaningful and sustained contact with real case studies where two-echelon distribution systems based on mobile depots were used, and a lack of information in the collected literature and reports addressing these types of distribution systems. Furthermore, despite the effort to establish meaningful contacts with some stakeholders, little information could be collected, and some potentially useful contacts did not follow up with our efforts to collect additional information.

We also note that this work has considered only pre-established constant travel times as an underlying assumption. The exact space-time synchronisation between urban and city freighters at satellites requires a strong interdependency between urban and city freighters schedules, and in an environment where travel and service times are dynamic, it may be a challenge to abide to a proposed plan based on constant travel times. In the worst case scenario, given the exact space-time synchronisation between vehicles, missing a single service time could yield all other routes infeasible, due to the interdependence between vehicles schedules.

8.2.1 Future work

The proposed heuristic solution method, and the DSS where it is embedded, can be used by decision makers to design and plan two-echelon urban freight distribution systems, allowing for the comparison between different alternative systems. Therefore, it would be interesting to apply the proposed work to a real-case, and study the impacts of selecting different distribution systems under alternative scenarios.

Aside from the operational side of the problem, there is the need to tackle more strategic problems such as establishing the location and characteristics of the satellites, their procurement areas, demand levels, fleet dimension and characteristics that will allow for these initiatives to be profitable, while accounting for environmental and social dimensions.

An interesting subject is the use of "containers" in urban freight transport. Containerisation has been used in several two-echelon urban freight distribution initiatives, providing better control, and faster transfer of loads between vehicles, by avoiding extra handling costs. The research on more efficient transshipment operations for city centre deliveries using containers is something that could be pursued (Mühlbauer & Fontaine, 2021), and further explored under broader logistic concepts such as that of the Physical Internet (Crainic & Montreuil, 2016).

Given the environmental impacts of urban freight transport, another research venue is to consider the use of electric vehicles used in the context of two-echelon distribution systems, collaboration in last mile distribution, and the use of subcontracted delivery services.

The consideration of constant travel times in a setting where travel times are dynamic is an important issue, particularly because the exact space-time synchronisation requirements between vehicles' schedules are highly dependent on the accuracy of the travel times. In the worst case, missing a single scheduled service may yield the rest of the plan infeasible. Given this, possible research venues entail the development of solution methods that, instead of considering constant travel times, would rather account for time-dependent travel times, stochastic travel times or dynamic two-echelon vehicle routing problems with exact synchronisation at satellites.

Given the multi-objective/multi-criteria aspect of the problem, another research venue is the study and development of multi-objective/multi-criteria frameworks to solve the problems addressed in this work. The proposed auxiliary evaluation metrics could be considered as alternative objectives to be pursued, as could the objectives of other stakeholders.

Another natural development is the continuous improvement of the proposed DSS. This includes improvements in the heuristic solution method as well as in the GUI. The first phase of the improvements of the DSS would be to perform a system requirement analysis next to the users, followed by the development of the required functionalities.

Appendix A

List of publications and communications

During this doctoral thesis, the progress of the work and our main achievements have resulted in the following publications and communications:

Publications

- Oliveira, B., Ramos, A. G., & de Sousa, J. P. (2022). "A heuristic for two-echelon urban distribution systems". Transportation Research Procedia, 62, 533-540. DOI: 10.1016/j.trpro.2022.02.066
- Oliveira, B., Ramos, A. G., & de Sousa, J. P. (2021). "A generic mathematical formulation for two-echelon distribution systems based on mobile depots". Transportation Research Procedia, 52, 99-106. DOI: 10.1016/j.trpro.2021.01.090
- Oliveira, B., Ramos, A. G., & de Sousa, J. P. (2020). "A classification of two-tier distribution systems based on mobile depots". Transportation Research Procedia, 47, 115-122. DOI: 10.1016/j.trpro.2020.03.075

Communications

- Oliveira. B., Ramos. A. G., & de Sousa. J. P. (September 2021). "A heuristic for two-echelon urban distribution systems". In 24th Euro Working Group on Transportation meeting (EWGT2021). Aveiro, Portugal. (Remote presentation)
- Oliveira. B., Ramos. A. G., & de Sousa. J. P. (September 2020). "A generic mathematical formulation for two-echelon distribution systems based on mobile depots". In 23rd Euro Working Group on Transportation meeting (EWGT2020). Paphos, Cyprus. (Remote presentation)

- Oliveira. B., Ramos. A. G., & de Sousa. J. P. (September 2019). "A classification of two-tier distribution systems based on mobile depots". In 22nd Euro Working Group on Transportation meeting (EWGT2019). Barcelona, Spain.
- Oliveira. B., Ramos. A. G., & de Sousa. J. P. (June 2019). "Two-tier distribution systems based on mobile depots used in the context of city logistics". In 3rd Doctoral Congress in Engineering (DCE19), 1st Symposium on transportation Systems and mobility. FEUP, Portugal.
- Ramos. A. G., Oliveira. B., & de Sousa. J. P. (June 2019) "Two-tier systems in the context of Hyperconnected City". In 30th European Conference on Operational Research (EURO2019). Dublin, Ireland.
- Oliveira. B. (May 2019). "City Logistics - An introductory overview of urban freight distribution - Part II". In GITMOB session, FEUP, Portugal.
- Oliveira. B. (April 2019). "City Logistics - An introductory overview of urban freight distribution - Part I". In GITMOB session, FEUP, Portugal.
- Oliveira. B. (March 2019). "Design, planning and evaluation of two-tier distribution systems in the context of city logistics". In project StoSS - Sectorization to Simplify and Solve seminars, ISCAP – Polytechnic of Porto, Portugal.
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