Transshipment Networks for Last-Mile Delivery in Congested Urban Areas

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Abstract

This work develops a systemic approach for enabling transshipment operations in congested urban areas, based on two fundamental city logistics needs: efficient utilization of existing infrastructure and flexibility for logistics operators. Specifically, this research introduces the concept of urban transshipment networks (UTNs), a collection of strategically located urban logistics spaces, for efficient and flexible last-mile delivery operations in congested urban areas. By implementing the UTN framework, logistics operators can select the transshipment locations, vehicle types and operating schedules that best fit specific distribution strategies, and, simultaneously, comply with access restrictions and overcome some of the logistics complexity of dense urban zones. This concept is particularly relevant for retail dynamics observed in large metropolitan areas in the emerging world.

A two-echelon location-routing model formulation is proposed to address the UTN design problem. The formulation combines a mixed-integer programming model with a closed-form routing cost approximation. The model was tested through a consumer goods distribution case study in Latin America. Results suggest that, given proper fleet type and capacity, UTNs can significantly improve delivery process efficiency in highly congested districts.

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In loving memory of Yaya and Joaquín

Daniel E. Merchán
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1 Chapter 1 - Introduction

1.1 Urban Logistics in Emerging Markets

Former Mayor of Denver Wellington Webb once stated: “the 19th century was a century of empires, the 20th century was a century of nation states. The 21st century will be a century of cities”. Urbanization projections seem to support this claim: as of 2012, 52.6% of the world’s population dwelled in urban areas, and by 2030, cities will harbor close to two-thirds of the world’s inhabitants (United Nations, Department of Social and Economic Affairs, 2014). On average, the rate of population living in urban areas grows by 65 million per year. Such growing urbanization phenomenon is particularly complex in emerging economies. In 2012, urban population accounted for 79% of the emerging world’s inhabitants, and it has been projected to reach approximately 85% by 2030 (Blanco & Fransoo, 2013) (Dobbs, et al., 2011). According to projections by McKinsey Global Institute, over the next 20 years only four of the top 25 megacities will be located in the developed world (Dobbs, et al., 2011).

Although several benefits of massive urbanization have been identified such as access to education, services and job markets; numerous ever-pressing challenges arise from the increased demand for housing, goods and services (Gilbert, 1996).

In general, population growth and infrastructure development take place at a significantly different pace in the emerging world. Furthermore, land scarcity and constrained income levels lead towards unbalanced urban developments: the average population density of megacities in the emerging world is rarely observed in developed economies. For instance, Bogota has approximately half of the population of the Metropolitan Area of York, but its average population density is six times greater. Usually, traffic congestion and limited road accessibility appear as the first symptoms of these organic urban expansions (Blanco & Fransoo, 2013).

Large metropolitan regions in the developing world are also characterized by major income disparities. Generally, the median income per capita is significantly lower than the average income per capita and large fractions of the population live below the poverty line. An informal economy is at the core of this urban context, resulting in considerably different consumer acquisition patterns, compared to the high income segments of the population.
Retailers are usually family operated business with limited establishment size and product assortment, and privilege cash-based transactions. Literature refers to this set of retail establishments as the traditional channel or nanostores (Blanco & Fransoo, 2013). In Latin American countries, traditional channel market share for consumer packaged goods ranges from 44 to 96% (Garza, 2011).

The traditional channel requires a different logistics approach that of modern retailing. Delivery volumes are relatively small, information technology capabilities are limited and a daily delivery route could include up to 100 of these small retailers or nanostores. These logistics operations take place in permanently congested areas with limited infrastructure, resulting in inefficient delivery processes for companies and even greater congestion challenges for cities (Blanco & Fransoo, 2013).

Innovative urban logistics solutions are needed to address the unique challenges of logistics operations in emerging markets. This work introduces a potential new approach for delivering freight in dense urban areas that fosters light-freight vehicles, leverages existing infrastructure and minimizes the investments needed from public and private sector. The proposed approach will ultimately reduce the kilometers traveled by large freight vehicles in dense urban areas, leading to less congested, less polluted and safer urban areas, without hurting the operational performance of logistics operators.

1.2 Research Goals and Contributions

This research project aims to help companies design new logistics paradigms to efficiently serve customers in congested urban areas. Specifically, this research:

- Introduces a new urban logistics solution, urban transshipment networks, inspired in existing industry practices and designed particularly for critical urban zones in the developing world.
- Proposes an analytical framework to guide the design of urban transshipment networks and explore its performance in a wide range of operational scenarios
- Illustrates the impact of urban transshipment networks using a real industry case.
The results of this work provide relevant insights to the practitioner’s community and contribute to the research gap of location-routing models applied to real-world urban logistics challenges.

### 1.3 Outline

Subsequent chapters in this document are structured as follows. Chapter 2 presents an overview of existing urban logistics infrastructures to enable multi echelon systems, along with a discussion of its main advantages and disadvantages. Chapter 2 also introduces the concept of urban transshipment networks (UTNs). In Chapter 3, a location routing formulation for the associated network design problem is presented. In Chapter 4, the location-routing model is applied to a consumer goods manufacturer’s operation in the historic center of Bogota. The analysis discusses solution quality, sensitivity and robustness.
Chapter 2 - Transshipment Networks for Last Mile Delivery

2.1 Moving Freight in Congested Urban Areas

Cities require continuous supplies of goods and services to sustain life. Thus, urban freight systems are an essential service to urban population and economy, but also generate significant amounts of congestion, green-house gas emissions and other externalities. The larger the population, the more complex flow of goods will be and, therefore, the greater the challenges to design and manage sustainable urban freight systems. But mobility challenges are not only a function of population size but also of density. São Paulo and Mexico City are often regarded as the largest metropolitan areas in Latin-America, both with population sizes over 20 million inhabitants. However, Bogota, with a population close to 8 million inhabitants and a population density of 18,300 inhabitants per square kilometer, is the most dense city in the region, far more dense than Sao Paulo (7,500 inh/km$^2$) or Mexico City (9,500 inh/km$^2$) (Demographia, 2015). Mobility challenges are as large in the Colombian capital, as in Sao Paulo or the Mexican capital.

Every city has nodes of major economic activity. Often referred as downtown, central business district or city center, these type of districts concentrate large amounts of retail establishments, and consequently, drive major levels of freight flows. As cities expand, other critical areas emerge, either due to commerce intensity (e.g. shopping districts), population concentration (e.g. slums) or due to a major point of interest (e.g. university districts). In this sense, cities become polycentric metropolis, with highly intense movement of people and goods across the city (Figure 2.1).
Figure 2.1 Polycentric view of Mexico City and São Paulo. Both cities have multiple zones of major population density.

Reaching dense zones is both important and difficult for consumer goods manufactures and logistics operators. These zones generally account for significant portions of consumers demand. Yet, road and parking infrastructures tend to be highly congested. City government bodies often enact truck access restrictions to these zones, as a measure geared towards reducing traffic congestion and disruptions.

Nevertheless, the demand for freight trips to urban areas, and, in particular, to dense zones, continues to grow and is getting more complex, due to several factors including:

**Cost of land and zoning regulations**
As both, the cost of land and zoning regulations have pushed industrial facilities to the outskirts, more trips are required to sustain the provision of goods from sub-urban warehouses to the city.

**Limited retail space**
The high cost of land in dense areas also impacts retailers' procurement decisions. As real estate costs increase and spaces become increasingly constrained, retailers will privilege front-of-house space and reduce space for storage to its minimum. From a logistics standpoint, this implies that retailers will need to be replenished more frequently, increasing the flow of freight vehicles into this areas.
Product diversification

As consumption patterns change and diversify, companies expand products offerings that need to be displayed in the store’s limited shelf space. As previously discussed, constrained space at the retail location implies more frequent replenishments. Furthermore, products diversity and packaging formats adds complexity to every delivery operations. For instance, in the cement industry in Latin America, customers have been moving away from the traditional 25 Kg cement bag and now ask for smaller packaging sizes. Then, companies now offer smaller bags (even of 1Kg). This impacts their last mile delivery operation as different bag sizes need to be handled in different ways.

e-Commerce and Omni-channel

The rapid growth of e-commerce, particularly in the developed economies, and the overlap of this sales channel with the physical channels, demand ever increasing amounts of deliveries in different transportation modes to commercial and residential areas. Such interconnected system of intense commerce will continue to draw attention of practitioners and policy makers over the coming years.

2.2 Multi-Echelon Distribution Systems

Multi-echelon distribution systems have emerged as an alternative to serve complex urban zones. Fundamentally, multi-echelon systems imply using: 1) different freight transportation modes along the delivery route, and 2) intermediate logistics platforms or urban logistics spaces to consolidate and transship freight. Such systems allow companies to still leverage economies of scale form larger warehouses and shipments in the outskirts of the city, but also to comply with regulations that aim to reduce the environmental and social footprints of logistics operations in dense urban areas.

In broad terms, urban logistics spaces (ULSs) can be defined as physical areas holding the equipment needed to enable transshipment and/or consolidation of urban freight deliveries. ULS are generally implemented on top of existing infrastructure, such as underground parking lots. In general, these spaces are privately operated but public authorities actively participate in the approval process, provide subsidies and define incentive mechanisms (Dablanc, 2011). Common types of ULSs include urban consolidation centers, nearby
delivery areas (vehicle reception points) and packstations (urban logistics box), each having a different service scale (Figure 2.2) (Boudoin, Morel, & Gardat, 2014). ULSs case studies have been extensively documented in the literature such as in the report compiled by Dablanc (2011).

Figure 2.2 Urban Logistics Spaces.

Source: Janjevic et al. (2013) from Boudoin

ULSs range from large platforms generally located in the outskirts of the city and connected to multimodal transportation hubs, known as urban logistics zones; platforms nearby city centers to enable freight transfer from trucks to light-freight vehicles (LFVs), or urban consolidation centers; urban freight-dedicated spaces at the neighborhood or block level, such as the nearby delivery areas, and solutions at the building level, as packstations or urban logistics boxes (Boudoin et al., 2014). Even though these solutions operate at different scales, the overarching goal is the same: to consolidate freight to reduce part load trips.

This section explores two of these solutions in greater detail, which are particularly relevant for this thesis.

2.2.1 Urban Consolidation Centers

Urban Consolidation Centers (UCCs) have been a popular urban logistics solution, particularly in Western Europe. Motivated by the need to make better use of load capacity
of freight vehicles, UCCs can be described as logistics platforms used to consolidate and transfer freight coming from external locations onto smaller, less-disruptive vehicles adapted for dense city zones (Allen, Browne, & Leonardi, 2012). These platforms have also been referred in the literature as satellites (Crainic, Ricciardi, & Storchi, 2004), micro-consolidation centers (Janjevic et al., 2013), freight distribution centers or urban distribution centers (Allen et al., 2012). In general, no storage and warehousing operations are performed in these platforms.

Multiple examples of UCCs and different implementation formats can be found across Western Europe and Japan. The examples of CityPorto in Padua, CEMD in Lucca, the Motomachi UCC in Yokohama, or the DHL-operated UCC in Bristol represent the “traditional” UCC system, in which a consolidation center and the fleet of LFVs are administered through public-private partnerships (PPPs). Other cases include the Eco-logistics project in Parma, where restrictions were enforced to unauthorized vehicles in the city center. Carriers, however, were given the option to eco-certify their own vehicles or use an authorized third-party logistics service provider. In the Netherlands, Binnenstadtservice, a privately owned logistics service provider offers storage and eco-friendly distribution, and operates in close collaboration with the retail establishments.

2.2.1.1 UCC Assessment

Allen et al. (2012) presented a survey of 114 UCC projects out of which 68 reached the trial/operational phase and only 24 reported results in quantified metrics. In general, within the urban area of scope, UCCs reported vehicle load factors improvements between 15-100%, reduction of freight vehicle kilometers traveled between 60-80%, reduction in greenhouse gas emissions between 25-80%.

Nonetheless, financial limitations are the major drawback of UCCs. Investment costs are extremely high and very few success histories without major government subsidies have been reported (Allen et al., 2012) (Janjevic et al., 2013). Indeed, in most UCC initiative’s, government bodies have played a major financial role, especially to cover the high cost of land in dense areas. For carriers, the additional cost of transshipment and changes in operational procedures does not surpass the financial benefits of consolidation Verlinde et
al. (2012). From an operational perspective, UCCs also limit carrier’s flexibility by establishing specific operational and delivery processes, not always consistent with the carrier’s own distribution strategy. This top-down approach has undermined the interest of carriers and consumer goods manufacturers that generally prefer to closely monitor the last mile operation. Overall, UCCs can be feasible under very specific conditions and given major public subsidies.

2.2.2 Nearby Delivery Areas

Nearby Delivery Areas (NDA) fall within the Vehicle Reception Point category (Figure 2.2). NDA consist of underground or surface parking lots, and on-street spaces for freight consolidation and transshipment, at the neighborhood level. Additional equipment needed includes a small (15-20 m²) cabin for administrative purposes. From a NDA, last-mile deliveries are executed using handling equipment or electric tricycles (Dablanc, 2011). Key differences from UCCs include the fact that NDAs are privately owned networks and operate on a smaller scale (Verlinde et al., 2012).

NDA were first introduced in Bordeaux (espace de livraison de proximité) in 2003 as a public effort and in 2005 the company La Petite Reine¹ became the sole private operator. Over the past years, similar solutions have been implemented in other cities including Paris, Bordeaux, Dijon and Rouen² (Dablanc, 2011).

2.2.2.1 NDA Assessment

NDA advantages, compared to UCCs, include low investments and easiness to replicate. Overall, NDA are most suited for parcel delivery systems and their impacts have been documented with detailed quantifications in terms of emissions reductions and distance traveled (Dablanc, 2011). Limitations of NDA include: 1) limited coverage area (Verlinde et al., 2012), and 2) inflexible last-mile operation for companies since it has outsourced to the NDA operator.

¹ Project site: http://www.lapetitereine.com/fr/index.php
² Project site: http://www.rouen.cci.fr/elp/
2.2.3 Other Relevant Transshipment-Based Solutions

Recently two additional transshipment-based urban logistics solutions have been introduced: TNT's FreightBus in Lyon and Mobile Depot in Brussels. In both cases, goods are bundled in a suburban depot, and large trucks are used to carry the goods and equipment to a vehicle reception point. From there, the company uses LFVs to deliver the goods. Essentially, the large vehicles becomes a mobile warehouse. Vert Chez Vous’ operation in Paris uses a similar approach but combining trucks, barges and electric cargo-bicycles (Janjevic et al., 2013).

2.3 Urban Transshipment Networks for Last Mile Delivery

2.3.1 Adapting Existing Solutions to Different Contexts

The previous section reviewed advantages and limitations of UCCs and NDA. Another limitation not yet discussed refers to transferability: these solutions were developed within specific industry and urban conditions and might not be easily transferred to other contexts. Specifically, significant differences between developed and emerging markets in terms of population density, severe traffic congestion, consumption patterns, fragmentation of retail channels and income disparities, hinder the feasibility of existing urban logistics solutions and adapted/revised solutions are needed. This section discusses some of these challenges in greater detail.

Companies are reluctant to engage in product consolidation initiatives

Product consolidation across carriers is complex, at least in the consumer goods industry, and has been one of the most significant challenges of UCCs. Product consolidation aims to increase the load factor of freight vehicles in urban zones, but reaching the necessary agreements to enable consolidation across companies is not trivial, particularly when competitors are involved.

In emerging markets, this could be even more problematic. In the nanostore channel, companies compete for the highly limited store shelf space and store budget. Indeed, it is common that the driver collects payments from customers and actively engages in marketing
and sales efforts. Therefore, the nature of this channel requires that companies oversee the last-mile operation, diminishing the possibility to engage in consolidation efforts.

*Infrastructure is highly constrained and public attention to freight solutions is scarce*

Most ULS solutions aim to utilize existing infrastructure, such as parking lots, to reduce the allocation of resources needed, particularly given the high cost of land in dense urban zones. Still, allocating some of this infrastructure solely for logistics purposes might not be feasible, given the high demand of parking spaces in these zones and the limited attention to freight from policy makers (Blanco, 2014). On the other hand, if carriers decide to implement their own *micro-warehouse* within the city center, an effective capacity utilization will be difficult to achieve as this space will be underused after normal business hours. In general, last-mile operations in emerging markets begin early in the morning until early evening. Off-hour deliveries are rarely observed in nanostores due to limited business hours or safety concerns.

New solutions could foster shared infrastructure usage, where space is allocated to logistics operations only within the time period of major delivery intensity, specifically in the morning from 9am-12pm and from 2-4 pm (Merchán, Blanco, & Bateman, 2015).

2.3.2 Urban Transshipment Network Concept

This thesis introduces the concept of urban transshipment networks (UTNs), a collection of *urban logistic spaces* to enable freight transfer between large trucks and smaller, light-freight vehicles. Two major types of transshipment spaces are considered:

- **Transhipment centers (TCs)**: off-street, larger spaces (e.g. parking lots);
- **Transhipment points (TPs)**: on-street parking spots and loading/unloading bays

Infrastructure requirements at each transshipment space is minimal. For TCs, only space for vehicles parking and basic weather protection are needed. No storage equipment is required, as products will be kept in the truck until they get transferred to the smaller vehicles. At the end of the day, the truck will return to the distribution center. For TPs, no infrastructure is needed at all.
The term *transshipment centers* is not new in the literature. Indeed, it was used for the early UCC projects (Allen et al., 2012). However, during the 1990s, the term UCC became popular, given the emphasis on consolidation. In this thesis, the term transshipment center will be used to emphasize the core concept of this proposal: transshipping freight from trucks to LFVs.

This work also emphasizes the “network” perspective of this solution. Instead of focusing on one specific infrastructure, this work considers a collection of feasible spaces that carriers could flexibly select, based on evolving business needs and urban conditions.

### 2.3.3 Foreseeable Benefits of Transshipment Networks

As other urban logistics spaces, the main purpose of UTNs is to reduce the number and distance traveled by large trucks, and consequently, reduce the social and environmental footprint of freight operations. However, as opposed to UCCs or ELPs, the public investment needed to enable UTNs is marginal. Companies will need to cover the cost of renting the parking spaces, and, of course, will have to invest in light-freight vehicles. Further analyses are required to determine the most cost-effective vehicle type for each operation. A case study in this regard follows in Chapter 4.

Overall, UTNs provide great flexibility to logistics operators. No unique delivery approach is imposed and companies can choose the locations, vehicle types and operating times that best fit their logistics strategies. Companies still oversee the entire distribution chain and no outsourcing is enforced. In addition, no strong partnerships need to be enforced. UTNs only require simple rental agreements with parking lot operators, which benefits both parties.

Leveraging ubiquitous infrastructure such as parking lots, also increases the robustness of UTNs since location of TCs not need to be permanent. Furthermore, this proposal is easily replicable in other dense or restricted areas within the city.

### 2.3.4 Foreseeable Limitations

In theory, UTNs will provide less benefits compared to UCCs or ELPs, since no freight consolidation is enforced. Further operational and financial analysis are needed to confirm or reject this hypothesis and the subsequent chapters of this thesis will contribute towards
this goal. In addition, two other challenges will need to be addressed. Coordination between drivers might be complex, particularly if only on-street TPs are used. This challenge can be addressed with proper communications and GPS technologies, or by always using more spacious TCs were vehicles can park and wait, if needed. Furthermore, product safety and handling challenges need to be considered. At the TCs, trucks will remain parked and company-controlled surveillance might not always be available. Finally, transshipment operations always increase product handling which adds costs and risks of product damage.

2.3.5 Transshipment Networks Example: Beverage Distribution in Copa Cabana – Rio de Janeiro

The UTN concept has been inspired in several logistics practices observed across industries and cities. This section briefly overviews one of those practices: a new approach for delivering beverages in a popular touristic zone in Brazil.

The Copacabana area is one of the major touristic attractions is Rio de Janeiro. As such, this neighborhood is characterized by high density of stores and food service establishments, as well as intense vehicle and pedestrian traffic. In an effort to alleviate congestion, municipal authorities restricted freight vehicle parking within the area (Fernandes-Ferreira, Marujo, & de Almeida D’Agosto, 2014).

Coca Cola Industrias, a local franchise of The Coca Cola Company, used to deliver in Copacabana using rigid trucks. After the parking ban, the company has devised a new distribution approach (Figure 2.4). A truck will reach the area early in the morning (7 am) and park in one of the few on-street authorized locations. From there, motorcycles will complete the deliveries to stores. On average, a motorcycle will execute five delivery trips per day. The company operates a network of 30 motorcycles to serve 50 routes in the area.
A recent study suggests that, after implementing motorcycle deliveries, CO₂ emissions generated by this operation have reduced by 50% (Fernandes-Ferreira, Marujo, & de Almeida D'Agosto, 2014). This results could help appease initial concerns of non-governmental organizations about the environmental feasibility of this proposal. The company, however, still faces some operational challenges related to driver coordination.
3 Chapter 3 - Analytical Framework for the Urban Transshipment Network Problem

3.1 Overview

This chapter introduces a mathematical formulation for the urban transshipment network (UTN) problem. The model presented in this work was adapted from the two-echelon capacitated location-routing (2E-CLRP) formulation developed by Winkenbach, Kleindorfer, & Spinler (2015). In general terms, this mixed-integer programming model determines the cost-efficient network configuration for last mile delivery by obtaining: 1) the number and location of intermediate depots given a set of candidate locations, and 2) the optimal fleet configuration (size and vehicle types) to serve a specific urban area or district. Moreover, using sensitivity analysis and operational scenarios, this model provides insights into the trade-offs between different network configuration alternatives.

Given the complexity to reach congested urban areas, practitioners and researchers have explored multi-echelon distributions systems, in which: 1) different freight transportation modes are used along the delivery route, and 2) smaller, intermediate logistics spaces are used for freight consolidation and/or transshipment. Such systems allow companies to still leverage economies of scale from larger warehouses and shipments, but also to reduce the environmental, social and traffic impacts of logistics operations in dense urban areas. If properly designed, these systems might also reduce total distribution cost to reach customers in these zones. Therefore, it is critical to explore analytical approaches that guide the design and assessment of multi-echelon networks. The subsequent section explores the recent literature on mathematical models and solution techniques for this class of distribution networks.

3.2 Literature Review

3.2.1 Models for 2-Echelon Distribution Applied to City Logistics

Mathematical models for multi-echelon distributions systems are not recent (Laporte, 1988). However, specific applications to city logistics systems have been only reported over
the past 15 years. In one of the earliest contributions, Taniguchi et al. (1999) explored analytical models using queuing theory and non-linear optimization models to determine the size and location of public logistics terminals, a set multi-company consolidation platforms. Similarly, Crainic et al. (2004) introduced a location-allocation model for distribution of commodities to central business districts through satellites. As explained in Chapter 2, the essential role of public logistics terminals is similar to the role of satellites: at these intermediate depots (IDs), freight is consolidated and transshipped from large trucks to light-freight (and possibly less-polluting) vehicles (LFVs), suitable for congested urban areas.

Subsequent publications have focused on developing models to incorporate operational planning considerations in multi-echelon systems, specifically routing decisions. These new class of NP-hard problems are known as 2E vehicle routing problems (2E-VRP). Gonzalez Feliu, Perboli, Tadei, & Vigo (2008) introduced a flow-based mathematical formulation for the 2E capacitated vehicle routing problem (2E-CVRP), which finds the optimal routing sequence given a set of existing IDs and given a capacitated fleet of vehicles for each distribution echelon. Gonzalez Feliu et al. (2008) also described basic variants of the problem, including time windows, synchronization and pickup-delivery operations. The model was tested using small-sized instances (12 to 50 customers and 2 and 4 IDs).

Subsequently, several solution methods have been developed for larger instances of 2E-VRPs and 2E-CVRPs:

- A method to obtain a general lower-bound by aggregating lower bounds of sub-problems, found through capacity relaxation or shortest distance procedures (Crainic, Mancini, Perboli, & Tadei, 2008);
- math-based heuristics for a partitioned problem (Perboli, Tadei, & Vigo, 2011);
- a family of valid inequalities and branch and cut framework (Perboli, Tadei, & Masoero, 2010);
- a Multi-Star heuristic that combines clustering and local search methods to solve each echelon sequentially (Crainic, Mancini, Perboli, & Tadei, 2010);
an adaptive large neighborhood search heuristic suitable for larger instances up to 200 customers and 10 satellites (Hemmelmayr, Cordeau, & Crainic, 2012).

Furthermore, Crainic, Ricciardi, & Storchi (2009) proposed an extension to the basic 2E-VRP in city logistics applications by introducing a time-dependent vehicle routing formulation, which incorporates scheduling and fleet synchronization decisions. In addition, Crainic, Perboli, Mancini, & Tadei (2010) proposed an experimental approach to assess the impact on the overall routing cost of IDs' availability and location, and customers' spatial distribution. This approach was later extended, beyond cost solely as a function of distance, to incorporate more realistic cost scenarios considering route topology, operational costs and CO2 emissions (Crainic, Mancini, Perboli, & Tadei, 2012).

3.2.2 Location-Routing Models

Fundamentally, a location and routing framework considers simultaneously location (strategic) decisions and tactical-operational plans. Specifically, Location-Routing Problems (LRPs) seek to determine the network configuration, i.e. location of IDs and routing sequences, that minimizes the fixed and operating costs of vehicles and IDs, and satisfies customer demand and systems constraints, which are generally related to vehicle/IDs capacity or service time (Ambrosino & Scutella, 2005). The significant interdependence between strategic and operational decisions motivated the research community to develop an integrated framework, which reduced the risk of sub-optimizing the distribution system by considering location and routing decisions separately, as occurs in 2E-VRPs. However, the computational complexity of the VRP has limited the possibility to consider these decisions simultaneously (Perl & Daskin, 1985).

The literature on LRP is fairly extensive and mostly focused on single-echelon distribution systems. Several surveys in LRP developments have been made available over time including the work by Laporte (1988), Nagy & Salhi (2007), and more recently by Prodhon & Prins (2014), and Drexl & Schneider (2014) and (2015). In one of the earliest surveys, Laporte (1988) also introduced a notation to describe LRPs, based upon levels of interaction. The notation specifies the number of layers considered in the problem, \( \lambda \), and the type of arc connecting the layers: 'R' for a dedicated replenishment arc or 'T' for a tour. The notation
was expanded in Boccia, Crainic, Sforza, & Sterle (2011) using an overline to specify the echelons in which location decision were made. For instance, $2/\overline{T}$ refers to a single echelon system (2 layers) linking depots and customers using tours, in which location decisions for depots are made.

Regarding location-routing applications for systems with more than one distribution echelon, several developments have been proposed over the past years within the context of 2E city logistics systems. These developments will be discussed in detail in the next section. However, the literature on more than 2E systems remains scarce. Ambrosino & Scutella (2005) proposed mathematical programming formulations for the 3E location-routing problem, extending tree-index arc-based and flow-based formulations previously introduced by Perl & Daskin (1985) and Hansen, Hegedahl, Hjortkjaer, & Obel (1994). Also, Gonzalez-Feliu (2012) explored a generic n-echelon LRP, presented a mixed-integer programming formulation based on partitioned sets, and discussed several possible applications, including urban distribution systems.

### 3.2.3 Location-Routing Models in City Logistics

Recently, specific applications of location-routing models to city logistics contexts have been proposed. Boccia et al. (2011) explored location-routing extensions for the 2E city logistics distribution systems described in Crainic et al. (2004). Authors introduced three mixed-integer programming models for this new class of problems, 2E-LRPs, and presented experiments with small instance sets. This work has been extended with metaheuristic solution procedures over the past years. A tabu search heuristic based on an iterative-nested approach has been proposed by Boccia, Crainic, Sforza, & and Sterle (2010) and Crainic, Sforza, & Sterle (2011). Testing instances ranged from small (2 DCs, 3 IDs and 8 customers) to large (5 DCs, 20 IDs and 200 customers). In addition, Contardo, Vera, & Crainic (2012) developed a branch-and-bound procedure for mid-sized instances and an adaptive-large neighbor metaheuristics for larger problems.

However, these contributions on 2E-LRPs within city logistics contexts have not yet included real-world applications. To the best of the author's knowledge, only Winkenbach et al. (2015) have addressed a real industry problem by proposing a mixed-integer linear
programming formulation for capacitated 2E-LRP (2E-CLRP), along with a 2-stage solution heuristic and a closed form approximation for optimal routing cost. The model was applied to a postal service operation in two city-wide case studies. Their results suggest that network design considerations are heavily dependent on specific demand characteristics of the city, such as population density, and on targeted service levels; motivating therefore the need for analytical frameworks adapted to real-world city-logistics decisions. The authors also suggest comparing direct versus multi-echelon networks in specific city segments, to better accommodate differences in demand patterns and urban conditions. This thesis will specifically contribute to this applied research gap.

3.2.4 Continuum Approximation Methods

In general, due to size and complexity, real-world applications of LRPs are computationally infeasible for metaheuristics such as those proposed in Boccia et al. (2010), Crainic et al. (2011), and Contardo et al. (2012). Therefore, different solution approaches are needed, that reduce the complexity of the problem, particularly the routing component, but still provide near-optimal results (Smilowitz & Daganzo, 2007) (Drexl & Schneider, 2015), such as the augmented route length estimation (ARLE) formula proposed by Winkenbach et al. (2015). The ARLE method expands previous analytical approximations introduced by Smilowitz & Daganzo (2007) and Daganzo (2005), to account for heterogeneous vehicle capacity and service time constraints. The ARLE approximation proved to significantly reduce the computational times while maintained the quality of the solution within a 10% of those provided by tabu-search metaheuristics (Winkenbach et al., 2013).

Although approximation methods in distribution systems design have been explored over the past decades, the idea of combining continuum approximations with numerical optimization techniques is recent (Newell, 1973) (Smilowitz & Daganzo, 2007). In particular, continuum approximation methods are ideally suited for planning purposes, when demand forecasts are uncertain and aggregate. Once detailed data is available, operational decisions can be modeled with discrete optimization methods (Smilowitz & Daganzo, 2007). Even though this approach assumes a hierarchical decision making process, in which routing decisions play a subservient role (Winkenbach et al., 2015); it offsets the difficulties in
collecting detailed demand and cost data and solving discrete optimization models for large-scale, strategic planning problems (Smilowitz & Daganzo, 2007).

### 3.2.5 Specific Contributions

Based on existing literature and given the applied nature of the problem considered, this thesis will result in the following specific contributions to multi-echelon location-routing modeling frameworks:

1) Expand the applicability of 2E-LRPs to real world decision-making contexts, by specifically modelling the design of urban transshipment networks (UTNs);
2) Explore the impact of zone-specific demand patterns and urban contexts in designing multi-echelon distribution networks.

### 3.3 A Location Routing Formulation for the UTN Problem

#### 3.3.1 Problem Statement

In general terms, the urban transshipment network (UTN) problem seeks to determine the optimal network configuration (i.e. number, location and capacity of transshipment spaces), fleet composition and routing guidelines to serve critical urban districts. As described in section 2.1, these urban areas exhibit high retail density, constrained infrastructure and, therefore, significant levels of vehicle congestion. Consequently, reaching customers in these zones with trucks is challenging and, often, restricted.

The model assumes that the district can be served using two competing, but non-mutually exclusive network configurations: direct and transshipment networks. In the direct delivery configuration, customers are served directly from a distribution center located in the outskirts of the city. Large freight vehicles or trucks, with homogeneous capacity are used for last-mile delivery. This is the existing network configuration.

In the transshipment or multi-modal network configuration, trucks are used from the distribution center to serve transshipment spaces located in the surroundings of the district (first echelon). Here, freight is deconsolidated and transferred to light-freight (and possibly less-polluting) vehicles, suitable for dense city areas, to reach customers or other
transshipment spaces (additional echelons). These type of vehicles include vans, motorized/non-motorized 2-3 wheelers, and hand carts for pedestrian deliveries. For practical considerations, henceforth only the type of transshipment spaces defined as transshipment centers (TCs) will be considered. The reader is referred to section 2.3 for further details.

Using the notation Laporte (1988) and extended by Boccia et al (2011), the transshipment network configuration can be represented as a $3/R/\bar{T}$ system, in which:

- $\lambda=3$ layers (or 2 echelons) are considered: distribution centers (DC), transshipment centers (TCs), and customers.
- DCs and TCs are connected using type ‘R’ (dedicated) routes; while TCs and customers are connected via type ‘T’ routes (tours).
- Location decisions are only made for TCs. Locations of DCs are fixed.

Similarly, the direct delivery network is represented as a $2/T$ system, in which customers are served directly from DCs with type ‘T’ routes.

### 3.3.2 Model Assumptions

**Demand**

Demand information is assumed to be static and deterministic.

**District type, size and partition**

The UTN problem considers dense urban districts with intense logistics flows. The area size ranges from approximately one to two square kilometers. Additionally, each square-kilometer will be partitioned in equally-sized segments.

**Maximum service time**

The model assumes a maximum daily service time.

**Transshipment centers**

The modeling framework also assumes that locations for transshipment centers are available within the district (generally, but not necessarily, in the periphery). Similarly, at
each location, space available is constrained but sufficient for vehicle parking and transshipment operations.

**Vehicle speed**

Different speed ranges are assumed per vehicle type.

Figure 3.1 provides a schematic representation of the UTN problem.

![Schematic representation of direct and transshipment networks](image)

Figure 3.1 Schematic illustration of direct and transshipment networks, serving a specific urban district

### 3.3.3 Mathematical Formulation

As abovementioned, the 2E-Capacitated Location-Routing Model introduced in this section was inspired by the formulation proposed by Winkenbach et al. (2015) to specifically explore the impact of transshipment networks to serve critical city districts, given their unique demand patterns and urban conditions. Differences in the proposed formulation arise mostly from problem settings specific to the UTN case.

Tables 3.1 – 3.5 summarize the notation used for model components, parameters and model variables.
Table 3.1 Objective function components

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>Total delivery cost per day</td>
</tr>
<tr>
<td>$K^F$</td>
<td>Facilities fixed cost per day</td>
</tr>
<tr>
<td>$K^U$</td>
<td>First echelon (1E) transportation cost per day</td>
</tr>
<tr>
<td>$K^V$</td>
<td>Second echelon (2E) transportation cost per day</td>
</tr>
<tr>
<td>$K^G$</td>
<td>Capacity utilization cost per day</td>
</tr>
</tbody>
</table>

Table 3.2 General model parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_s$</td>
<td>Customer density in city segment $s$</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Average customer demand in segment $s$</td>
</tr>
<tr>
<td>$w$</td>
<td>Wage per hour</td>
</tr>
<tr>
<td>$c_i^F$</td>
<td>Fixed cost of enabling a TC at location $i$ per day</td>
</tr>
</tbody>
</table>

Table 3.3 First echelon parameters and endogenous variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{i,s}^O$</td>
<td>$L_1$ or $L_2$ norm distance from DC to TC at location $i$</td>
</tr>
<tr>
<td>$\sigma^O$</td>
<td>1E line-haul vehicle speed</td>
</tr>
<tr>
<td>$k^O$</td>
<td>Accessibility factor</td>
</tr>
<tr>
<td>$c_{i,s}^O$</td>
<td>1E vehicle operating cost per hour</td>
</tr>
<tr>
<td>$c_{i,s}^F$</td>
<td>1E vehicle fixed cost per day</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of active TCs</td>
</tr>
<tr>
<td>$t_a$</td>
<td>Administrative setup time per trip at DC</td>
</tr>
<tr>
<td>$t_o$</td>
<td>Operational setup time per trip at DC</td>
</tr>
<tr>
<td>$g_{i,s}^U$</td>
<td>Physical 1E vehicle capacity</td>
</tr>
</tbody>
</table>

Table 3.4 Second echelon parameters and endogenous variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{i,s,v}$</td>
<td>$L_1$ norm distance from TC at location $i$ to the centroid of segment $s$</td>
</tr>
<tr>
<td>$\sigma_v$</td>
<td>2E speed (within district) for vehicle type $v$</td>
</tr>
<tr>
<td>$k_v$</td>
<td>2E road circuity factor for vehicle type $v$</td>
</tr>
<tr>
<td>$k$</td>
<td>Tour factor for 2E routing</td>
</tr>
<tr>
<td>$c_v^O$</td>
<td>2E vehicle type $v$ operating cost per hour</td>
</tr>
<tr>
<td>$c_v^F$</td>
<td>2E vehicle type $v$ fixed cost per day</td>
</tr>
<tr>
<td>$f_{i,s,v}$</td>
<td>Average total distribution cost to serve segment $s$ from TC at $i$ using vehicle type $v$</td>
</tr>
<tr>
<td>$m_{i,s,v}$</td>
<td>Average number of 2E tours per vehicle type $v$ starting from TC at location $i$</td>
</tr>
<tr>
<td>$n_{i,s,v}$</td>
<td>Average number of customers served per vehicle type $v$ per tour from TC $i$</td>
</tr>
<tr>
<td>$d_{i,s,v}$</td>
<td>Average number of full-load tours a vehicle type $v$ can complete within the MST</td>
</tr>
<tr>
<td>$\delta_{i,s,v}$</td>
<td>starting from TC located in $i$ to city segment $s$</td>
</tr>
<tr>
<td>$c_v^T$</td>
<td>Capacity of 2E vehicle type $v$ in terms of average number of stores that can be served</td>
</tr>
<tr>
<td>$q_{i,s,v}$</td>
<td>Number of type $v$ vehicles needed to serve segment $s$ from TC at location $i$</td>
</tr>
<tr>
<td>$t_{i,s,v}$</td>
<td>Average time per tour of vehicle type $v$ in segment $s$</td>
</tr>
<tr>
<td>$t_{v}^O$</td>
<td>Average operational setup time per tour using vehicle type $v$</td>
</tr>
<tr>
<td>$t_{v}^S$</td>
<td>Average service time at each customer using vehicle type $v$</td>
</tr>
<tr>
<td>$t_{v}^P$</td>
<td>Average time to park vehicle type $v$ at each customer location</td>
</tr>
</tbody>
</table>
Table 3.5 Physical capacity parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q^V_p$</td>
<td>Space requirement for 2E vehicle type $v$ at a TC</td>
</tr>
<tr>
<td>$q^U_p$</td>
<td>Space requirement for 1E vehicle at a TC</td>
</tr>
<tr>
<td>$c^E_i$</td>
<td>Cost of unit of space at TC located in $i$</td>
</tr>
<tr>
<td>$e_i$</td>
<td>Physical space capacity at TC located in $i$</td>
</tr>
</tbody>
</table>

Note that accessibility factor $k^o$ and road circuity factor $k'_v$ are scalar multiplier that adjust city-level ($L_1$ or $L_2$) and district-level ($L_1$) distance estimations respectively, to account for road network features that impact travel directness. These features include road density, urban form and regulations, and need to be captured for each case, at city and district levels (Merchain, et al. 2015). The specific values for $k^o$ and $k'_v$ to be used in this case study will be obtained in Chapter 4. In addition, the parameter $k$ is another dimensionless, norm-specific multiplier used to estimate tour distances for the vehicle routing problem (VRP). Daganzo (2005) suggests $k \approx 1.15$ if the number of stores is significantly larger that the number of tours needed to serve the area, as it is assumed to be the case of most UTN problems.

Two sets of decision binary variables are defined:

$$X_i \begin{cases} 1 & \text{if location } i \text{ accommodates a TC} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{i,s,v} \begin{cases} 1 & \text{if TC located in } i \text{ serves city segment } s \text{ using vehicle type } v \\ 0 & \text{otherwise} \end{cases}$$

The objective function accounts for the total daily distribution cost and includes the following components: the fixed cost of enabling a TC (3.1); the transportation cost between the distribution and TGCs, or 1E distribution cost, (3.2); the transportation cost between the transshipment centers and the customers in each zone, or 2E distribution cost (3.4), and the cost of physical capacity utilization at each TC location (3.11).

$$K^F = \sum_i c^F_i X_i$$  \hspace{1cm} (3.1)

$$K^U = \sum_i X_i \left[ 2 \frac{k^o p^o}{\sigma^o} (w + c^{0,U}) \right] + (N) tw + N t^w + (N)c^{F,U}$$  \hspace{1cm} (3.2)

$$N = \sum_i X_i$$  \hspace{1cm} (3.3)

$$K^V = \sum_i \sum_s \sum_v Y_{i,s,v} f_{i,s,v}$$  \hspace{1cm} (3.4)
\[
f_{i,s,v} = q_{i,s,v} m_{i,s,v} t^1_{v} w + q_{i,s,v} m_{i,s,v} n_{i,s,v} t^6_{v} w + q_{i,s,v} m_{i,s,v} n_{i,s,v} t^p_{v} (w + c^o_v) + q_{i,s,v} m_{i,s,v} \left[ 2 \frac{k^L_v r_{i,s}}{s_v} \left( w + c^0_v \right) \right] + q_{i,s,v} m_{i,s,v} \left[ n_{i,s,v} \left( \frac{k^U_v k^L_v}{s_v \sqrt{\gamma_s}} \right) \left( w + c^0_v \right) \right] + q_{i,s,v} c^f_v \] (3.5)

\[
t^R_{s,v} = \xi^V \left( \frac{k^L_v}{s_v \sqrt{Y_s}} + \xi_{s,v} + t^p_v \right) \] (3.6)

\[
\delta_{i,s,v} = \frac{\tau}{t^R_{s,v} + t^U_{v} + 2 k^U_v r_{i,s}} \] (3.7)

\[
n_{i,s,v} = \xi^V \min \left[ 1, \delta_{i,s,v} \right] \] (3.8)

\[
m_{i,s,v} = \max \left[ 1, \delta_{i,s,v} \right] \] (3.9)

\[
q_{i,s,v} = \frac{y_s}{\xi^V \delta_{i,s,v}} \] (3.10)

\[
K^G = \sum_i c^f_i \left[ \left[ \sum_s Y_{i,s,v} (q_{i,s,v} \varphi^V) \right] + \varphi^V \right] \] (3.11)

Equations 3.5-3.10 represent the Augmented Route Cost Estimation (ARCE) method proposed by Winkenbach et al. (2015), which extends previous contributions by (Daganzo, 2005) and (Smilowitz & Daganzo, 2007). By obtaining \( t^R_{s,v} \), the average tour time needed to serve a segment \( s \) using a specific vehicle type \( v \) (3.6), the method calculates \( \delta_{i,s,v} \), the number of full-load tours a vehicle departing from TC at \( i \) can complete within the maximum service time (MST) (3.7). It is then possible to obtain the average number of customer served per tour \( n_{i,s,v} \) (3.8), the average number of tours needed \( m_{i,s,v} \) (3.9), and the average number of vehicles needed \( q_{i,s,v} \) (3.10) given vehicle capacity constraints, for vehicle type \( v \) serving segment \( s \) from TC at \( i \). Finally, the average total distribution cost to serve segment \( s \) from TC at \( i \) using vehicle type \( v \), \( f_{i,s,v} \), is obtained (3.5).

Then, the mixed-integer linear programming model can be formulated as follows:

\[
\text{Min } K = K^F + K^U + K^V + K^G
\]

Subject to

\[
\sum_i \sum_v Y_{i,s,v} = 1 \quad \forall \ s \] (3.12)

\[
\sum_v Y_{i,s,v} \leq X_i \quad \forall i, s \] (3.13)
\[ Y_{0,s,v} = 0 \quad \forall s, \forall v \neq 1 \] (3.14)

\[ Y_{i,s,1} = 0 \quad \forall i \neq 0, \forall s \] (3.15)

\[ \sum_s \sum_v Y_{i,s,v} q_{i,s,v} \varphi_v^v \leq (\epsilon_i - \varphi_v^v) X_i \quad \forall i \] (3.16)

\[ \sum_i X_i \geq \alpha \] (3.17)

\[ Y_{i,s,v}, X_i \in \{0,1\} \] (3.18)

Constraints (3.12) ensure that all segments are served and constraints (3.13) restrict allocation of segments and vehicles only to active TCs. A fictional TC located at the DC, location \( i = 0 \), is used to model the direct delivery network. Therefore, only trucks are available at this location (3.14) and are not available at all other TCs candidate locations (3.15). Constraint (3.16) restricts the space usage in every TC and constraint (3.17) determines a lower bound on the number of active TCs, if needed.
Chapter 4 – UTNs: A case study in the historic center of Bogota, Colombia

This chapter presents a case study of the urban transshipment networks (UTN) problem for a confectionary manufacturer. In particular, using the mixed-integer linear programming formulation described in Chapter 3, this section explores the feasibility to serve Bogota’s historic downtown through a network of transshipment centers.

4.1 City Overview

Bogota, the capital of Colombia and one of the most populated cities in Latin America, is the nation’s nerve center for political, economic, academic, cultural and touristic activities. As of December 2015, Bogota had an approximate population of 8.9 million inhabitants and a population density close to 18,300 residents per km², being the most dense city in the Americas (Demographia, 2015). The population of Bogota’s greater metropolitan area, which includes 11 additional municipalities, is approximately 12 million people (SDP Bogota).

4.2 Company Overview

The company selected for this study is among the largest consumer packaged goods (CPG) companies in Colombia and the second largest in the confectionary industry with close to 25% of the market share. The company reaches markets in more than 70 countries with a product portfolio of roughly 2440 SKUs. Sweets, chocolate, biscuits and tuna correspond to 95% of the company’s sales (Mejía, Agudelo, & Hidalgo, 2015).

The company’s revenue for 2013 was close to USD $500 million. The domestic business operations represent 60% of the total revenue and Bogota accounts for 30% of the company’s sales volume in the country (Mejía et al., 2015).

4.2.1 Strategic Importance of the Nanostore Channel

In Colombia, close to 55% of consumer packaged goods are purchased through the nanostore or traditional channel (Garza, 2011). For the company, this channel accounts for 70% of its total sales. The company serves approximately 42,000 nanostores in Bogota and 135,000
nationwide, which represents approximately 85% of its customer base. In this channel, 36 out of 2440 SKUs generate 50% of the revenue.

Given its relevance and unique characteristics, the nanostore channel requires specific distribution strategies, different from those used in modern retailers. For instance, as previously explained, all consumer goods companies compete to capture as much market share and as much of storeowner's cash as possible. Consequently, offering high-quality last-mile delivery services happens to be as important as product quality or operational efficiency. In addition, even though the company has a dedicated sales team, the delivery crew plays a key role in the sales, marketing and customer loyalty efforts as they frequently interact with store owners and help to build a close business relationship.

4.2.2 Last-Mile Delivery Operation Overview

The company has devised a specific distribution strategy to serve the nanostores channel. Few years back, the company would serve this channel using an on-board sales model: the driver will visit the store and capture, prepare and deliver the order in-situ. Extended store service times and low delivery efficiency and effectiveness levels, motivated a new approach, using a pre-sales format. Nowadays, orders are collected by a specialized sales team, prepared in the distribution center and delivered to customers within a 48-hours timeframe. Even though the new approach required additional resources for sales activities, the benefits in terms of delivery efficiency have offset these extra costs: the average number of stores visited per delivery route per day jumped from 30 to 100 (Mejía et al., 2015). Key facts about the operation are summarized in Table 4.1.
### Table 4.1 Last-mile operation - key facts

<table>
<thead>
<tr>
<th>Sales format</th>
<th>Pre-sales. Orders captured via salesperson visit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order-to-cash cycle</td>
<td>48 hours</td>
</tr>
<tr>
<td>Drop size (USD $)</td>
<td>Average: $12.5; Range: $7-$25</td>
</tr>
<tr>
<td>Drop size (Kg)</td>
<td>8</td>
</tr>
<tr>
<td>Avg. daily orders city-wide</td>
<td>6,500</td>
</tr>
<tr>
<td>Stores served per week</td>
<td>~42,000</td>
</tr>
<tr>
<td>Daily value of product per truck</td>
<td>$1,250</td>
</tr>
<tr>
<td>Delivery frequency</td>
<td>20% of customers weekly – 80% of customers twice a week</td>
</tr>
<tr>
<td>Stores per delivery route</td>
<td>Between 90 and 110 per day per truck</td>
</tr>
<tr>
<td>Stores delivery time</td>
<td>4 – 7 min</td>
</tr>
<tr>
<td>Key technologies</td>
<td>Handhelds, SAP®, WSM &amp; GIS</td>
</tr>
<tr>
<td>Delivery crew</td>
<td>One driver and one helper</td>
</tr>
<tr>
<td>Outsourcing</td>
<td>Transportation outsourced to 3PLs</td>
</tr>
<tr>
<td>Fleet size</td>
<td>73 trucks</td>
</tr>
<tr>
<td>Warehouse operation</td>
<td>Two shifts: 1) order picking &amp; 2) order preparation</td>
</tr>
</tbody>
</table>

#### 4.2.3 Territory Design

To serve the nanostore channel, the company has divided the city in 109 sales zones corresponding to one of the four large territories or macro-zones. Each sales zone encompasses between 385-390 nanostores. All customers are visited twice a week, except those in macro-zone 4, approximately 7,200 stores, which are visited only once per week.
4.3 Zone of Scope

Per request of the company, this study will focus on the historic center of Bogota, zone known as *La Candelaria* (within macro-zone 4), given its major commercial density and highly congested road-network. Over the past few years, the local administration has increased effort to make parts of this zone more pedestrian-friendly and has prioritized public transportation and bicycles. *La Candelaria* has a population of approximately 27,500 inhabitants in an area of 1.8 square kilometers, (population density of 15,277 inh/km²). Furthermore, nearly 300,000 people commute to this zone for work or studies every day (SDP Bogota).

Specifically, the study will explore the feasibility of urban transshipment networks in two districts, each of approximately one square-kilometer area (Figure 4.2):

- **District 1 (La Candelaria):** covers portions the neighborhoods *Centro Administrativo, La Catedral, Santa Inés* and *La Capuchina*.
- **District 2 (San Victorino):** covers portions of the neighborhoods *San Victorino* and *Voto Nacional*.
The area is bounded by Carrera 16 (north), Calle 7 and Av. de los Comuneros (south), Carrera 4 (east) and Carrera 21 (west). Districts are divided by Av. Caracas. Similar road-network, traffic and density conditions in both districts will be assumed.

![Figure 4.2 Visualization of the commerce-intense districts selected in Downtown Bogota](source: Google Maps™)

From a logistics standpoint, the importance of the nanostore channel implies an intensive distribution of goods to tens of thousands stores all over the city. However, this has become increasingly complex in severely congested areas as La Candelaria and San Victorino (Figure 4.3).
A brief analysis of the companies’ distribution schedule reveals that they operate every day in the zone (Figure 4.4).
4.4 Model Parameters and Implementation

This section describes how model parameters were estimated for this specific case-study.

4.4.1 Transshipment Location, Distances and Speed.

The density of parking lots in La Candelaria is high. In general, a public parking lot that could potentially host a transshipment center can be found every 2-3 blocks. Therefore, the model can assume that one transshipment location will be available at each corner of the districts.

The real distance from the distribution center to the districts will be used, i.e. *r*₁° = 30 km. For this line-haul distance, the estimated vehicle speed is *a*° = 35 km/h (MIT Megacity Logistics Lab, 2015). The value for each *r*_i,s, is obtained using the *L*_1 distance between the assumed transshipment locations and the centroid of every district segment. The estimated speeds values for every vehicle types within the district are summarized in Table 4. Notice that traffic congestion, road network and regulations impact different vehicles in different ways (MIT Megacity Logistics Lab, 2015).
Table 4.2 District level speed for different vehicle types

<table>
<thead>
<tr>
<th>$\sigma_v$ (km/h)</th>
<th>Trucks</th>
<th>Vans</th>
<th>Bicycles</th>
<th>Handcart</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>5.5</td>
</tr>
</tbody>
</table>

4.4.1 Accessibility, Road Circuity and Tour factors

*Accessibility Factor*
For this case-study $k^0=1$ since the real distance between the distribution center and the districts will be used.

*Road Circuity Factor*
Using the method described in Merchán et al. (2015), the road circuity factor per vehicle type, $k'_v$, can be obtained (Table 4.3).

Table 4.3 Road circuity factors for different vehicle types

<table>
<thead>
<tr>
<th>$k'_v$</th>
<th>Trucks</th>
<th>Vans</th>
<th>Bicycles</th>
<th>Handcart</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.83</td>
<td>1.83</td>
<td>1.45</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Overall, the large values of $k'_v$ for trucks and vans captures the complexity of driving through this zone.

*Tour factor*
As explained in Chapter 3, $k \approx 1.15$ since the number of stores is significantly larger that the number of tours needed to serve the area (Daganzo, 2005).

4.4.2 Store Density

The company has approximately 300 customers spread across the two districts observed (Figure 4.4). District 1 encompasses 160 stores, while district 2 contains 140 customers. This number is consistent with the estimate of 100-200 nanostores per 100 inhabitants in the emerging world suggested by Blanco & Fransoo (2013). Only district 1 will be considered initially. The district will be divided in 4 segments, each with the same store density, ie. $\gamma_s = 40$. 

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4.4.3 Fixed and Operational Costs

Vehicle fixed and operating cost

Based on internal company records and industry benchmarks, the following approximate cost breakdown for the daily transportation cost will be used to allocate the fixed and operating cost of different vehicle alternatives.

Table 4.4 Percentage breakdown of daily distribution cost

<table>
<thead>
<tr>
<th></th>
<th>Trucks</th>
<th>Vans</th>
<th>Bicycles</th>
<th>Handcart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver (and helper) wage</td>
<td>60 %</td>
<td>60 %</td>
<td>90 %</td>
<td>100 %</td>
</tr>
<tr>
<td>Other fixed cost (investment, insurance &amp; surveillance)</td>
<td>20 %</td>
<td>20 %</td>
<td>5 %</td>
<td>-</td>
</tr>
<tr>
<td>Variable costs (fuel, maintenance and tires)</td>
<td>20 %</td>
<td>20 %</td>
<td>5 %</td>
<td>-</td>
</tr>
</tbody>
</table>

Even though the cost breakdown is similar, vans have a lower daily distribution cost given the reduced capital investment required and the assumption that no helper is needed in this kind of vehicles. The specific values obtained for \( c_{o,u} \), \( w \), \( c_{f,u} \), \( c_{o,v} \) and \( c_{f,v} \) cannot be disclosed due to confidentiality requirements.

Transshipment centers fixed and operational costs

The case-study assumes no cost to enable a transshipment center at each location as no infrastructure or equipment investment will be needed \( c_f = 0 \). The daily cost of a square-meter at each TC is obtained based upon local rates for vehicle parking, \( c_f = 0.5/m^2/day \).

4.4.4 Operational Parameters

Demand

Daily store demand has been assumed to be deterministic and static with an average value of \( \gamma_s = 8 \text{ kg} \).

Maximum service time

A daily maximum service time of 8 hours has been assumed, which is consistent with the daily working hours of the distribution crew.
**Operational and administrative setup**

For trucks, an operational setup time $\tau = t_1^t = 0.5$ hours, which also includes any time due to administrative setup $t^a$. The operational setup for 2E vehicles, in hours, is $t_2^t = 0.5$ for vans, $t_3^t = 0.33$ for bikes and $t_4^t = 0.1$ for handcarts. Finally, the store service time for all vehicle types is $t^s = 0.083$ (ie. 5 min). Vehicle parking time will not be considered in this case due to limited data available to generate a precise estimation of $t^p$.

**4.4.5 Vehicle and Transshipment Center Capacity**

Vehicle capacities have been estimated using vehicle specifications from the company as well as industry standards. Using the vehicles' physical capacity and the average demand per store, the average capacity of stores served per vehicle type are: $\xi_1^v = 100$ for trucks; $\xi_2^v = 50$ for vans, $\xi_3^v = 10$ for bikes and $\xi_4^v = 5$ for handcarts. Similarly, using industry specifications, the space in m² needed for each vehicle type at the TCs is $\varphi_1^v = 10$ for trucks; $\varphi_2^v = 8$ for vans, $\varphi_3^v = 2.5$ for bikes and $\varphi_4^v = 1$ for handcarts. Finally, the space available at each TC is $\varepsilon = 32$ m², equivalent to four regular parking spaces.

**4.4.6 Model Implementation and Validation**

The 2-Echelon Capacitated Location Routing formulation for the UTN problem was implemented in PYTHON 2.7 and solved using GUROBI 5.6 x64 on an Intel @ Core ™ i7-3540 M CPU @ 3.0 GHz and 8.0 GB of physical memory running a 64-bit operating system.

**4.5 Model Results and Discussion**

**4.5.1 Baseline Scenario**

Results for a baseline scenario considering only district 1 suggest daily distribution cost reductions between 20% and 45%, depending on the vehicle type used (Figure 4.5). Given its capacity and low fixed costs, bicycles represent the most cost-effective option.
A fleet size of approximately three bicycles should suffice to serve the area. Recall that the model assumes one person per vehicle type, except for trucks were two people per vehicle are needed. Distribution using handcarts is more costly since at least one extra person will be required (Table 4.5).

Table 4.5 Results per fleet type

<table>
<thead>
<tr>
<th>Fleet Type</th>
<th>Cost Reduction (%)</th>
<th>TCs active</th>
<th>Fleet size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trucks</td>
<td>-</td>
<td>0</td>
<td>2.1</td>
</tr>
<tr>
<td>Bicycles</td>
<td>42.5</td>
<td>1</td>
<td>2.9</td>
</tr>
<tr>
<td>Vans</td>
<td>25.7</td>
<td>1</td>
<td>2.3</td>
</tr>
<tr>
<td>Handcart</td>
<td>22.3</td>
<td>1</td>
<td>4.2</td>
</tr>
</tbody>
</table>

The optimal configuration suggests serving all four segments within the district using a fleet of three bicycles and operating only one transshipment center (Figure 4.6). Furthermore, given the large number potential transshipment center locations available in the zone, the exact location of the transshipment center has minor impact on the solution.
4.5.2 Store Density

Results suggest that trucks are feasible in zones with less than 50 stores per km² (Figure 4.7), reinforcing the idea to use different vehicle types based on density and congestion patterns.
As previously explained, the company's density of customers in Bogota does not exceed 200 stores per square-kilometer. However, by exploring different store density scenarios, the model can indirectly provide insights on the impact of demand variability on the results. Other approaches could have been used to capture the relevant effect of demand variability on the results, unfortunately, very limited demand information was available for this study.

As store density increases, results suggest either combining different vehicle types within the zone, or adding more transshipment centers. For this basic scenario, if stores’ density would reach a value of 500 stores, pedestrian deliveries should be used for the segment closer to the transshipment center, while bicycles should still be used to serve the remaining three segments. However, for larger density values, it is optimal to add another TC (Figure 4.8). The number of vehicles needed per vehicle type increases linearly with respect to store density (Figure 4.9)
4.5.3 Transshipment Center Capacity

Urban transshipment networks are designed on top of existing parking infrastructure. Parking lots are highly available across the districts, but space is constrained in each one of them. So far the model has assumed that approximately four parking spaces (approximately 32 m²) will be available at each candidate TC (parking lot). This section explores the sensitivity of the model to space availability in each TC.
If parking space at each TC is constrained (i.e. only 2 spaces available), results suggest combining bicycle with pedestrian deliveries for store densities between approximately 50 per km² to 200 per km² (Figure 4.10), or adding a second TC (Figure 4.11) for larger density values. If more space is available, the operation will require only one TC and will use pedestrian deliveries only for density values greater than 300.

Figure 4.10 Fleet selection for 2 parking spaces available at each TC (top left), for 3 parking spaces (top right) and for 5 parking spaces (bottom).
4.5.4 Bicycle Capacity

The basic scenario assumes that a bicycle can serve, on average, ten stores. Since the average drop size range is 7-8 Kg, and assuming a cargo capacity of 100 Kg per bicycle, this implies that bikes will run, on average, at 70-80% of their capacity. However, industry specifications suggest that a cargo bikes could carry up to 180 kilos (2-wheelers) and 250 (3-wheelers) (De Decker). Therefore, it is important to explore the sensitivity of bicycle load capacity, to explore the robustness of the solution in cases of increased demand, as well as to gain insights on the appropriate design specifications of the vehicles.

The results suggest that bicycles with capacity to serve six stores or less should not be considered (Figure 4.12). Furthermore, if the capacity is at least eight stores, bicycles are still the predominant mode of transportation and, depending upon the store density or demand conditions, will need to be supplemented with pedestrian or van deliveries. The fleet size required is never greater than eight bicycles (Figure 4.13).
Figure 4.12 Optimal fleet type for different bicycle capacity scenarios: 5 stores (top left), 8 stores (top right), 10 stores (bottom left) and 15 stores (bottom right)
Figure 4.13 Optimal fleet size for different bicycle capacity scenarios: 5 stores (top left), 8 stores (top right), 10 stores (bottom left) and 15 stores (bottom right)

4.5.5 Sensitivity of Key Financial Parameters

One of the major drivers for the prevalence of bicycles as the most cost-effective transportation mode is the corresponding low fixed cost. The current daily fixed cost for bikes is $1.3. Data suggest that up to a threefold increase, the optimal transportation mode remains unchanged (Figure 4.14). Such a wide range denotes the robustness of the solution and opens the possibility to consider other similar vehicle types such as motorized or electric 2/3 wheelers.
On the other hand, the fixed cost has also a major impact on the optimality of trucks. In particular, the fact that trucks need a two-people crew increases significantly the fixed vehicle cost of this mode. Assuming that trucks can operate with only one person, which reduces the fixed cost in approximately 60%, trucks become the most convenient solution for a wider range of districts with up to 130 stores per km² (Figure 4.15).

Figure 4.14 Fixed Cost Sensitivity - Bicycles

Figure 4.15 Optimal fleet selection given a 1-person crew
Finally, so far the model has assumed that the fixed cost of activating a TC in a parking lot is negligible and the company only incurs in variable cost of utilizing the space. This assumption arises mainly from the fact that no specialized logistics infrastructure is needed to enable them. Still, the optimality threshold for this daily fixed cost is approximately $50.

4.5.6 Distribution Density

The initial scenario assumed an even concentration of stores across the four segments. This assumption is now relaxed and three additional scenarios are considered, including (*) which closely resembles the real context of the company. In all scenarios, bicycle distribution remains as the optimal fleet type and the total cost variation remains less than 5% (Table 4.6). The number of active TCs remains the same, but the location varies based on the density concentration per segment.

Table 4.6 Daily distribution cost variation for different store concentration scenarios

<table>
<thead>
<tr>
<th>( \gamma_1/\gamma_2/\gamma_3/\gamma_4 )</th>
<th>Optimal Daily Distribution Cost</th>
<th>Cost Variation to Baseline (%)</th>
<th>TCs active</th>
</tr>
</thead>
<tbody>
<tr>
<td>40/40/40/40 (Baseline)</td>
<td>319</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>100/20/20/20</td>
<td>311</td>
<td>-3%</td>
<td>1</td>
</tr>
<tr>
<td>10/10/10/130</td>
<td>305</td>
<td>-4%</td>
<td>1</td>
</tr>
<tr>
<td>60/60/20/20 *</td>
<td>315</td>
<td>-1%</td>
<td>1</td>
</tr>
</tbody>
</table>

† Distribution costs have been masked for confidentiality considerations.

4.5.1 Extending Coverage to a Second District

The analysis considers now the case in which the coverage area extend to a second district. Two specific cases are explored: a) each district is divided in four segments, and b) the entire area is divided in four segments (Figure 4.16).
In all cases, the variability compared to the first scenario, in which the concentration of stores is evenly distributed, is less than 3% (Table 4.7). The number of TCs is still one and bicycles are still the most cost-efficient transportation mode. Overall, this result suggests that both, the district segmentation approach and the stores concentration do impact the overall network design.

Table 4.7 Daily distribution cost variation for different store concentration and two area segmentation approaches: (a) eight segments, (b) four segments.

<table>
<thead>
<tr>
<th>( \gamma_1/\ldots/\gamma_5 )</th>
<th>Optimal Daily Distribution Cost(^\dagger)</th>
<th>Cost Variation to Baseline (%)</th>
<th>TCs active</th>
</tr>
</thead>
<tbody>
<tr>
<td>40/40/40/40/40/30/30</td>
<td>511</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>a</td>
<td>60/60/20/55/20/20/20/20*</td>
<td>517</td>
<td>+1%</td>
</tr>
<tr>
<td></td>
<td>60/20/60/20/20/55/55/55</td>
<td>522</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>80/80/70/70</td>
<td>502</td>
<td>-2%</td>
</tr>
<tr>
<td>b</td>
<td>100/100/50/50</td>
<td>502</td>
<td>-2%</td>
</tr>
<tr>
<td></td>
<td>125/125/25/25</td>
<td>501</td>
<td>-2%</td>
</tr>
</tbody>
</table>

\(^\dagger\) Distribution costs have been masked for confidentiality considerations.

4.5.2 Suggestions for Network Design

Results for the case study are summarized in the following network design criteria:

- Feasible density range for distribution in trucks: <130 stores/km\(^2\)
- Feasible density range for distribution in bikes: >130 stores/km\(^2\)
- Bike capacity: > 10 stores/bike
- Transshipment center capacity: > 4 loading/unloading spaces
4.6 Solution Feasibility

The results strongly suggest to consider bicycles for last-mile delivery in highly congested areas such as La Candelaria. However, is this truly feasible in practice? Some consumer goods companies have started to test this solution in La Candelaria (Figure 4.17).

![Figure 4.17 Bicycle deliveries in La Candelaria.](image)

Source: Google Street View™

To this author’s knowledge, this study represents the first approach to explore the impact of cargo bikes and other modes of transportation for consumer goods deliveries in congested urban areas in the emerging world.

Certainly, the company will have to implement major changes in the way they currently operate, which can certainly be costly. Transitioning to a multi-echelon system implies disrupting a stable process. This is particularly complex given the current agreements with logistics service providers operating in the zone. However, trends in urban development suggest that zones continue becoming more pedestrian friendly in the near future and companies need to start planning how they will serve these important city areas under these new mobility schemes. Overall, the estimated investment needed to purchase the bicycle fleet is approximately between 10-20% of the cost of one truck.
5 Conclusions and Future Work

This thesis introduces a new approach for last-mile delivery in dense urban areas, inspired in the specific urban logistics contexts observed in emerging markets. For companies, urban transshipment networks offer operational efficiency and flexibility, overcoming several of the limitations observed in other urban logistics solutions. For cities, this solution reduces the amount of kilometers travel by large freight vehicles, increases the load factors of freight vehicles in constrained urban environments, stimulates the use of light freight vehicles, leverages existing infrastructure and does not relay on intense public funding.

The location-routing formulation for the UTN problem combined a mixed-integer programming formulation with continuous approximation methods, inspired in the formulation by Winkenbach et al. (2015). This modeling strategy was particularly beneficial to explore a real-world scenario with nearly 300 customers. Specific contributions of the model in this thesis include a set of factors to capture urban context features such as road density, congestion and directionality constraints (one-way streets).

In the case study explored, results suggest that for urban zones with high retail densities, bicycle deliveries are the most cost effective delivery option, mostly because of this vehicle’s low fixed cost. Also, proper capacity levels for vehicles and transshipment centers are important to keep the solution robust and need to be determined on a case-by-case basis. The solution is less sensitive to factors such as the concentration of stores and the location of the transshipment centers.

The research problem presented in this thesis can be extended in multiple ways. First, this model could be scaled to an entire city operation to further explore the impact of different density levels and urban conditions in the network configuration. These results would also inform existing sales territory planning techniques used in most companies. Second, several of the parameters in the model could be refined such as parking, service and loading times per vehicle type. For this study, parameter values used were drawn from previous research and preliminary company estimations, but more precise estimations could improve the quality of the results. Finally, the modeling framework could also incorporate stochastic demand considerations using robust optimization techniques.
6 Bibliography


