Delivery and dispatching in urban transportation systems in Namur-Liege area

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DELIVERY AND DISPATCHING IN URBAN TRANSPORTATION SYSTEMS IN NAMUR-LIEGE AREA

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Chapter 1: Introduction

City Logistics has become a major issue in recent years due to several factors such as e-commerce, urbanization and climate change. Urban transportation systems have to evolve to face actual challenges. Their flexibility and efficiency must be improved. With this in mind, innovative distribution networks are designed and their related models are solved to enhance the overall performance of urban distribution (Crainic, Ricciardi & Storchi, 2004[1] and Merchán & Winkenback, 2018[2]).

In this master's thesis, a new model is studied: the Multi-Echelon Multi-Satellite Multi-Product Capacitated Vehicle Routing Problem with one-day delay allowed. The two following chapters give an overview of the context and of the state of the art. Certain models already discussed in the literature as well as the methods used to solve this category of vehicle routing problems are examined.

The problem studied is detailed in the fourth chapter. An example of an equivalent project is given. The fifth chapter described the development of the local search based metaheuristic. The theoretical concepts on which it has been built are reviewed. The pseudocode is given to illustrate the working of the metaheuristic. In this chapter, the foundations and main principles of the heuristic proposed are set. In addition, a greedy heuristic to construct a lower bound is provided. The sixth chapter concerns the testing phase of the developed method. This has been realized in two steps. First, numerical experiments on randomized small instances have been performed. At this stage, the metaheuristic has been improved in order to provide better solutions in a shorter amount of time. The question of the delay's tolerance is discussed; some conclusions are drawn from tests. Secondly, the metaheuristic is used to solve large instances based on realistic data over the Namur-Liège area. For the two steps, the construction of the instances and the parameters' selection are explained. The performance for each instance's size is assessed.

Subsequently, a note on methodology and project management is stated. Traditionally, this research thesis concludes on a global survey of the work accomplished and on the perspectives of the modern distribution network studied.

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[1] Crainic, T. G., Ricciardi, N., & Storchi, G. (2004). Advanced freight transportation systems for congested urban areas. *Transportation Research Part C: Emerging Technologies*, *12*(2), 119-137.
[2] Merchán, D., & Winkenbach, M. (2018). High-Resolution Last-Mile Network Design. *City Logistics 3: Towards Sustainable and Liveable Cities*, 201-214.

Chapter 2: Urban Transportation Systems

A. Context

These days, cities encounter multiple socioeconomic trends. The world's global population is growing and tends to concentrate in urban areas. In 2018, 55% of the world population lives in cities. By 2050, 68% is forecast to live in urban areas (United Nations, 2018[3] and Nimtrakool, Gonzalez-Feliu & Capo, 2018[4]). Simultaneously, e-commerce is rising and contributes to an increase and a change in demand from customers (Letnik, Mencinger & Bozicnik, 2018[5] and Goodchild et al., 2018[6]). In the world, the Internet is more and more widespread, which enhances the popularity of online shopping (Savelsbergh & Van Woensel, 2016[7] and Visser, Nemoto & Browne, 2014[8]). Hence, many customers want to be delivered at home, at work or wherever they want, preferably in a short time (Goodchild et al., 2018). Growing population, urbanization, e-commerce and home delivery are some challenges of cities which force urban distribution to be more adaptive (Mancini, 2013[9] and Letnik et al., 2018).

Urban freight transport is essential to the development and the prosperity of cities. However, it is known to generate negative impacts on living conditions, such as congestion, pollution, traffic noise and crashes (Nimtrakool et al., 2018). Urban freight transport has to tackle these issues by elaborating more sustainable ways of operating in cities (Antun, Reis & Macario, 2018[10]).

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[3] United Nations. (2018, May 16). 68% of the world population projected to live in urban areas by 2050, says UN. Retrieved from https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

[4] Nimtrakool, K., Gonzalez-Feliu, J., & Capo, C. (2018). Barriers to the adoption of an urban logistics collaboration process: a case study of the Saint-Etienne urban consolidation centre. *City Logistics 2: Modeling and Planning Initiatives*, 313-332.

[5] Letnik, T., Mencinger, M., & Bozicnik, S. (2018). Dynamic Management of Urban Last-Mile Deliveries. *City Logistics 2: Modeling and Planning Initiatives*, 23-37.

[6] Goodchild, A., Ivanov, B., McCormack, E., Moudon, A., Scully, J., Leon, J. M., & Giron Valderrama, G. (2018). Are cities' delivery spaces in the right places? Mapping truck load/unload locations. *City Logistics 2: Modeling and Planning Initiatives*, 351-368.

[7] Savelsbergh, M., & Van Woensel, T. (2016). 50th anniversary invited article—city logistics: Challenges and opportunities. *Transportation Science*, *50*(2), 579-590.

[8] Visser, J., Nemoto, T., & Browne, M. (2014). Home delivery and the impacts on urban freight transport: A review. *Procedia-social and behavioral sciences*, *125*, 15-27.

[9] Mancini, S. (2013). Multi-echelon distribution systems in city logistics.

[10] Antún, J. P., Reis, V., & Macário, R. (2018). Strategies to Improve Urban Freight Logistics in Historical Centers: The Cases of Lisbon and Mexico City. *City Logistics 3: Towards Sustainable and Liveable Cities*, 349-366.

Urban freight transportation often refers to last-mile deliveries. Last-mile distribution is considered as the least efficient, the most polluting and the most expensive part of the supply chain. It represents 13 to 75% of the total cost related to the supply chain (Zhou, Baldacci, Vigo & Wang, 2018[11]). Urban freight vehicles account for a relatively low percentage of vehicles circulating in cities and of kilometres travelled. Nevertheless, urban freight transport has a proportionally high impact in terms of energy use and CO_2 emissions (Simo, Crainic & Bigras, 2018[12] and Dablanc, 2007[13]). Indeed, urban freight vehicles have to stop at each end-client, which is more polluting than driving without stops (Dablanc & Montenon, 2015[14]). Moreover, delivery companies operate in a competitive industry. They tend to reduce their cost to the minimum. This forces some companies, especially SMEs to extend the lifetime of their fleet and to place older vehicles in urban areas. Some of them do not dispose of a terminal located close to city centres, which means that the rounds start far from the city (Dablanc, 2007). Additionally, a considerable part of the vehicle journey is covered with an empty or half-empty load. Urban freight transportation is responsible for over 20% of traffic congestion in cities. It is explained by multiple factors. Cities tend to be difficult to access because of narrow streets and inefficient area devoted to deliveries (Letnik, 2018). There are few parking spots available which constrain deliverers to double park or to travel additional kilometres in order to find an alternative spot (Anderluh, Hemmelmayr & Nolz, 2017[15]). As a result of all these issues, delivery companies need to adapt their operations in cities. This includes a better cooperation between the different organizations, a more efficient coordination of the flows of goods, especially a higher consolidation of the loads (Aljohani & Thompson, 2018[16])

In the academic as well as in the politic sphere, solutions have been proposed to tackle these problems. Researchers have created the concept of "City Logistics" through which they

[11] Zhou, L., Baldacci, R., Vigo, D., & Wang, X. (2018). A multi-depot two-echelon vehicle routing problem with delivery options arising in the last mile distribution. *European Journal of Operational Research*, *265*(2), 765-778.
[12] Simo, M., Crainic, T. G., & Bigras, Y. (2018). Simulation of a City Logistics Solution for Montreal. *City Logistics 3: Towards Sustainable and Liveable Cities*, 47-63.
[13] Dablanc, L. (2007). Goods transport in large European cities: Difficult to organize, difficult to modernize. *Transportation Research Part A: Policy and Practice*, *41*(3), 280-285.
[14] Dablanc, L., & Montenon, A. (2015). Impacts of environmental access restrictions on freight delivery activities: Example of low emissions zones in europe. *Transportation Research Record*, *2478*(1), 12-18.
[15] Anderluh, A., Hemmelmayr, V. C., & Nolz, P. C. (2017). Synchronizing vans and cargo bikes in a city distribution network. *Central European Journal of Operations Research*, *25*(2), 345-376.
[16] Aljohani, K., & Thompson, R. G. (2018). Optimizing the Establishment of a Central City Transshipment Facility to Ameliorate Last-Mile Delivery: a Case Study in Melbourne CBD. *City Logistics 3: Towards Sustainable and Liveable Cities*, 23-46.

develop models to improve urban transportation (Taniguchi, 2014[17]). The European Union, the politic authority in the context of this report, implements measures, such as pedestrian zones or zones with access restrictions (Anderluh et al., 2017).

Low Emission Zones in Europe

To reach CO_2 emissions' reduction and air quality requirements, limitations regarding transport are implemented in urban areas (Settey, Gnap & Benova, 2019[18]). On this path, low emission zones, also called LEZs, have been put in place in a few cities across the world. An LEZ is defined as a delimited area that cannot be entered by vehicles exceeding specific emissions standards. The goal is to minimize the amount of pollutants being released into the air (Maes, Sys & Vanelslander, 2011[19]). LEZs' policies can vary from one city to another in regards to the criteria defined. Restrictions can covered many aspects, such as the geographical extent of the policy, the period of time over which it is active, the emissions standard and the type of vehicles allowed. Government bodies apply different approaches regarding the implementation and the control of the limitations (Browne, Allen & Anderson[20], 2005).

Especially in Europe, LEZs target motor freight vehicles because of their significant negative effects on pollution and congestion (Dablanc & Montenon, 2015). The European Union is committed to the achievement of sustainable development. It has set guidelines concerning road vehicles, transport system and mobility. These decisions have created a fertile ground for the development of LEZs (Russo & Comi, 2018[21]and European Commission, 2011[22]). First, LEZs have been implemented in Sweden. Then, Germany, Netherland, northern Italy and London have followed. Today, there are more than 250 LEZs in many different cities in

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[17] Taniguchi, E. (2014). Concepts of city logistics for sustainable and liveable cities. *Procedia-social and behavioral sciences*, *151*, 310-317.
[18] Settey, T., Gnap, J., & Beňová, D. (2019). Examining the impact of the deployment of low emission zones in Europe on the technological readiness of road freight transport. *Transportation Research Procedia*, *40*, 481-488.
[19] Maes, J., Sys, C., & Vanelslander, T. (2011). Low emission zones in Europe: their impact on sustainability and logistics. In *Proceedings of the METRANS National Urban Freight Conferences 2011, Long Beach, 12-14/10/2011* (pp. 1-23).
[20] Browne, M., Allen, J., & Anderson, S. (2005). Low emission zones: the likely effects on the freight transport sector. *International Journal of Logistics: Research and Applications*, *8*(4), 269-281.
[21] Russo, F., & Comi, A. (2018). From city logistics theories to city logistics planning. *City Logistics 3: Towards Sustainable and Liveable Cities*, 329-347.
[22] European Commission. (2011). White Paper 2011: Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. Retrieved from https://ec.europa.eu/transport/themes/strategies/2011_white_paper_en

Europe (Settey et al., 2019). LEZs are therefore considered as a typical tool to improve the liveability of cities (Dablanc, Cruz & Montenon, 2018[23]).

The impacts of the implementation of an LEZ on urban delivery have to be considered. Indeed, the LEZ has to be accepted by firms and they should have a sufficient amount of time to organize the transition. Carriers have to renew their fleet, which incurs cost for delivery companies. Those with smaller financial resources might be pushed out of business (Dablanc & Montenon, 2015). This modernization of urban fleet leads to a diminution of air pollutants released, as well as, indirectly, a potential reduction of road accidents thanks to safer vehicles (Settey et al., 2019).

B. City Logistics

City Logistics has gained increasing attention from researchers, especially since the 2000s. Many of them have suggested different definitions of the concept. The most commonly used definition has been formulated in Taniguchi (2014): "*City Logistics is the process for totally optimising the logistics and transport activities by private companies with support of advanced information systems in urban areas considering the traffic environment, the traffic congestion, the traffic safety and the energy savings within the framework of a market economy*". In the literature, City Logistics is also denoted as urban distribution or last-mile logistics (Savelsbergh & Van Woensel, 2016).

City Logistics refers to an integrated system, which aims to globally optimize logistics activities. The optimization of the logistics concerns more efficient but also more sustainable urban freight movement (Mancini, 2013). City Logistics takes into account economic, social and environmental costs, as well as, all its stakeholders, such as carriers, administrators, residents and any groups involved in urban mobility (Antun et al., 2018). One distinctive feature of City Logistics is that urban deliveries are considered to have negative impacts on the living conditions of urban residents (Savelsbergh & Van Woensel, 2016). Therefore, the main goal is to improve the mobility, sustainability and liveability of cities thanks to consolidation and cooperation (Taniguchi et al., 2018 and Crainic, Ricciardi & Storchi,

[23] Dablanc, L., Cruz, C., & Montenon, A. (2018). Les «zones à émissions réduites» en ville: comment s' adaptent les entreprises de transport de marchandises?.

2009[24]). Within the scope of City Logistics, various innovative solutions have emerged (Mancini, 2013). These improvements affect many fields, for instance, the manufacturing of greener and safer vehicles or the development of more appropriated distribution models.

[24] Crainic, T. G., Ricciardi, N., & Storchi, G. (2009). Models for evaluating and planning city logistics systems. *Transportation science*, *43*(4), 432-454.

Chapter 3: Literature Review

For years, distribution models have been broadly studied in the literature (Vidal, Crainic, Gendreau, Lahrichi & Rei, 2012[25]). In this chapter, the well-known vehicle routing problem (VRP) and some of its variants will be reviewed. It will lay the foundations of the central subject of this literature review, the multi-echelon vehicle routing problem. Several variants and solving methods of the model will also be examined.

A. Vehicle Routing Problem

1. Description of the initial problem

The VRP was first academically formulated in "The Truck Dispatching Problem" by Dantzig and Ramser (1959)[26]. Since then, the field has gain many and varied advancements. The basic version of the VRP as well as its numerous variants, are highly developed in scientific publications (Crainic et al., 2009 and Laporte, 2019[27]).

In its simplest version, the aim of the VRP is to design the route that minimise the cost to deliver goods from a depot to the customers. The classic VRP is built on several assumptions. A single depot, but many customers are considered. Schematically, the depot and the customers represent vertices $V = \{0, \dots, n\}$ which are linked by arcs $A = \{(i, j): i, j \in V, i \neq j\}$. There is a single product delivered to each customer for which the demand is known beforehand. A fleet of homogeneous capacitated vehicles perform the delivery, starting from the depot. The number of vehicles required can be optimized or given arbitrarily. The best route is selected thanks to a travel cost matrix c_{ij} that mainly represents distances or travel times. Practically, each vehicle of the fleet starts from the depot and visits a certain number of customers. Then, it returns to the depot. The demand fulfil throughout a tour cannot exceed the capacity of the vehicle. A customer-demand cannot be divided; a customer is delivered by a single vehicle (Crainic et al., 2009 and Laporte, 2019). The system considers only one tier

[25] Vidal, T., Crainic, T. G., Gendreau, M., Lahrichi, N., & Rei, W. (2012). A hybrid genetic algorithm for multidepot and periodic vehicle routing problems. *Operations Research*, *60*(3), 611-624.
[26] Dantzig, G. B., & Ramser, J. H. (1959). The truck dispatching problem. *Management science*, *6*(1), 80-91.
[27] Laporte, G. (2009). Fifty years of vehicle routing. *Transportation science*, *43*(4), 408-416.

of consolidation-distribution. It refers to direct shipping (Cuda, Guastaroba & Speranza, 2015[28]).

This kind of problem focuses on the operational planning. Tactical decisions have already been taken upstream (Cuda et al., 2015). In logistics and in many different sectors, numerous practical applications are based on the VRP formulations (Crainic et al., 2009 and Vidal et al., 2012). Indeed, these applications lead to cost saving, especially valued in sectors where logistics and transportation represent high costs (Perboli, Tadei & Vigo, 2011[29]). Several variants of the problem have been designed to fit with actual constraints and requirements of freight transport (Laporte, 2009). The field has been enriched by many researches on added characteristics of the classical VRP. Improvements have been made on the problem solving. Due to their considerable computation time, exact methods can only solve relatively small instances; hence, heuristics have been developed to solve real-life applications, providing the opportunity to solve large instances (Crainic et al., 2009). The VRP is a useful model, but it has some limitations. For example, if the depot is located far from the customers, multiple freight vehicles will have to travel a long time between the depot and the customers (Crainic & Sgalambro, 2014[30]). In order to avoid these limitations, more complex routing models have been developed throughout the years.

2. Variants

A broad range of variants of the VRP has been studied in the scientific literature. Most variants address one or multiple specific topics. These aspects try to capture at best the real-life constraints faced by freight transportation. Common variants are related to time period. The typical VRP considers a single time period, whereas freight transportation is usually planned on a weekly basis. This problem is seen as the multi-period problem, where periods

[28] Cuda, R., Guastaroba, G., & Speranza, M. G. (2015). A survey on two-echelon routing problems. *Computers & Operations Research*, *55*, 185-199.
[29] Perboli, G., Tadei, R., & Vigo, D. (2011). The two-echelon capacitated vehicle routing problem: models and math-based heuristics. *Transportation Science*, *45*(3), 364-380.
[30] Crainic, T. G., & Sgalambro, A. (2014). Service network design models for two-tier city logistics. *Optimization Letters*, *8*(4), 1375-1387.

are typically days (Mancini, 2016[31]). Another problem related with time, is vehicle routing problem with time windows. In this model, customers (or even depots) are planned to be visited at a specific time (Crainic et al., 2009). In a way, it matches customers' requirements to be served within a precise time slot.

Another problem encountered in reality is the multi-depot problem (Vidal et al., 2012). Large distribution networks usually dispose of multiple depots to store goods (Mancini, 2016). According to the capacity of the freight vehicles, multiple-tour models can be required. In this problem, either each vehicle is assigned to a particular depot, which means that each trip of the vehicle must start and end at this particular depot, as in the Multi-Depot VRP by Toth and Vigo (2002)[32]. Or, vehicles are not assigned to a specific depot. Their only imperative is to start their journey where they ended it in the previous time period. This last option allows avoiding a long return trip to the assigned depot, with an empty truck, when another closer depot is available, as in the Multi-Depot Multi-Period VRP with Heterogeneous Fleet by Mancini (2016).

In real-life applications as well as in the scientific literature, several characteristics are combined within the same model. Developed models are getting more and more complex, which leads to an increasing difficulty to solve these models to the optimality or heuristically (Mancini, 2016). As an example, Vidal et al. (2012) proposed a metaheuristics which is, inter alia, based on an evolutionary algorithm. It succeeded in solving the Multi-Depot Periodic VRP with capacitated vehicles and time limit. These complex models have been and are still useful to develop a relatively new class of VRPs, the Multi-Echelon Vehicle Routing Problems.

[31] Mancini, S. (2016). A real-life multi depot multi period vehicle routing problem with a heterogeneous fleet: Formulation and adaptive large neighborhood search based matheuristic. *Transportation Research Part C: Emerging Technologies*, *70*, 100-112.
[32] Toth, P., & Vigo, D. (Eds.). (2002). *The vehicle routing problem*. Society for Industrial and Applied Mathematics.

B. Multi echelon VRP

1. Description of the basic version

The Multi-Echelon VRP is an extension of the classical VRP (Gonzalez-Feliu, Perboli, Tadei & Vigo, 2008[33]). It represents an alternative to conventional distribution models (Grangier, Gendreau, Lehuédé & Rousseau, 2016[34]). The difference lies in the fact that the freight goes through intermediate depots between its origin and its destination (Perboli et al., 2011). The most studied version of the ME-VRP is the Two-Echelon VRP, which means that the distribution network includes two transport levels (consolidation and distribution) (Gonzalez-Feliu, 2011[35]). In the literature, the topic has been introduced in Gonzalez-Feliu et al. (2008). Among others, the authors proposed a mathematical model for the Two-Echelon Capacitated VRP, which is the most basic version of ME-VRP. Main notions of the family of two-echelon problem are described in Gonzalez-Feliu (2011). Several other authors have shown interest in this class of problem (Zhou et al., 2018). An overview of the different contributions on this topic is reported in Cuda et al. (2015).

Multi-Echelon distribution systems lead to an improvement in the consolidation of loads (Mancini, 2013). Freight of different manufacturers and/or delivery companies, is consolidated at the intermediate facilities. This type of integrated systems requires a high level of coordination. Indeed, facilities and vehicles are shared between loads of multiples parties. Considering a distribution network as a whole enhances the efficiency of transportation flows (Perboli et al., 2011).

The purpose of multi-echelon systems is to make freight transport more efficient, which includes a reduction of the total transportation cost. It also takes into account the environmental impact of transport activities. Indeed, multi-echelon city logistics typically consider eco-friendly vehicles for the last-mile delivery in city centres. This strategy permits to maintain polluting motor vehicles out of urban areas (Mancini, 2013). Multi-echelon systems are thus highly appropriate for medium to large cities (Crainic & Sgalambro, 2014). The multi-tier model also brings more flexibility to distribution activities. Most studied

[33] Gonzalez-Feliu, J., Perboli, G., Tadei, R., & Vigo, D. (2008). The two-echelon capacitated vehicle routing problem.
[34] Grangier, P., Gendreau, M., Lehuédé, F., & Rousseau, L. M. (2016). An adaptive large neighborhood search for the two-echelon multiple-trip vehicle routing problem with satellite synchronization. *European Journal of Operational Research*, *254*(1), 80-91.
[35] Gonzalez-Feliu, J. (2011). Two-echelon freight transport optimisation: unifying concepts via a systematic review.

models only take into consideration inbound transport activities within cities because the entering flows are usually much higher than the exiting flows (Crainic et al., 2009). In practice, many applications have been developed in the field, for example, express delivery by carriers or e-commerce (Hemmelmayr, Cordeau & Crainic, 2012[36]). Multi-echelon models are widely used in supply chain and logistics, in many different sectors closely or remotely related to distribution activities (Perboli et al., 2011).

In the following paragraphs, the Two-Echelon VRP and its main components will be described. The 2E-VRP refers to indirect shipping. Indeed, freight (or part of it) passes through intermediate sites before being delivered to the final customers (Zhou et al., 2018).

The itinerary of the freight starts at depots, also called consolidation or distribution centres (Cuda et al., 2015). These terminals are commonly located beyond the city limits, far from many customers (Boccia, Crainic, Sforza & Sterle, 2011[37]). They have high capacity of storage. For the modelling, it can be assumed that their capacity is unlimited (Grangier et al., 2016). In the most basic version of the 2E-VRP, a single depot is considered (Gonzalez-Feliu, 2011).

Consolidation of the freight into 1st-echelon vehicles is made at these primary facilities (Mancini, 2013). 1st-echelon vehicles are generally large vans. They bring goods to intermediate sites, called satellites (Nguyen, Crainic & Toulouse, 2013[38]). Trucks can deliver one or multiple satellites in one tour, then, they return to their respective depot (Boccia et al., 2011 and Crainic et al., 2009). According to the constraints chosen, the trucks can also perform the deliveries to customers located outside of the city. An easy way to implement this is to place a satellite next to a depot (Savelsbergh & Van Woensel, 2016). Depending on the settings, certain satellites may not be supplied.

Satellites provide little or no storage (Boccia et al., 2011). The installations available are relatively limited. An upper bound capacity is defined in terms of number of parcels that can be shipped through the satellite or of number of city-freighters that can be charged in the facility (Crainic et al., 2004). In relation to the capacity of the satellites, time synchronization

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[36] Hemmelmayr, V. C., Cordeau, J. F., & Crainic, T. G. (2012). An adaptive large neighborhood search heuristic for two-echelon vehicle routing problems arising in city logistics. *Computers & operations research*, *39*(12), 3215-3228.
[37] Boccia, M., Crainic, T. G., Sforza, A., & Sterle, C. (2011). Location-routing models for designing a two-echelon freight distribution system. *Rapport technique, CIRRELT, Université de Montréal*, 91.
[38] Nguyen, P. K., Crainic, T. G., & Toulouse, M. (2013). A tabu search for time-dependent multi-zone multi-trip vehicle routing problem with time windows. *European Journal of Operational Research*, *231*(1), 43-56.

between 1st-echelon and 2nd-echelon vehicles may or may not be necessary (Anderluh et al., 2017). Secondary facilities are situated close or within the city centre, typically closer to customers (Crainic et al., 2009). One requirement is that 1st-echelon vehicles need to be able to reach these satellites without compromising the environmental impact of the system (Cuda et al., 2015). Satellites can be supplied by multiple depots (Zhou et al., 2018). The freight is unloaded, sorted and consolidated in smaller environment-friendly vehicles which perform the last-mile delivery to customers in urban areas (Crainic et al., 2004). Each city-freighter travels to deliver its assigned customers (Crainic et al., 2009). City-freighters can complete multiple trips. They can go back to their initial satellite (or to another one, regarding the settings defined) and reload to start a new route. At the end of the day, once again, each vehicle returns to a satellite (Anderluh et al., 2017).

A specific fleet is dedicated to each level of the distribution network. Vehicles are similar within an echelon but different between the two echelons (Zhou et al., 2017). Indeed, a sufficient standardization is required to efficiently manage the operations (Crainic et al., 2009). Usually, vehicles are capacitated, which means that the model can be referred to as the Two-Echelon Capacitated VRP (Gonzalez-Feliu, 2011). As previously explained, the satellites' fleet is composed of much smaller vehicles than the depots' fleet (Grangier et al., 2016). These smaller and eco-friendly vehicles are generally cargo-bikes, well-fitted in urban areas. They can easily travel in narrow streets within the city centre and avoid traffic jams (Cuda et al., 2015). The number of vehicles available at each echelon can be either a decision variable, or decided beforehand. However, most of the time, a limit on the vehicles potentially usable is set at each level (Hemmelmayr et al., 2012).

Regarding the customers, they are categorized depending on their location. Inner city residents are served by satellites, whereas outer city residents are directly served by depots (Boccia et al., 2011). Each customer is visited exactly once, regardless of the vehicle, which means that a customer-demand cannot be split among multiple vehicles (Zhou et al., 2018). The demand for each customer is known before the routing and it must be satisfied (Gonzalez-Feliu, 2011).

The 2E-VRP aims to efficiently solve the customers' allocation and the routing problem for the integrated two-echelon system (Mancini, 2013). Thus, the objective is to minimize the total routing and handling cost.

This description of the 2E-VRP exclusively takes into account the operational level of the distribution network. However, the strategical level is essential to efficiently perform transport activities. The location of the facilities can greatly impact the performance of a distribution network (Hemmelmayr et al., 2012). This latter question will be studied in the subsequent section of the report.

Finally, two-echelon distribution systems require more treatment, thus more handling cost. However, in most cases, this additional cost is balanced with the cost reduction due to consolidation and economies of scale. Externalities related to congestion and pollution are also reduced (Boccia et al., 2011).

2. Variants

The description of the 2E-VRP proposed in the previous subsection can vary depending on the settings chosen by the authors or imposed by real-life constraints. More complex models have been studied in literature to fit the intricacy of real-life applications for distribution networks (Cuda et al., 2015).

As already mentioned, the simplest variant of the 2E-VRP is its capacitated version. The specificity of this model is that all vehicles within an echelon have the same fixed capacity. In addition, satellites are also capacitated (Perboli et al., 2011). Another variant is the multi-depot 2E-VRP. In this model, at least two depots serve the satellites, and possibly the customers (Mancini, 2013). Then, the multi-trip, or multiple-tour, problem is quite common. For example, if the 2^{nd}-echelon vehicles are very small, a full load would not be sufficient to cover an entire work-day. The vehicles are therefore allowed to perform multiple tours. They reload at a satellite before starting any additional round (Grangier et al., 2016). These three features are basic and widely used in more elaborate models.

In the multi-product or multi-commodity problem, each customer has a demand for one or multiple specific products. These products may vary in size. Some of them may require a particular attention, for example, they could need to be handled with care or maintained at a certain temperature. Generally, a heterogeneous fleet is necessary to deal with the requirements of the different products. (Crainic et al., 2009).

Researchers have shown great interest in time-related 2E-VRP. This is very consistent given the real-life constraints of planning and scheduling distribution activities. Three types of models which include time settings can be distinguished. First, the time-dependent VRP takes into account multiple time periods. These cases are studied to match the reality. Indeed, typical planning considers multiple periods of time. Therefore, in this model, the demand of each customer is linked to a specific period (Soysal, Bloemhof-Ruwaard & Bektas, 2015[39]).

Secondly, the time-synchronization 2E-VRP, introduced in Crainic et al. (2009), has received considerable attention in the literature. Among others, the problem is discussed in Grangier et al. (2016) and Anderluh et al. (2017) with a greater focus on the implementation of the model. In this model, no permanent 2nd-echelon facilities are needed. No storage is required either. Existing infrastructures, such as car parks, city squares, kiss and ride areas or any urban spaces dedicated to logistics can be employed as satellites to unload freight. This model permits to avoid paying expensive rents in urban areas (Grangier et al., 2016). Concretely, trucks and city-freighters meet at satellites, at precise time. At satellites, trucks are unloaded and, if needed, freight is consolidated. Then, immediately, city-freighters are loaded in order to deliver their assigned final customers. To manage an efficient synchronization, an exact departure time from the depot must be set for each truck (Crainic et al., 2009).

Thirdly, the 2E-VRP with time windows takes into consideration specific time slots for the transfer of goods. The model introduced in Crainic et al. (2009) is based on hard time windows for the unloading/loading activities at satellites, whereas for customers' deliveries, soft time windows are considered. Especially combined with a synchronized model, the respect of precise time slots at satellites is essential (Mancini, 2013).

Another aspect tackled, for example in Zhou et al. (2018), is the delivery options offered to the final customers. In the 2E-VRP with pickup and deliveries, customers can choose between self-pickup or home delivery. Therefore, from satellites, goods are delivered to customers as well as to pickup facilities. Pickup facilities and satellites can potentially be merged.

This section solely represents a limited overview of the richness and diversity of the subject. Many different variants of the 2E-VRP have been developed. They combine multiple aspects to reflect as accurately as possible the reality. What seems to be a detail can have an important

[39] Soysal, M., Bloemhof-Ruwaard, J. M., & Bektaş, T. (2015). The time-dependent two-echelon capacitated vehicle routing problem with environmental considerations. *International Journal of Production Economics*, *164*, 366-378.

impact on cost. For instance, in Anderluh et al. (2019)[40], they proposed to define a grey zone between the city-centre area and areas far from the city. This aims to allow a customer located in the grey zone to be delivered by a truck or a city-freight depending on the solution which incurs the lower cost. Eventually, all these different models share a common ground, the willingness to consider environmental and social aspects in the development of distribution networks.

C. Location problem

In the 2E-VRP, the number of satellites available and their location are known. This type of problem concentrates on the operational level of planning, which is the routing phase. However, the facilities' location and availability have an important impact on distribution networks. The 2E-Location Routing Problem deals with tactical and strategic decisions (Cuda et al., 2015). Opening the right number of facilities at the optimal locations is essential to efficiently manage cost. Indeed, this prevents unnecessary cost of opening and running superfluous facilities, as well as extra routing costs (Mancini, 2013).

In practice, customers' locations are fixed and known, whereas facilities' locations are not totally determined beforehand. A set of potential location is assigned respectively to depots and satellites. In this model, the number of facilities to be opened is a decision variable. The most strategic locations for the facilities are selected from the group of candidate locations. An opening cost for depots and satellites is obviously taken into account in the optimization. Regarding the routing phase, it is handled exactly as the classical 2E-VRP (Cuda et al., 2015).

The 2E-LRP consists in three decisions. First, the number and the locations of depots and satellites which will be exploited in the distribution network are determined. Secondly, the allocation of customers to satellites and satellites to depot is decided. Thirdly, the routing from depots and satellites is performed (Boccia et al., 2011). The aim of the problem is to minimize the total cost of the distribution solution (Cuda et al., 2015).

A main challenge is 2E-LRP is to connect the two echelons together (Gonzalez-Feliu, 2011). Indeed, the added-value of this model is to consider the location and the routing problem as a

[40] Anderluh, A., Nolz, P. C., Hemmelmayr, V. C., & Crainic, T. G. (2019). Multi-objective optimization of a two-echelon vehicle routing problem with vehicle synchronization and 'grey zone'customers arising in urban logistics. *European Journal of Operational Research*.

whole. The two aspects are solved simultaneously and not as two distinct problems (Boccia et al., 2011). Due to its important influence on urban logistics, the Location Routing Problem has been broadly addressed in the literature, in single and two-echelon versions (Zhou et al., 2018).

D. Solving methods

Routing problems are complex to solve. Besides the easiest instances, with a very small number of arcs, routing problems are not solvable in polynomial time (Lenstra & Kan, 1981[41]). Consequently, the vehicle routing problem and each of its variants are NP-Hard (Crainic et al., 2009).

Regarding the ME-VRP, at early stages of the field, the distribution network was usually not solved as a whole. It was rather decomposed into a succession of single-echelon routing problems (Mancini, 2013). However, Perboli et al. (2011) proposed the first solving method for the 2E-VRP. From that point onwards, exact methods (Baldacci, Mingozi, Roberti & Calvo, 2013[42]; Jepsen, Spoorendonck & Ropke, 2013[43]) and heuristics (Crainic, Mancini, Perboli & Tadei, 2011[44]; Hemmelmayr et al., 2012) have been equally considered in scientific papers (Cuda et al., 2015).

1. Exact methods

Exact methods offer the optimal solution, but they require an extended computational time. These methods can exclusively be used on relatively small instances because the computational time required increases exponentially with the size of the instance. Exact solving methods are based on mathematical formulations. They are typically solved thanks to

[41] Lenstra, J. K., & Kan, A. R. (1981). Complexity of vehicle routing and scheduling problems. *Networks*, *11*(2), 221-227.
[42] Baldacci, R., Mingozzi, A., Roberti, R., & Calvo, R. W. (2013). An exact algorithm for the two-echelon capacitated vehicle routing problem. *Operations research*, *61*(2), 298-314.
[43] Jepsen, M., Spoorendonk, S., & Ropke, S. (2013). A branch-and-cut algorithm for the symmetric two-echelon capacitated vehicle routing problem. *Transportation Science*, *47*(1), 23-37.
[44] Crainic, T. G., Mancini, S., Perboli, G., & Tadei, R. (2011, April). Multi-start heuristics for the two-echelon vehicle routing problem. In *European Conference on Evolutionary Computation in Combinatorial Optimization* (pp. 179-190). Springer, Berlin, Heidelberg.

commercial solvers (Mancini, 2013). Gonzalez-Feliu (2008)[45], Perboli et al. (2011) and Jepsen et al. (2013) have proposed exact methods to solve small-sized examples for the 2E-VRP.

2. Heuristics

To overcome the limitations of exact methods, heuristics and meta-heuristics have been developed to provide fairly accurate solutions within short computational time. These methods do not ensure that the optimal solution is found. Moreover, even if the optimal solution is obtained, heuristics are not able to qualify it as such (Mancini, 2013). Nevertheless, they are especially useful to solve medium to large-sized instances, namely related to real-life applications (Zhou et al., 2018). Several types of heuristics are covered in the literature; the following list is obviously not comprehensive.

- Local Search

Local Search is based on the exploration of the solution space. Iteratively, starting from a current solution S', the heuristic examines the neighbourhood of S'. It moves from one solution to another by applying the Best Improvement or the First Improvement method. In the Best Improvement strategy, the whole neighbourhood of the current solution S' is analysed. The best neighbour of the neighbourhood of S' is set as the new current solution. This strategy intensively searches a limited area. In the First Improvement strategy, as soon as a better solution is found in the neighbourhood, this first better solution is set as the new current solution. This strategy explores a wider area than the Best Improvement method. At each iteration, the heuristic tries to find a solution which is related to a lower cost than the current solution. The performance of a local search heuristic highly depends on the definition of the neighbourhood of the solution. Local Search algorithms are easy to implement. However, the main limitation is that the algorithm can be quickly stuck in a local optimum. Moreover, the accuracy of the final solution can be conditioned by the quality of the starting

[45] Gonzalez-Feliu, J. (2008). *Models and methods for the city logistics: The two-echelon capacitated vehicle routing problem* (Doctoral dissertation).

solution of the heuristic (Laporte, 2009). In the 2E-VRP literature, an iterated local search is performed in Nguyen et al (2012)[46].

- Tabu Search

Tabu Search is a Local Search which avoids being trapped in local minima. This is done by creating a tabu list, which is a kind of search history. If all the neighbours of a solution are tabu, a worse solution is accepted to escape from the local minimum (Edelkamp & Schrodel, 2011[47]). In Nguyen et al. (2013), a tabu search heuristic is proposed for a complex single-echelon VRP. This time-dependent multi-zone multi-trip VRP with time windows is an interesting model to solve more complicated 2E-VRP.

- Simulated Annealing

Like Tabu Search, Simulated Annealing is a Local Search meta-heuristic able to evade local minima. At the beginning of the algorithm, worse solutions will be accepted. Progressively, the algorithm will be more and more rigid. The probability that a worse solution will be accepted decreases as the algorithm goes. In the last phase, the simulated annealing meta-heuristic works exactly like a local search. The performance of this meta-heuristic highly depends on the parameters set to decrease the probability of accepting a worse solution. It can be complicated to tune in practice (Mancini, 2013).

- Large Neighbourhood Search

The Large Neighbourhood Search is based on the fact that exploring large neighbourhoods leads to the discovery of better quality local optima. The algorithm is therefore more likely to provide an accurate solution. In practice in a LNS, a better solution is found thanks to destroy and repair operators which modify the current solution. An example of a destroy operator in routing problem would be to remove certain routes, leaving the other ones untouched. Then,

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[46] Nguyen, V. P., Prins, C., & Prodhon, C. (2012). A multi-start iterated local search with tabu list and path relinking for the two-echelon location-routing problem. *Engineering Applications of Artificial Intelligence*, *25*(1), 56-71.

[47] Edelkamp, S., & Schroedl, S. (2011). *Heuristic search: theory and applications*. Elsevier.

this destroyed solution is repaired into a feasible solution. Exploring a large neighbourhood is time consuming, thus filtering methods are established to improve the searching (Mancini, 2015 and Pisinger & Ropke, 2010[48]).

Recently, Anderluh et al. (2019) have constructed a metaheuristic solution based on LNS for the multi-objective, synchronized, two-echelon vehicle routing problem with 'grey zone'.

- Adaptive Large Neighbourhood Search

The Adaptive Large Neighbourhood Search is based on the same destroy and repair method as the LNS. This model is an improvement with respect to the LNS. Indeed, in this case, statistics from previous iteration are gathered to measure the performance of the heuristic and an adaptive weight algorithm is added to the LNS (Ropke & Pisinger, 2006[49]). Hemmelmayr et al. (2012) proposed an ALNS for the two-echelon multiple-trip VRP with satellite synchronization. This approach is very performing and accurate.

- Greedy Randomized Adaptive Search Procedure

The GRASP is a multi-start two-phase metaheuristic. Within each iteration, two phases are accomplished. The first phase consists of the construction of a solution thanks to a greedy randomized function. In the second phase, a local search is made on the obtained solutions (Mancini, 2013 and Feo & Resende, 1995[50]). In the literature, Crainic et al. (2011) developed a GRASP with Path-Relinking for the 2E-VRP.

- Evolutionary Algorithm

The Evolutionary Algorithm, or Genetic Algorithm is based on the Darwinian evolutionary theory, often defined as "the survival of the fittest". In an EA, a population of solutions is created. The individuals within the population continually compete with each other, the best

[48] Pisinger, D., & Ropke, S. (2010). Large neighborhood search. In *Handbook of metaheuristics* (pp. 399-419). Springer, Boston, MA.
[49] Ropke, S., & Pisinger, D. (2006). An adaptive large neighborhood search heuristic for the pickup and delivery problem with time windows. *Transportation science*, *40*(4), 455-472.
[50] Feo, T. A., & Resende, M. G. (1995). Greedy randomized adaptive search procedures. *Journal of global optimization*, *6*(2), 109-133.

solutions survive. The algorithm should lead to optimal regions of the search space where, hopefully, the optimal solution is located (Mancini, 2013). In Zhou et al. (2018), a hybrid multi-population genetic metaheuristic is proposed to solve the multi-depot two-echelon VRP with delivery options. The strategy combines genetic algorithm and local search.

E. Freight Vehicles

The last section of this literature review addresses the subject of freight vehicles in an urban logistics context. As already mentioned, in ME-VRP, the last-mile delivery is typically performed with cargo-bikes or small electric vehicles. These eco-friendly vehicles offer many advantages like a reduction in GHG emissions, noise and congestion for example. They are especially handy in dense city zones. However, they also show some drawbacks. The capacity of the city-freighters is relatively small and they can only travel a limited distance in one round (Crainic et al., 2004). Their limited autonomy imposes relatively short trip. Additionally, vehicles have to be recharged. The transit by a charging station and the time required to charge the battery of the vehicles have to be taken into account in the planning of operations. An extension of the 2E-VRP has been introduced to deal with the additional constraints related to the use of an electric fleet. Breunig et al. (2019)[51] proposed the Electric Two-Echelon Vehicle Routing Problem. This model is solved mathematically and with a LNS-based meta-heuristic.

[51] Breunig, U., Baldacci, R., Hartl, R. F., & Vidal, T. (2019). The electric two-echelon vehicle routing problem. *Computers & Operations Research*, *103*, 198-210.

Chapter 4: Problem studied

A. Description

As already mentioned, around the world, cities face challenges regarding urban distribution. A way to tackle these issues is to model more appropriate distribution networks. This master's thesis focusses on the development of a variant of the Multi-Echelon Vehicle Routing Problem. The specificities of the variant are described in this section. The model will be applied to the case of Liège. This particular model has been thought out with the city of Liège in mind, which justifies some characteristics. However, subject to relatively minor modifications, the model can easily fit other cities.

The model studied can be described as the Multi-Echelon Multi-Satellite Multi-Product Capacitated VRP with one-day delay allowed. It is combined with a location routing problem for the satellites. A planning horizon of a week including only business days (Monday to Friday) is considered.

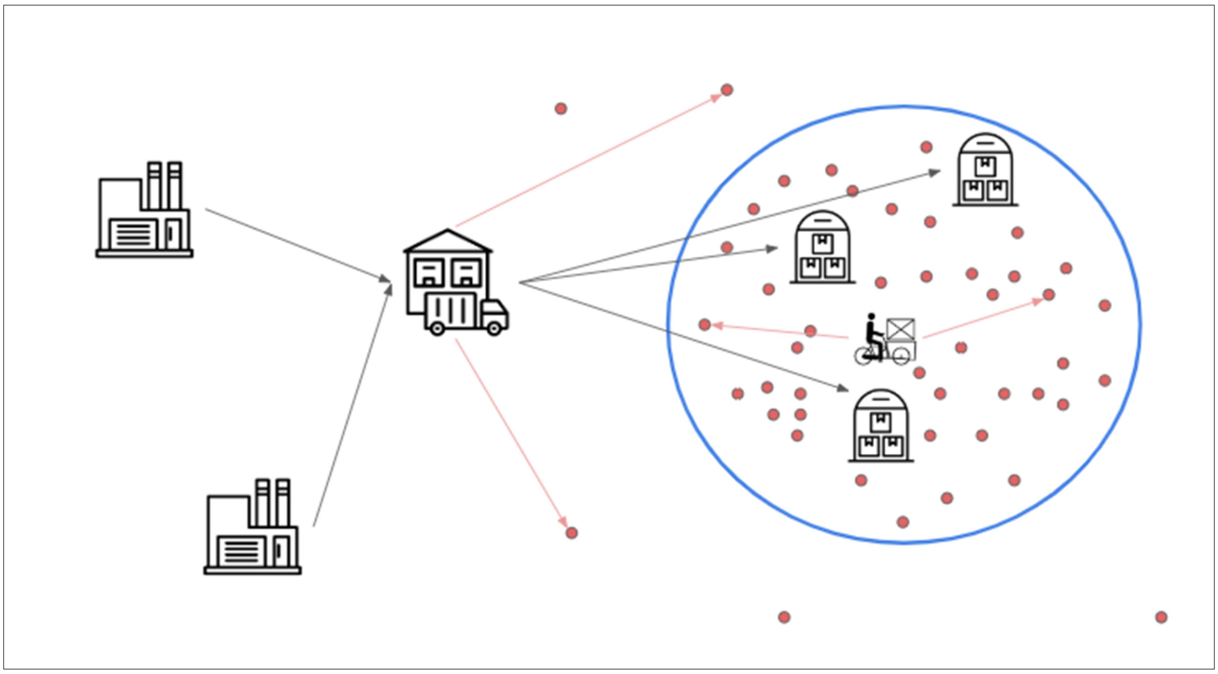

Figure 1: Distribution network scheme

Concretely, the parcels are prepared in the firms. Each firm takes care of the delivery of its own parcels to a cross-docking centre. From this depot, the packages for suburban customers are directly delivered by vans, whereas the packages for urban customers are dispatched in satellites within the city centre. Cargo-bikes are loaded at these satellites, then, they serve urban customers. The previous scheme describes the flows of goods. Customers are represented as red dots. The urban area is delimited by the blue circle. Several assumptions are made to build the model; they are reviewed echelon by echelon.

1. Firms

The firms are the starting point of the flow. Each of them offers a single product, different from one firm to another. Certainly, the model can be easily adapted for them to sell multiple distinct products. The products are considered relatively small. Indeed, the problem studied focusses on the delivery of small parcels. Each producing company is responsible to ship its packages to the depot of the delivery company. Thus, each producing company must possess its own fleet. For the uniformity, each of them owns a small van. A volume of 3 cubic meters and a maximal charge of 600 kilograms are considered. Up to two round trips are allowed to satisfy the demand but usually the packages are sent once a day in a single trip.

For the case of Liège-Namur area, the model helps to deal with an extra issue related to the Belgian economy. As a matter of fact, SMEs are essential to the Belgian economy. In 2017, 99.8% of Belgian companies were SMEs (SPF Economie, 2018[52]). Some of them are active in the retail sector. Among others, commercial companies often propose online sale and home delivery. These SMEs have a strong need in improving their delivery solutions, particularly in terms of consolidation. They can therefore find a great interest in sharing deliveries, as well as delivery facilities, with other SMEs.

The firms are typically located outside of the city centre. In the practical case of the example studied in this master's thesis, the firms are situated in Mons and Namur provinces.

[52] SPF Economie. (2018, December 10). Près d'un million de PME en Belgique. Retrieved from https://news.economie.fgov.be/170191-pres-d-un-million-de-pme-en-belgique

2. Cross-docking centre

First, at the cross-docking centre, the packages are unloaded from the vehicles of the producing companies. Then, they are sorted and consolidated into vans to perform deliveries to suburban customers and satellites. A satellite-demand or a customer-demand cannot be split into different itineraries or different vehicles. A satellite or a customer is served, at most once a day, by only one van (Crainic et al., 2009). At the end of their respective tour, the delivery vans return to the cross-docking centre.

A single depot is considered at this echelon. The capacity of the depot is so high in relation to the demand that it doesn't need to be taken into account in the model. This refers to the hub-and-spoke structure. In this layout, the depot acts like a hub. This network structure minimizes the connections between firms and the depot, as well as between the depot and satellites and allows economies of scale (Transport Geography[53]). Having a single depot is particularly relevant with respect to the practical example of Liège-Namur area. Indeed, the demand volume does not require multiple depots. Moreover, the geographical position of firms and customers enables the use of a single depot, strategically located between Namur and Liège. Commonly, crossdocking centre are located outside of cities, for example in industrial areas.

To reinforce the sustainability of the freight transportation, electric vans can be deployed to deliver goods to satellites and suburban customers (Balm, Moolenburgh, Anand & Ploos van Amstel, 2018[54]). This possibility is certainly achievable given the distance to be covered in the practical case of Liège. Considering autonomy of around 100 kilometres for the electric vans (DHL, 2019[55]), the EVs can start their journey in the depot and reach the satellites in the city of Liège. One of these satellites must be equipped with a fast charging station to enable the vans to be charged during the handling of goods (Total, 2018[56]). The capacity of electric vans is rather similar to delivery motor vans. The large version of the DHL's StreetScooter

[53] Transport Geography. (n.d.). Point-to-Point versus Hub-and-Spoke Networks. Retrieved from https://transportgeography.org/?page_id=653
[54] Balm, S., Moolenburgh, E., Anand, N., & Ploos van Amstel, W. (2018). The Potential of Light Electric Vehicles for Specific Freight Flows: Insights from the Netherlands. *City Logistics*, *2*.
[55] DHL. (2019, August 23). DHL Express teste une camionnette électrique StreetScooter en Belgique. Retrieved from https://www.dhlexpress.be/fr/dhl-nouvelles/camionnette-electrique-streetscooter/
[56] Total. (2018, October 17). Trouver les stations de recharge électrique rapide. Retrieved from https://www.total.be/fr/ma-station-service/les-carburants-en-station/trouver-les-stations-de-recharge-electrique-rapide

has a volume of 8 cubic meters and can be loaded up to 960 kilograms (DHL, 2017[57]). Due to the constraints of an EV fleet, customers outside of the city centre, served by vans, have to be located on relatively close outskirts of the city. The number of vehicles is not arbitrarily set; it is solved within the model.

3. Satellites

In the problem studied, a satellite is a small and mobile urban container. The locations of the satellites are not fixed and can change from one period to another. Indeed, at a given time, a set of potential locations for satellites is defined. The number of satellites needed at this given time is also solved by the model, it is a decision variable. Satellites have to be easily moved from one point to another (Savelsbergh & Van Woensel, 2016). The capacity of a satellite is therefore limited. Determining the optimal size of a satellite is a whole problem by itself. Arbitrarily, in this model, the volume of a satellite is assumed to be 3 cubic metres and the maximal charge 400 kilograms.

A typical location for a satellite is a parking. Surely, a parking offers enough place to load and unload the vehicles. Broadly speaking, a good satellite location has to provide an easy access for vans and cargo-bikes and to allow a convenient handling of goods. The location must permit to effortlessly manoeuvre the vehicles, narrow spaces are thus unsuitable. In some cases, it can be interesting to locate the satellites at the limit of the city to avoid dispensable congestion for example (Crainic et al., 2004 and Crainic et al., 2009).

The last-mile delivery from satellites is made by cargo-bikes. Among others, bikes have the advantage to reach customers situated in less reachable areas, such as pedestrian paths or historical centres (Savelsbergh & Van Woensel, 2016). Arbitrarily, the capacity of a cargo-bike can be of 0.7 cubic meter with a maximum charge of 100 kilograms (DHL, 2015[58] and Urbike[59]). Just as the vans' trips, each customer-demand is delivered by a single vehicle at most once a day. No split of a customer's order is allowed. Consequently, the volume of a

[57] DHL. (2017, November). Facts & Figures: StreetScooter. Retrieved from https://www.dhl.com/content/dam/dhl/local/global/core/documents/pdf/Fact_Sheet_StreetScooter_Work_and_Work_L_EN.pdf

[58] DHL. (2015, April 29). DHL introduces Cubicycle, an innovative cargo bike for urban distribution, to its Netherlands operations. Retrieved from https://www.dhl.com/en/press/releases/releases_2015/express/dhl_introduces_cubicycle_an_innovative_cargo_bike.html

[59] Urbike. (n.d.). Conteneurisation intelligente. Retrieved from https://urbike.be/conteneurisation-intelligente/

customer-demand cannot exceed the capacity of a cargo-bike. This assumption is automatically satisfied by the nature of the problem examined. In fact, the problem concentrates on the delivery of small packages to private individuals (Crainic et al., 2009). Regarding the model, it should be noted that the number of cargo-bikes required is determined by the heuristic. Moreover, it is assumed that each day, each cargo-bike is assigned to a specific satellite. Consequently, after their tour, cargo-bikes have to return empty to their designated facility.

4. Customers

Nowadays, customers buy as well to local stores as to multinational brands. Buying channels are multiplying. Globally, the trend of online shopping is increasing. It is now well set in consumption habits. Customers expect various delivery options, such as store pick-up, home delivery, pick-up in lockers or at collection points. They are accustomed to relatively short delivery times. Expectations in term of delivery's quality are growing (Dablanc, 2007).

In this model, customers are divided into two categories: van-customers and bike-customers. This distinction is based on their location. If the customer is situated in the city centre, he will be served by a cargo-bike. Otherwise, if the customer is located in the suburbs, he will be served by a van (Anderluh et al., 2017).

B. Contribution

In the field of Multi-Echelon VRP, the main contribution of this master's thesis is to tolerate a one-day delay for the delivery. To deal with a delay, the problem has to take into account a planning horizon. The different periods are connected with each other to effectively deliver parcels with at most a day of delay. The planning horizon chosen in this model is a week. Only business days are considered. On Monday, there is no backorder from the previous planning horizon. On Friday, the demand of the whole week must have been satisfied. The delayed orders are waiting an extra day at the producers. Packages cannot be on hold at another location. In fact, by definition in a cross-docking centre, the freight can only transit for up to 24 hours. In practice, freight tends not stay at a cross-dock for more than 12 hours. Concerning the satellites, their capacity is limited and they are supposed to be mobile and move from one point to another between days. Allowing overnight storage in these urban containers highly complicates the routing problem. At first glance, it seems more convenient to keep waiting orders in factories.

The major advantage to allow a delay is to increase the consolidation level of the distribution network. It is particularly interesting when dealing with a relatively small demand volume from different SMEs. This may lead to important cost reduction for the companies. Negative side effects of deliveries may also be diminished. Integrating a planning horizon in the model is also relevant because it better represents the real-life constraints and the concrete methods used by carriers to plan their itineraries.

A similar model, which combines all the features mentioned in this section, has not yet been surveyed in the literature. In this master's thesis, a local search based heuristic will be proposed to solve this specific variant of the Multi-Echelon VRP.

C. Example of Chronopost in Paris

Several initiatives have applied the Multi-Echelon VRP in order to improve urban transportation. An interesting example is the case of the delivery company Chronopost and its operations in Paris. The company is active in the delivery of parcels weighing less than 30 kilograms, for private individuals and businesses (DPD, 2019[60]). In 2019, Chronopost has achieved the goal of 100% green deliveries in Paris. The initiative is an inspiring application of sustainable logistics. It proposes a sustainable alternative for last-mile delivery while keeping good performance.

In Paris, the distribution network of Chronopost is divided in two echelons. The first echelon is composed of three urban logistics spaces (ELU). These facilities are located inside the city, in Concorde, Beaugrenelle and Bercy (Chronopost, 2019[61]). These locations have been chosen to be closer to the end-customers. The three facilities are not exactly the same. The facility at Beaugrenelle was originally a disused parking which has been reclaimed by Chronopost with the cooperation of local authorities. The building has a surface of 3000

[60] DPD. (2019, October 4). Chronopost annonce la livraison de l'intégralité de la ville de Paris en véhicules propres. Retrieved from https://www.dpd.com/group/fr/2019/10/02/chronopost-announces-the-delivery-of-the-entire-city-of-paris-in-low-emission-vehicles/
[61] Chronopost. (2019, November 5). Chronopost et la Logistique urbaine. Retrieved from https://www.youtube.com/watch?v=hcNuG_8vdrg

square meters and is supplied only by green energy. It treats five thousands parcels per day split into 42 tours. The facility is also a pick-up point for end-customers (Ville de Paris, 2015[62]). Concerning the facility of Bercy, its highlighted characteristic is that the depot is able to handle refrigerated goods if needed (Chronopost, 2018[63]). Unsurprisingly, to achieve the 100% green delivery goal, the whole fleet assigned to the ELUs is green, composed of electric vans for example (DPD, 2019).

The second echelon includes five Chrono City which are located in hyper-urban areas. These facilities are smaller, less than 500 square metres. They are constituted of two distinct spaces. An area is dedicated to the unloading and loading activities of the eco-friendly fleet. Indeed the last-mile delivery in hyper-urban areas is mainly performed by cargo-bikes. Another area is dedicated to customers' service. While developing Chrono City facilities, Chronopost has decided to add features to broaden the range of services offered to the customers and also to improve the customer experience. In this second area, customers can receive and send their packages. They can immediately try their purchases in the facility. If the product received does not match the customer's expectations, he can return the product with the help of Chronopost's employees (DPD, 2019).

In Paris, Chronopost has now a fleet of more than 290 environmental-friendly vehicles (Chronopost, 2019). This fleet allows serving the whole city of Paris, which is a great improvement in sustainable logistics for a big city (DPD, 2019). The company would like to extend the project to other French cities, again in partnership with local authorities (Ville de Paris, 2015). The two major advantages of the project is the pollution and congestion reduction triggered. It also leads the way for the same kind of strategies in other cities or for other carriers (DPD, 2019). Even if the process to reach a 100% green delivery is long, the goal can be achieved in many cities throughout the world, with the involvement of all the stakeholders.

[62] Ville de Paris. (2015, October 6). A la découverte de l'Espace Logistique Urbain de Beaugrenelle. Retrieved from https://www.youtube.com/watch?v=EOA433STuGY
[63] Chronopost. (2018, May 2). Nouvel Espace Logistique Urbain à Paris pour les livraisons alimentaires | Chronopost. Retrieved from https://www.chronopost.fr/fr/actualites/nouvel-espace-logistique-urbain-paris-pour-les-livraisons-alimentaires

Chapter 5: Local Search Method

A. Broad concept

To solve the problem described in the previous section, a local search heuristic has been implemented. This method has been chosen for the many advantages it presents. Local search is relatively easy to implement and to tune. Typically, it leads to good results with little computational time and low memory requirements. Local search methods are greedy. Most of the time, these heuristics provide a good solution but not the optimal. They are not able to evaluate if the solution is optimal, neither how far the solution is from the optimal. The main drawback of local search is that it gets stuck in local minima (Dechter, 2003[64]). This problem can be tackled, at least partially, by more advanced local search based metaheuristics.

Practically, a local search heuristic starts from an imperfect solution, determined randomly or thanks to a list-processing heuristic for example. In some cases, local search heuristics are combined with other methods to locally improve a solution obtained by these other methods. From the initial solution, the heuristic explores the neighbourhood to find a path which improves the current solution. Generally, the result of the cost function related to the problem determines if the neighbour solution is better than the current solution. Iteratively, the heuristic moves from one solution to another, guided by the objective function. The heuristic stops when a pre-set minimal solution is reached or when the final solution has not been improved for a certain number of iterations (Dechter, 2003 and Hoos & Stutzle, 2004[65] and Egri & Shultz, 2015[66]).

Th local search heuristic developed in this master's thesis is stochastic. The decisions taken by the metaheuristic are randomised. The initial candidate solution is also random (Hoos & Stutzle, 2004). Running the heuristic multiple times on the same instance will not terminate on the same final solution. Various approaches exist in local search. The one used in this report is the Steepest Descent, also called Gradient Descent or Best Improvement. It is one of the most intuitive strategies. In this heuristic, the neighbourhood of the current solution is explored. The current solution is substituted by the best solution in its neighbourhood.

[64] Dechter, R. (2003). *Constraint processing*. Morgan Kaufmann.
[65] Hoos, H. H., & Stützle, T. (2004). *Stochastic local search: Foundations and applications*. Elsevier.
[66] Egri, L., & Shultz, T. R. (2015). Constraint-Satisfaction Models.

Formally, the steepest descent metaheuristic is described in Crama (2019)[67] and in Prioro[68] as follows:

procedure Steepest Descent

---

begin
  choose initial solution x^1, $F^{best} := F(x^1)$, $x^{best} := x^1$ *and* $k := 1$
  while *stopping_criterion* **not true do**
    repeat
      find best solution $\bar{x}$ in $N(x^k) : F(\bar{x}) = \min\{F(x) : x \in N(x^k)\}$
      if $F(\bar{x}) < F(x^k)$ then $x^{k+1} := \bar{x}$, $F^{best} := F(\bar{x})$, $x^{best} := \bar{x}$ *and* $k := k + 1$
      else end
end

Figure 2: Steepest descent procedure

B. Neighbourhood

The concept of neighbourhood is essential in local search. A neighbour of a solution s is a solution s' which locally differs from s. The neighbour s' has at most k components which are different from the solution s. The parameter k can vary in relation to the size of the problem. It can be adjust experimentally. Consistently, the neighbourhood of a solution s is the set of neighbours s' which differs from the s for at most k solution components (Dorigo & Stutzle, 2003[69]). According to the dimensions of the problem, the complete neighbourhood may or may not be explored. Thus, the size of the neighbourhood varies from one problem to another. The choice of the neighbourhood's size is usually given in relation to a trade-off between the computational time and the quality of the solution. If the size of the neighbourhood is too small, the heuristic will stop prematurely, whereas if the neighbourhood is too big, the improvement will be too slow (Crama, 2019).

The neighbourhood structure is the set of potential solutions that can be reached with a single move of the heuristic. In practice, it is defined in terms of the transformations that can be applied to a current solution. The operations used are local changes; only a few components are changed from a present solution. According to the definition formulated by Dorigo &

[67] Crama, Y. (2019). Computational Optimization.
[68] Pióro, M., & Medhi, D. (2004). *Routing, flow, and capacity design in communication and computer networks*. Elsevier.
[69] Dorigo, M., & Stützle, T. (2003). The ant colony optimization metaheuristic: Algorithms, applications, and advances. In *Handbook of metaheuristics* (pp. 250-285). Springer, Boston, MA.

Stutzle (2003), "*a neighbourhood structure is a function* $N : S \rightarrow 2^s$ *that assigns a set of neighbours* $N(s) \subseteq S$ *to every* $s \in S$*"*. The neighbourhood structure is usually determined specifically for a given problem. Therefore, for a particular problem, there are many different manners to establish the neighbourhood structure. The performance of the metaheuristic partly depends on the selection of a relevant neighbourhood structure (Crama, 2019 and Dorigo & Stutzle, 2003).

In the first version of the metaheuristic proposed in this master's thesis, three neighbourhood structures have been built. The first neighbourhood structure focusses on the itinerary of vehicles starting from satellites. The neighbourhood is constructed thanks to a remove and append operation. On a random day, a bike-customer that is planned to be served is removed from the tour he is into. A satellite is chosen randomly, the satellite can be already open or not, the satellite can be the same as the one the bike-customer has just be removed from. The bike-customer is appended at the end of the randomly-chosen satellite route, if and only if the capacity of this satellite is sufficient to serve this extra bike-customer. The operator deals with multiple aspects that can be optimized. It allows to reassign bike-customers to different satellites and to change the itinerary of bikes.

The second neighbourhood is determined by applying a swap operation. It modifies the vans' routing. Two locations that have to be visited by a van on the same day are exchanged in the round. A van-customer and a satellite, two van-customers or two satellites can be swapped. The day and the two components exchanged are randomly selected. This operator is relatively basic and typical in routing problems. No check is made on the available capacity because a single unlimited depot is considered.

The third neighbourhood concerns the delayed orders. In the model, it is assumed that the delay is applied on the whole order of the customer. The customer-order of a given day, even if it contains different products from different firms, cannot be split. This third neighbourhood structure is based on a remove and append operation. Briefly, a randomly-chosen customer whether bike-customer or van-customer, is removed from the route he is assigned to, to be appended in another route the next day. Some conditions must be met to allow the transformation. Moreover, the neighbourhood structure is applied in a particular way in the program. These details are explained in the section D.4. of this chapter.

Concerning the size of these neighbourhoods, it is determined experimentally. More details about the neighbourhood's parameters are given in the section 4, which specifically deals with the implementation of the metaheuristic. In addition, the neighbourhood size may be diminished for medium to large size instances in order to limit the computational time. The number of elements changed in each neighbourhood structure is discussed in the chapter 7 which concentrates on numerical experiments.

C. Initial solution

There are two common ways to initialize a local search metaheuristic. First, the initial solution can be determined by a greedy list-processing heuristic. It follows the intuition that starting from a good solution leads to better results. Indeed, it can be the case, especially when the computational time has to be very short. Nevertheless, initializing the local search with a random solution can also lead to high-quality solutions. Mainly, running the metaheuristic multiple times on different random initial solutions is an interesting strategy to limit the influence of a bad initial solution. It is known as the multi-start strategy (Crama, 2019 and Lourenço, Martin & Stutzle, 2003[70]).

The metaheuristic developed in this master's thesis starts on a random solution. This seems like a relevant choice, namely to avoid being stuck in the same solution space, even when the heuristic is restarted. However, it might requires a longer computation time for very large instances. In this initial solution, bike-customers are randomly divided into the different satellites available and no delay is considered. The starting solution is thus related to a rather high cost. Nonetheless, initializing the heuristic on this solution leads to satisfactory results

D. Core of the heuristic

1. Settings

Formally, the Multi-Echelon VRP is mapped as a directed graph $G = (N, A)$. N is the set of all nodes which includes: the firms F, the delivery company D, the satellites S and the customers C. The set C includes bike-customers and van-customers. The planning horizon considered is $T = \{0,1,2,3,4\}$. The demand is known for the whole planning horizon and is represented in a three dimensions matrix of size (T, C, F). As already mentioned, each firm is

[70] Lourenço, H. R., Martin, O. C., & Stützle, T. (2003). Iterated local search. In *Handbook of metaheuristics* (pp. 320-353). Springer, Boston, MA.

assumed to offer a unique product. To simplify the notations, the set of firms is used as the set of products. The locations of all the nodes are given. The distance between two nodes is computed thanks to the Euclidean distance. In this case, the distance matrix is thus symmetrical. The capacities defined in the fourth chapter of this report are considered. A matrix of size (T, S, F) is set to store the quantities of each product that needs to be shipped to each satellite. Moreover, it is more convenient to check the capacities constraints in this configuration.

A solution matrix is needed to store all the itineraries of the planning period. It is a three dimensions matrix of size (T, N, N). Basically, a 1 occur when an arc (i, j) $(i \in N, j \in N, i \neq j)$ is used at time t $(t \in T)$. A 0 is set if the arc is not travelled at time t. An exception is made for the firms which can travel the same arcs at most twice. In this case, a 2 occurs if the arc is used twice by the firm's vehicle. This matrix helps to compute the total cost of the solution. To facilitate the implementation of the metaheuristic, two matrices, which contain vectors representing the itineraries respectively from the satellites and from the depot, are set. For example, for a given satellite at a given time, the vector is the sequence of bike-customers to be visited. This representation makes it easier to apply neighbourhood structure operations and to retrieve the solution.

A backorder matrix of size (T, C) is constructed to memorize the decision related to the delays of customers' orders. If the order of a customer is delayed at time t $(t \in (T-1))$, a 1 occurs, else a 0 occurs. The matrix is therefore binomial.

The elements mentioned are useful to run the metaheuristic. Some of them, such as the solution matrix and the routing vectors, seem redundant but in practice they make the programing and the interpretation of results easier.

2. Functions

i. Function "write solution"

To avoid redundancies in the code, a function is defined to write the solution matrix. The inputs of the function are the itineraries of the satellites and the depot, and the backorder decision matrix. The itineraries are adjusted to take into account the vehicles' capacity. For example, for a satellite's itinerary, the function reads the sequence of bike-customers to be visited. It adds customers to the first trip until the maximum capacity of a cargo-bike is reached. Then, the cargo-bike goes back to the satellite to load for the second trip. Customers are added to the second trip until the cargo-bike is full. And the process repeats until all the customers assigned to the satellite are served. The lading of vehicles may be optimized thanks to the application of the bin-packing problem. However, this aspect is not tackled in this paper. The same rule is applied on the depot's trips.

This function obviously takes into consideration the potential delays. If a customer delivered at time t ($t \in T \backslash \{0\}$) has a backorder at time $t-1$, the delayed order is effectively added to the quantities that need to be delivered at time t. The quantities are computed in terms of volume and weight in order to check the capacities' constraints of the vehicles.

The output of the function is the solution matrix for the planning horizon. It is represented as a (almost) binary matrix for each period of time.

ii. Objective function

In the metaheuristic, the objective function guides the local search. The problem studied focusses on the minimization of the costs incurred by the distribution network. The input of the cost function is a solution matrix. The distance matrix is also necessary to compute kilometres travelled. The output is a total cost in euros. This cost function is composed of different elements.

- **Handling parcels**

This component refers to the handling cost for the parcels along the distribution network. These costs take into account the loading and unloading activities at each echelon. Because no data was available, the estimations are very rough. The calculation is based on the time needed to unload and load a parcel multiplied by the labour cost. The hourly labour cost, including salary, social costs and insurances, can be estimated around 25 euros (Comité National Routier[71]). Arbitrarily, the time required to handle a parcel is in average 20 seconds. Other activities related to shipping are not included in this cost. Per parcel, the cost is thus

[71] Comité National Routier. (n.d.). Simulateurs. Retrieved from http://www.cnr.fr/Outils-simulation2/Simulateurs

computed as follows: $20 * \left(\frac{25}{3600}\right) = 0.14$ €. The parcels ordered by van-customers are handled 4 times (once at the firm, two times at the depot and once at the customer's location), whereas the orders of bike-customers are manipulated 6 times before being in the hands of the end-customers. Total handling cost per parcel for van-customers is 0.56 €, for bike-customers 0.84 €.

$$HP = 0.56 * van\ customers'parcels + 0.84 * bike\ customers'parcels$$

- **Cargo-bikes**

The cost related to cargo-bikes is decomposed in a fixed cost for the use of the vehicle and in a cost per kilometre. The buying cost of cargo bike can greatly vary in relation to its characteristics. Two main options appear, whether a trailer is fixed to a sufficiently powerful electric bike, or the electric cargo-bike is a complete entity designed for freight transport. The cost to buy and maintain an electric cargo-bike is estimated around 10000 € (Ebike, 2020[72]). The lifetime of an electric bike is approximated to 1000 full charges if the vehicle is equipped with a lithium battery (Bicycling, 2019[73]). The lifetime of a cargo-bike is estimated to 4 years with a daily charge on business days. The fixed cost per day for the acquisition and the maintenance of an electric cargo-bike is therefore: $\frac{10000}{4*52*5} = 9.62$ €. A trip per cargo-bike per day is assumed.

The cost per kilometre takes into account the labour cost and the cost of energy. The cost of a deliverer is considered to be 25 € per hour. A cargo-bike has an estimated speed of $12\ km/h$ (Provelo[74]). Per kilometre, the labour cost is 2.08 €. Concerning the cost of electricity, if one kilowatt hour costs 0.25 € and the battery of the cargo-bike consumes $0.5\ kWh$, the autonomy of the battery is around $50\ km$, a full charge costs 0.125 €. For a kilometre the

[72] Ebike (2020, April 23). Eight of the best electric cargo bikes. Retrieved from https://ebiketips.road.cc/content/advice/advice/eight-of-the-best-electric-cargo-bikes-103
[73] Bicycling. (2019, June 10). Your E-Bike Questions Answered. Retrieved from https://www.bicycling.com/bikes-gear/g20045132/your-ebike-questions-answered/
[74] Provelo. (n.d.). Le vélo, c'est sûr, c'est sain et c'est rapide ! Retrieved from https://www.provelo.org/fr/page/le-velo-cest-sur-cest-sain-et-cest-rapide

energy cost is insignificant, but the total variable cost of a kilometre travelled by a cargo-bike is estimated at 2.09 € (Le Soir, 2019[75] and Energuide[76] and Bicyclic[77]).

$$VS = 9.62 * cargo\ bikes\ used\ in\ T + 2.09 * kilometres\ travelled$$

- **Electric vans**

The acquisition cost of an electric van, like the StreetScooter of DHL for example, is between 40000 € and 55000 € (Bierwirth, Kirschstein & Sackmaan, 2019[78]). The lifetime of an EV depends on its battery. Car manufacturers, such as Nissan, ensure a lifetime of at least 8 years (Bebat[79] and Nissan, 2019[80]). The cost per day for an electric van is: $\frac{50000}{8*52*5} = 24.04$ € (considering acquisition cost and maintenance). In the problem, it is assumed that an electric van performs at most a trip per day.

Concerning the labour cost, if an average speed of 50 km/h is considered in the suburban and urban areas. The cost of a deliverer per kilometre is $\frac{25}{50} = 0.5$ €. The electricity cost is based on a battery of 40 kWh and a cost of 0.25 € per kilowatt hour. The autonomy of an electric van is about 100 km, while fully charged (DHL[81]). The energy cost per kilometre is: $\frac{40*0.25}{100} = 0.10$ €. The total variable cost per kilometre of an electric van is 0.60 €.

$$VD = 24.04 * electric\ vans\ used\ in\ T + 0.60 * kilometres\ travelled$$

[75] Le Soir. (2019, November 26). Le prix de l'électricité en Belgique parmi les plus chers d'Europe. Retrieved from https://www.lesoir.be/262870/article/2019-11-26/le-prix-de-lelectricite-en-belgique-parmi-les-plus-chers-deurope
[76] Energuide. (n.d.). What does my electric bike consume? Retrieved from https://www.energuide.be/en/questions-answers/what-does-my-electric-bike-consume/1714/
[77] Bicyclic. (n.d.). Culture GT Vario. Retrieved from https://www.bicyclic.be/fr/produit=culture-gt-vario&id=cultce4db4
[78] Bierwirth, C., Kirschstein, T., & Sackmann, D. (Eds.). (2019). *Logistics Management: Strategies and Instruments for digitalizing and decarbonizing supply chains-Proceedings of the German Academic Association for Business Research, Halle, 2019*. Springer Nature.
[79] Bebat. (n.d.). Quelle est la durée de vie de la batterie d'une voiture électrique ? Retrieved from https://www.bebat.be/fr/blog/duree-batterie-voiture-electrique
[80] Nissan. (2019). LEAF 2019 | Véhicule 100% électrique. Retrieved from https://fr.nissan.be/vehicules/neufs/leaf.html
[81] DHL. (n.d.). StreetScooter Brochure. Retrieved from https://www.streetscooter.com/wp-content/uploads/2019/01/StreetScooter-Brochure-EN-Web.pdf

- **Firms' vehicles**

The vehicles owned by the producers are assumed to be small utility vehicles. They are motor vehicles. The cost to buy and maintain a vehicle is estimated around 20000 € (Citroen[82]). The lifetime of this vehicle is supposed to be ten years. The cost of the vehicle per day is: $\frac{20000}{10*52*5} = 7.69$ €.

The variable cost includes the labour cost and the energy. The journeys are mainly outside of cities, therefore, the average speed of a vehicle is around $70\ km/h$. The labour cost per kilometre is: $\frac{25}{70} = 0.36$ €. Regarding the energy, new utility vehicle can consume about $5.5\ l/100km$ (Citroen). The cost of a litre of diesel is rounded down to one euro (Carbu, 2020[83]). The cost per kilometre is 0.05 €. The estimation of the total variable cost is 0.41 € per kilometre.

$$VF = 7.69 * firms'vehicles\ used\ in\ T + 0.41 * kilometres\ travelled$$

- **Satellites**

The cost of a satellite is difficult to determine. The container can be bought or rented. There is a cost to move the facility. The place where the container is drop can be rented or lent freely by the local authorities or thanks to a private partnership. The possibilities are numerous and strongly depend on the business model of the initiative. Consequently, an arbitrary fixed fee of 50 € per day is considered to use a satellite.

$$FS = 100 * satellites\ used\ in\ T$$

- **Depot**

As soon as a single order is transported in the time period, a cost to use the depot should be recorded. No data is available and the cost to use the cross-docking centre depends on the

[82] Citroen. (n.d.). Citroën Jumpy - Utilitaire - Prix, essai et caractéristiques. Retrieved from https://business.citroen.be/fr/vehicules-utilitaires/fourgons/citroen-jumpy.html
[83] Carbu. (2020). Les meilleurs prix pour chaque carburant en Belgique. Retrieved from https://carbu.com/belgique/meilleurs-prix/Belgique/BE/0

partnerships concluded in the project framework. Arbitrarily, a daily fee of 200 € is considered to transport goods through the cross-docking centre.

$$FD = 200 * days\ of\ depot's\ use$$

Total cost function

The objective is to minimize the following total cost function:

$$Cost\ function = HP + VS + VD + VF + FS + FD$$

It is important to note that, in the problem, delaying an order does not incur additional cost, neither penalty. The cost function based on the solution matrix is easy and quick to compute. It is the key element for the local search to make decisions at each iteration.

3. Procedure

The optimization procedure applied to solve the problem is a local search metaheuristic, more precisely a steepest descent. Nevertheless, in the metaheuristic proposed in this paper, some modifications have been made compared to the classic local search. The input of the metaheuristic is a random initial solution and the output is a locally optimal solution.

```
pseudocode steepest descent based metaheuristic

Initialize a random solution x and its objective function F(x)
Set best solution x* = x and F(x*) = F(x)
    best neighbour x̄ = x* and F(x̄) = F(x*)
Initialize F(start_solution) = F(x*) and F(end_solution) = 0

While F(start_solution )! = F(end_solution) do
        Update F(start_solution ) = F(end_solution)
        Set i = 1
        While i ≤ 3
                Repeat size(N^i(x*)) times
                        Set new_solution = x*
                        Repeat k-time(s) to change k-element(s) of new_solution
                                Apply local change of N^i to new_solution
                        If F(new_solution) < F(x̄)
                                Update x̄ = new_solution and F(x) = F(new_solution)
                If F(x) < F(x*)
                        Set x* = x̄ and F(x*) = F(x)
                Update i+= 1
        Update F(end_solution) = F(x*)
```

Figure 3: Pseudocode metaheuristic

The metaheuristic constructed follows the same principles explained in the point *A. Broad concept of this section*. The main difference is that the three neighbourhood structures are applied successively. $N^i(s)$, in the pseudocode above, represents the neighbourhood of a solution built with the neighbourhood structure i. The neighbourhood structures have been briefly described under the title *"Neighbourhood"*. More details about their implementation in the heuristic are provided in this part of the report.

In this problem, it was hard to figure out a single transformation which provides the entire neighbourhood of a solution. For that reason, three ways to perform a local change have been thought out. An alternative manner to deal with it would have been to generate a probability which determines the neighbourhood structure to be applied at the given iteration. Coherently, the performances of the two methods were rather similar. Therefore, the method described in the pseudocode was kept; the local changes are applied successively.

As already mentioned previously, when the solution and its objective function are set, the corresponding matrices (satellites and depot routing, backorders) are set as well. Local changes are not directly applied to the solution matrix, but on the matrices which save the routing and the backorders.

- First neighbourhood structure: Satellites

The first neighbourhood structure changes the rounds starting from satellites and the customers' allocation to satellites. Changing the customers' assignment to satellites entails changes in the depot routing. The implementation is made following the pseudocode above.

```
pseudocode neighbourhood structure 1

Choose a random time t (t ∈ T)
       a random satellite s (s ∈ S)
If new_satroad of s at t is not empty
     Choose a random customer c (c ∈ bike customers) in new_satroad of s at t
     Remove c from new_satroad of s at t
     Choose a random satellite s′ (s′ ∈ S)
     If the capacity of s′ at t is sufficient to serve c in addition
          Append c to new_satroad of s′ at t
          If new_satroad of s at t is empty
               Remove s from new_depotroad at t
          If s′ is not in new_depotroad at t
               Append s′ to new_depotroad at t
     Else
          Append c to new_satroad of s at t
```

Figure 4: Pseudocode first neighbourhood structure

- Second neighbourhood structure: Depot

In the second neighbourhood structure, a local change is applied on the depot route. Two elements are exchanged. The pseudocode is straightforward.

```
pseudocode neighbourhood structure 2

Choose a random time t (t ∈ T)
If new_depotroad at t contains more than one element
     Swap randomly two elements of new_depotroad at t
```

Figure 5: Pseudocode second neighbourhood structure

- Third neighbourhood structure: Backorder

This last neighbourhood structure concerns the delayed orders. An element of the backorder matrix is modified. Consequently, the satellites and depot routes are altered as well. The first part of the pseudocode allows backorders for bike-customers, whereas the second part allows backorders for van-customers. The coin is biased according to the percentage of van and bike-customers

```
pseudocode neighbourhood structure 3

Choose a random time t (t ∈ T)
Toss a biased coin (80 – 20%)
If coin == 1
        Choose a random customer c (c ∈ bike customers at t)
                a random satellite s (s ∈ S)
        If the capacity of s at t is sufficient to append c
                If t == 0 or c is not backordered at t − 1
                        If c is not already backordered at t
                                Backorder c at t
                                Remove c from new_satroad of its satellite s′ at t
                                If new_satroad of s′ at t is empty
                                        Remove s′ from new_depotroad at t
                                If c is not assigned to any satellite at t + 1
                                        Append c to new_satroad of s at t + 1
                                        If s is not in new_depotroad at t + 1
                                                Append s to new_depotroad at t + 1
If coin == 0
        Choose a random customer c (c ∈ van customers at t)
        If t == 0 or c is not backordered at t − 1
                If c is not already backordered at t
                        Backorder c at t
                        Remove c from new_depotroad at t
                        If c is not in new_depotroad at t + 1
                                Append c to new_depotroad at t + 1
```

Figure 6: Pseudocode third neighbourhood structure

- Stopping criterion

The typical stopping criterion in local search is to stop the search when the solution cannot be improved by a local change. In the case of this metaheuristic, the program stops when a local change related to any of the three neighbourhood structures cannot lead to a better solution. In medium to large size instances, the choice to not explore the entire neighbourhood of the solution can be made. Consequently in this situation, it can be useful to allow the metaheuristic to perform some additional iterations even when the local optimum seems reached. A vector can be set to save the cost of the k-th last iterations. If all the elements of the vector are identical, the heuristic stops. Stopping criteria will be discussed in the chapter 6 on numerical experiments.

E. Lower bound

A lower bound is a solution which is smaller than any feasible solution, or equal to the optimal solution. In this paper, a lower bound representing an infeasible solution will be established. Indeed, no optimal solution has been computed in this master's thesis framework. Moreover, one of the objectives of this paper is to test the metaheuristic on realistic data. On medium to large instances, exact methods are extremely costly in terms of computational time.

Lower bounds are useful in minimization problems. At least partly, they help to assess the quality of the local optimum provided by an algorithm. In fact, if the lower bound is sufficiently close to the optimum, it is possible to accurately assess the performance of the heuristic thanks to the error rate (Crama, 2019). The lower bound proposed in this paper gives a wide estimation of the optimal solution. Still, it allows to know if the final solution found by the heuristic is very far or not from the optimal solution.

Lower bounds can be constructed in many different ways. The method applied for this lower bound is to relax constraints from the minimization problem. The capacities constraints are relaxed. In addition, this solution is not based on true routes. The lower bound proposed is therefore infeasible. The details of its construction are given in the following paragraphs, echelon by echelon.

For this lower bound, the orders are aggregated with the aim of reducing fixed daily costs. Transport activities are planned on t ($t \in T$) when it is an even number, and on the last day of the planning horizon. This set of periods is T'. Concretely, at t even, the demand of t and of $t-1$ is satisfied. For the last t, only the demand of this last day is satisfied.

- Satellites

The set of bike-customers to be served at each $t'(t' \in T')$ is defined. For the routing, a single satellite is considered at each t'. For each t', the minimum distance between any potential satellites and the bike-customers at t' is selected and added twice (round trip) to the total distance travelled in cargo-bikes, $distance_{sat}$. For each bike customers delivered at t', the minimum distance between him and any another bike customers is selected and added to $distance_{sat}$.

Even if in the routing problem a unique satellite is used, the minimum number of satellites required to satisfy the demand at t' is still computed. At each t', the total volume and weight of the demand is measured. To determine the minimum number of satellites needed at t', the following formula is applied: $\mathrm{ceil}\left(\max\left(\frac{\mathrm{volume_{demand}}}{\mathrm{volume_{sat}}}, \frac{\mathrm{weight_{demand}}}{\mathrm{weight_{sat}}}\right)\right)$. Almost the same formula is used to determine the number of trips travelled in cargo-bikes at t'; $volume_{sat}$ is replaced by $volume_{bike}$, and $weight_{sat}$ by $weight_{bike}$.

- Depot

The set of van-customers to be delivered at each $t'(t' \in T')$ is known. At each t', the minimum distance between the depot and, the set of potential satellites and the set of van-customers, is retrieved and added twice (round trip on symmetrical distance matrix) to the total distance travelled by electric vans, $distance_{depot}$. A single satellite is considered for the routing. Therefore, the minimum distance between any satellite and, the depot and the van-customers, is added to $distance_{depot}$. Then, for each customer c in the set of van-customers at t', the minimum distance between c and any other van-customer is selected and appended to $distance_{depot}$.

In the routes, the capacities are neglected. However, the number of trips which start from the depot is calculated. The total volume and weight of the demand is measured at t'. The following formula is applied: $ceil\left(\max\left(\frac{volume_{demand}}{volume_{van}}, \frac{weight_{demand}}{weigh_{\ van}}\right)\right)$.

- Firms

Regarding the journey of the firms' vehicles, for each t' $(t' \in T')$, the distance from the firm to the depot, as well as the return trip are taken into account if the firm has at least one order at the time period. These distances add up to form the total distance travelled by firms' vehicles, $distance_{firm}$.

To determine the minimum number of trips needed to satisfy the demand, the volume and the weight of the total demand at each t' is computed. The number of trips required is given by the formula: $ceil\left(\max\left(\frac{volume_{demand}}{volu\ \ _{firmvehicl}}, \frac{weigh\ \ _{demand}}{weigh\ \ _{firmvehicle}}\right)\right)$.

Total cost

The lower bound is given by the cost function described in the section *2.ii. Objective function* of this chapter. The calculation to obtain the lower bound is therefore:

$$distance_{sat} * 2.09 + distance_{depot} * 0.6 + distance_{firm} * 0.41 + number_{sat} * 50$$
$$+ number_{bike} * 9.62 + number_{van} * 24.04 + number_{firmvehicl} * 7.69$$
$$+ number_{depot} * 200 + parcels_{van} * 0.56 + parcels_{bike} * 0.84$$

F. Technical requirements

The script of the metaheuristic has been written in the programming language Python. It was run on the interface Spyder (Anaconda). No library especially made for local search has been used in the implementation. All the functions, local changes and matrices have been designed specifically for the problem studied. Some common libraries have been utilized for the metaheuristic, such as pandas, numpy, random and copy. To write the solution on graphs, the library matplotlib has been used. It should be mentioned that the major part of my learning over Python has been made during the development of this master's thesis. W3schools.com tutorials and Stack Overflow forums have been really helpful to implement this heuristic.

Chapter 6: Numerical Experiments

One of the advantages of local search algorithms is to determine good solutions in relatively short amount of time and with basic live memory. Consequently, the main aspect to evaluate a metaheuristic is the trade-off between the quality of the solution and the computation time (Dorigo & Stutzle, 2003).

In this master's thesis, the interest of numerical experiments is twofold. First, the heuristic will be tested on multiple instances. The goal is to assess the performance of the heuristic and to tune the local search in order to better the trade-off between quality and time. The metaheuristic can thus potentially be modified in the testing phase. These numerical instances, even if they will be partly defined randomly, they still will be in accordance with the geography of the area of Liège-Namur. Indeed, instances cannot be set totally randomly; they have to somehow fit with the problem studied.

Secondly, the metaheuristic will be tested on realistic data, on the case of Liège-Namur area. These instances will be less randomized. In fact, the locations of the firms, the depot and the satellites should be true potential locations for the type of facility. Concretely, for example, a satellite should not be located in a pedestrian or a firm in a wood. For that reason, a brief analysis of the geographical locations of the facilities will be carried out. The aim is to retrieve the most realistic data from documents about the area, satellite imagery and my knowledge as a native of the region. The various tools used to create the instances and map the results will be described further in this chapter.

The aim of this chapter is finally to evaluate the advantage of a one-day delay tolerance to deliver orders. This characteristic of the Multi-Echelon VRP is the main contribution of this paper. Conclusions will be drawn from the test instances and from the more realistic instances. Comments will be made on the interest of allowing backorders.

A. Test instances

This part of the chapter concerns tests on totally made-up instances. This section will deal with small and medium instances. Larger instances will be developed with realistic data. Testing the metaheuristic on various instances is essential. Basically, it permits to know if the heuristic is working properly. Primary observations on the relevance of the metaheuristic used to solve the problem can be stated at this stage. These observations often lead to changes in the heuristic. Once tuned, the performances of the metaheuristic will be evaluated and the negative and positive aspects of the method will be highlighted. Examples of complete solutions will be provided. Lastly, comparisons between optimized solutions with and without allowing a delay will be carried out.

1. Instances' construction

The instances tested are randomized. They are built following the characteristics of the problem studied. Two sizes of instances are defined:

- Small instances: 2 firms, 1 depot, 3 potential satellites, 20 to 50 customers
- Medium instances: 4 firms, 1 depot, 4 to 7 potential satellites, 50 to 100 customers

The number of customers served is randomly chosen in the range set. For medium instances, the number of potential satellites is also randomly chosen in the given range. Each instance has a planning horizon of five days. 20% of the total customers are van-customers, they are randomly chosen among the set of customers. Other customers are bike-customers.

A single product is sold by each firm. The volume and the weight of each product are determined randomly in intervals. The minimum volume of a product is $0.000125\ m^3$, which corresponds to a package of dimensions $5\ cm * 5\ cm * 5\ cm.$ The maximum volume is $0.2815\ m^3$, which corresponds to a box of $75\ cm * 75\ cm * 50\ cm$. Concerning the weight, the product can weigh between $0.1\ kg$ and $10\ kg$. The maximal limitations in terms of volume and weight are rather low compared to offers of well-known carriers (Bpost, 2020[84]). It is appropriated to the problem studied. To deliver rather big packages, the distribution network should potentially be adjusted. This case won't be analysed in this paper.

The demand matrix is randomized. Logically, an order is set for each customer at a random time t ($t \in T$) and for the product of the random firm f ($f \in F$). Additionally, Some of the customers are allowed to order the same product multiple times or multiple products, on the same day or on different days.

[84] Bpost. (2020). Préparer un colis. Retrieved from https://www.bpost.be/site/fr/envoyer/envoyer-des-paquets/preparer-un-colis

The different facilities and the customers have to be located in specific areas. The scheme below illustrates the potential locations of the nodes. The areas are defined according to the geography of the real case of Liège-Namur. The firms are located in the yellow zone, which has a surface of $2000\ km^2$. It represents the area of Mons and Namur. The depot is located in the blue zone, between Namur and Liège. The pink zone represents the region of Liège. The red zone is the city centre (wide estimation of $49\ km^2$) where satellites and most customers are situated. Each node is randomly determined within its respective area.

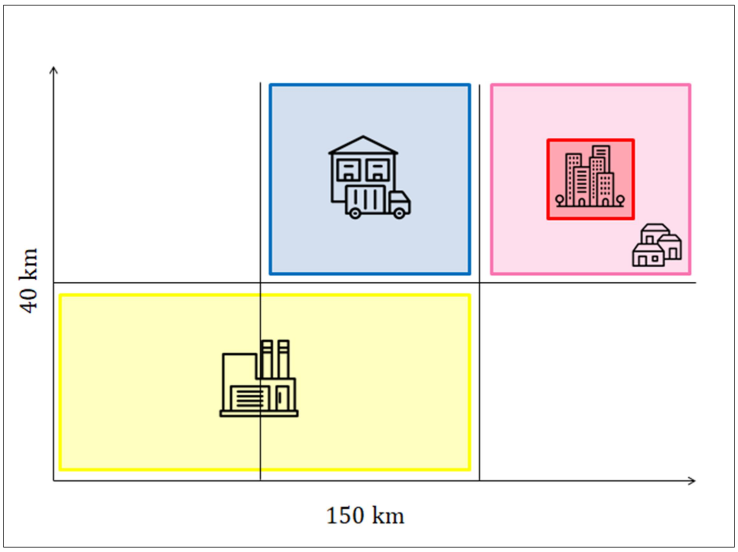

Figure 7: Scheme location in test instances

Regarding the capacities of the facilities and vehicles at each echelon, they are set as explained in the section A of the fourth chapter of this paper. They do not vary according to the size of the instance.

2. Tuning

In the development phase of the metaheuristic, a unique small instance was used. In fact, at this stage, the aim was to build a heuristic which was working properly and which was providing feasible solutions. The development was made on a theoretical vision, which was neglecting some aspects of the performance. Improving the performance and creating the metaheuristic simultaneously was confusing. Potential errors were more difficult to identify and the impact of a specific improvement was hard to evaluate because the foundations of the metaheuristic were not reliable. The followed strategy in this master's thesis was to develop a reliable metaheuristic and to review it to improve its performances. The first subsection will focus on significant improvements on the working of the metaheuristic. The second subsection will discuss the fine tuning of parameters.

i. Improvement of the metaheuristic

The basic metaheuristic described in the chapter 5 was promising. Once it was working smoothly and I was getting comfortable with all of its aspects, it was tested on various small instances. Running the heuristic on small instances permits to easily target where it could be upgraded. Displaying the solution on graphs to clearly see the routes was very useful. On small instances, it was possible to detect where the heuristic could do better. For example, when some arcs are crossing each other in the same route or when too many satellites are open. These observations can be made just by analysing graphs. Given that different neighbourhood structures have been built and that they focus on specific local changes, it was simple to identify where the metaheuristic should be modified to reach the expected solution. For the most part, the principle of the metaheuristic defined previously was kept. Nevertheless, some points have been modified and features have been added in order to improve the global performance of the metaheuristic.

- **Additional neighbourhood structure**

The analysis of the first results showed that the routes from the satellites were intuitively too far from the best solution. Too many arcs between bike-customers were crossing each other, increasing the distance travelled by cargo-bikes. In fact, the neighbourhood structure related to satellites (*section D. 3 of the chapter 5*) is probably too wide. Therefore, a very simple neighbourhood structure has been added to the metaheuristic. The local change operated is simply a swap between two bike-customers assigned to the same random satellite at a random time. This leads to an interesting improvement of the solution, closer to the optimality. The extra neighbourhood structure does not burden much the metaheuristic. The additional operations performed require very little computation time.

- **Order of the local changes applied**

A part of the contribution of this master's thesis is to evaluate the impact of allowing a delay in the delivery of small parcels. Rapidly, it was observed that backorders were crucial to reduce costs, especially when the volume of the demand is relatively small. The gain to aggregate the demand of two days is important.

Another observation made at this stage was that the random initial solution was always poor. Indeed, this initial solution forbids delays. Moreover, bike-customers are split in between all the potential location for satellites. In these settings, the network does not benefit from any economies of scale. To quickly improve this poor initial solution, backorders must be set and the number of open satellites must be reduced. To apply this strategy, the order of local changes performed has to be modified. Additionally, adjusting the parameters, linked to the neighbourhood size or the number of moves accepted on the solution for example, is also required to fast improve the initial solution. The latter tuning will be discussed in the second title of this subsection.

The order of neighbourhood structure which yields the best performance is the following:

1. Backorders: A random customer-order at a given time is delayed at the following day.
2. Inter-satellites routing: A bike-customer is assigned at another satellite or appended at the end of its current satellite, at a given time.
3. Intra-satellites routing: Two bike-customers assigned to the same satellite at a given time are swapped.
4. Intra-depot routing: Two van-customers or satellites are swapped at a given time.

The second and third points may seem redundant but the performances of the metaheuristic are better and more reliable when both neighbourhood structures are applied successively. In the problem studied, this approach seems to be efficient.

- **Deterministic insertion of customers**

While reviewing the metaheuristic, an aspect of the local changes on backorders and on intra-satellites routes was too stochastic. For these two neighbourhood structures, it was defined that a randomly chosen customer c $(c \in C)$ at a given time would be removed from its route and appended at the end of another. However, appending arbitrarily the customer c at the end of the route is not efficient. Indeed, according to the place where the customer c is added in the sequence, the impact on the cost can greatly vary.

In addition, even if it is still interesting to append the customer c at the end of the sequence, adding it at its best position in the sequence can diminish the number of iterations required to reach the local optimum. Consequently this improvement leads to a reduction of the computational time.

Concretely, the arcs from the customer c to every customer already in the route are retrieved. The arc which corresponds to the minimum distance is selected. The customer c is inserted just before the customer $c'(c' \in C\backslash\{c\})$ located the closer to him. This approach should minimise the total distance of the route.

ii. Fine tuning of the parameters

At this stage, the upgraded version of the metaheuristic is available. However, some parameters must be set appropriately. Three aspects are discussed in this subsection. First, by referring to the definition of a neighbour, the maximum number of components which differs between the solution and its neighbour is determined. Secondly, the size of the neighbourhood is set. Thirdly, to improve the performance of the metaheuristic, it is allowed to run multiple times the same neighbourhood structure before passing to the subsequent neighbourhood structure. The number of iterations allowed is therefore determined. These three aspects are examined for each neighbourhood structure.

To keep a reasonable computation time, it might be necessary to restrain the neighbourhood size. To mitigate the influence of a reduction of the neighbourhood's search space, some adjustments can be made on the stopping criterion. The metaheuristic proposed stops when the solution has not been improved during two complete iterations.

To set the right value for each parameter, it is important to determine the objectives of the fine tuning. In this case, two goals are targeted. The metaheuristic should return a good solution in a reasonable computation time. In addition, the metaheuristic should most of the time lead to a satisfactory solution. The idea is to reinforce the reliability of the metaheuristic.

- **Small instances**

All of the following parameters have been tuned for small instances. The value given to each parameter is set experimentally. These settings lead to the best trade-off between computation time, quality and reliability.

  - Backorders

It was observed that a fast way to obtain a good solution was to delay the adequate orders. Once every order, which represents a lower transportation cost when delayed, is effectively delayed, there is no need to keep searching the neighbourhood structure related to backorders. Therefore, local changes for backorders can only occur on the three first complete iterations of the metaheuristic. Afterwards, the neighbourhood structure is skipped. The other parameters are defined in the table below.

Parameters	Values
Maximum number of moves accepted	5
Neighbourhood size	25
Maximum number of elements changed	5

  - Other neighbourhood structures

Parameters	Intra-satellites routing	Inter-satellites routing	Depot routing
Maximum number of moves accepted	5	3	1
Neighbourhood size	25	25	10
Maximum number of elements changed	5	6	2

- **Medium instances**

For these instances' sizes, most parameters have been set arbitrarily thanks to experiments. The computation time was an important driver in the parameters' tuning of larger instances, especially when the instances are run on a relatively limited computer.

- Backorders

Similarly for small instances, orders are delayed in the first three iterations of the metaheuristic. Then, the neighbourhood structure is skipped.

Parameters	Medium
Maximum number of moves accepted	10
Neighbourhood size	25
Maximum number of elements changed	10

- Other neighbourhood structures

Parameters	Intra-satellites routing	Inter-satellites routing	Depot routing
Maximum number of moves accepted	5	5	3
Neighbourhood size	25	25	15
Maximum number of elements changed	5	10	6

To conclude this section, two remarks can be stated. It can be noticed that the whole neighbourhood of the current solution is not explored. In fact, only a part of the neighbourhood is explored. The metaheuristic is thus not a pure steepest descent. Also, all of the parameters have been adjusted experimentally. In practice, these parameters have been tested on various different instances and have shown promising results.

3. Evaluation and performance

The metaheuristic built, improved and tuned must be properly assessed. It should be reminded that the heuristic has been constructed thanks to theoretical concepts. Then, it has been improved and tuned thanks to many experiments. Its performance will be evaluated for each size of instances. In this section, the performance of the metaheuristic on small and medium instances will be reviewed. Large instances will be discussed in realistic tests on Liège-Namur area.

i. Small instances

- **Multiple trials on random instances**

To assess the performance of the metaheuristic on small instances, the lower bound described in the chapter 5 is used. On larger instances, the lower bound is less relevant due to the specific constraints relaxed for its construction. The larger the instance is, the more the constraints related to capacities play an important role on the optimization process. The table below represents the results given by twenty trials on randomized instances. The results displayed correspond to the first run of each different random instance. On a sample of twenty trials, the final solution provided by the metaheuristic is 26% higher than the lower bound. This percentage can probably be reduced if a multi-start strategy is applied. However, on the first run, the results are satisfactory. Moreover, the quality of the solutions provided is quite stable. The metaheuristic tends to always end up on an acceptable solution.

trial	C	lower_bound	solution	percentage	seconds
1	37	1381,5	1707,31	24%	47
2	34	1205,96	1520,27	26%	32
3	28	1351,06	1505,09	11%	18
4	50	1364,88	1733,14	27%	79
5	47	1302,68	1575,24	21%	95
6	31	1136,94	1492,83	31%	22
7	42	1286,47	1607,67	25%	50
8	31	1300,79	1576,77	21%	39
9	45	1367,48	1734,52	27%	50
10	40	1160,36	1444,05	24%	54
11	38	1368,07	1633,73	19%	42
12	46	1387,88	1776,38	28%	61
13	46	1146,67	1477,35	29%	48
14	43	1182,17	1513,16	28%	36
15	25	1228,13	1436,08	17%	14
16	38	1315,33	1646,35	25%	37
17	38	1310,2	1804,89	38%	43
18	43	1371,81	1812,17	32%	56
19	26	1220,02	1463,05	20%	15
20	37	1273,77	1977,5	55%	32

Figure 8: Small instances solutions compared to lower bound

- **Focus on a single instance**

  a. Characteristics

The instance chosen is composed of 2 firms, 1 depot, 3 potential satellites' locations, 35 customers (28 bike-customers and 7 van-customers), 39 parcels delivered (20 of product 0 and 19 of product 1) in 5 periods of time. Two different products are delivered.

	Volume	Weight
Product of firm 0	0.01028758 m^3	0.3 kg
Product of firm 1	0.03811651m^3	7. kg

The location of the nodes is given by the graph below. Yellow dots are firms, the blue dot is the depot, green dots are potential satellites locations, pink dots are van-customers and red dots are bike-customers. The distances are measured in kilometres.

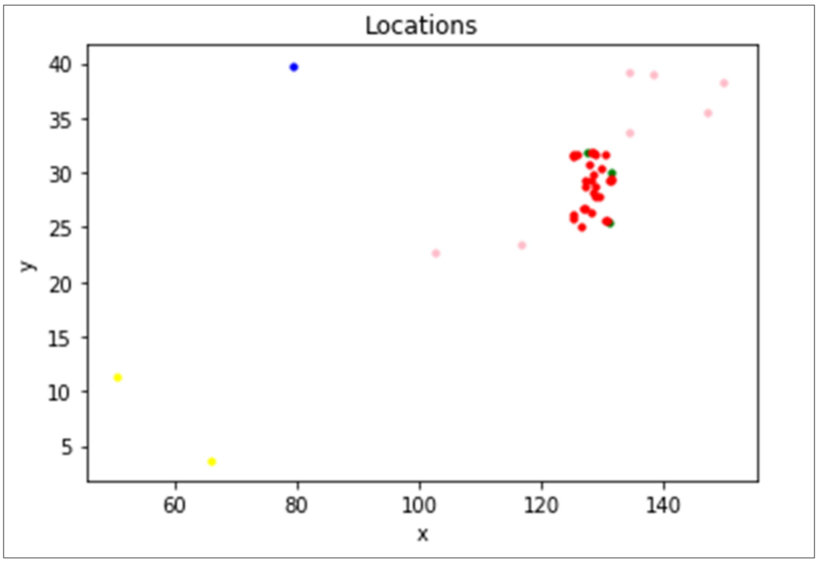

Figure 9: Locations graph - Small instance

  b. Performance

Ten trials have been performed on the same small instance. The results are given in the following table. The final solution tends to be in the same range of total cost. On small instances, the metaheuristic seems to match the expectations in terms of reliability of the final solution. The range between the best and the worst trial is of 187€.

trial	seconds	lower_bound	start_solution	end_solution	percentage
1	30	1245,27	3220,64	1452,68	17%
2	23	1245,27	3269,97	1534,65	23%
3	23	1245,27	3193,88	1624,25	30%
4	23	1245,27	3306,28	1627,5	31%
5	27	1245,27	3242,32	1450	16%
6	23	1245,27	3258,92	1539,26	24%
7	22	1245,27	3310,46	1548,51	24%
8	27	1245,27	3241,12	1461,64	17%
9	25	1245,27	3262,39	1440,41	16%
10	28	1245,27	3293,79	1449,97	16%

Figure 10: Trials on a small instance

The way the solution is improved is shown in the graphs below. They take into account the evolution of the best trial. The first graph represents the evolution of the total cost after each complete iteration. This graph takes into account the solution provided at the end of an iteration on the four neighbourhood structure successively.

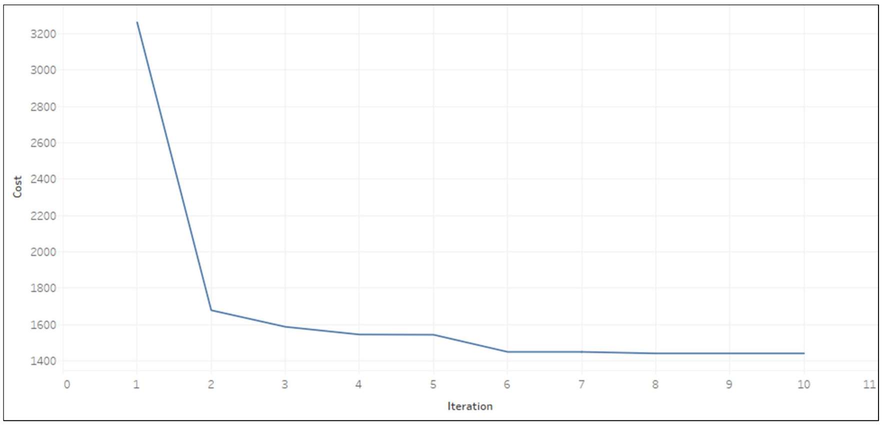

Figure 11: Evolution of the total cost at each complete iteration

The second graph is more detailed. It shows the evolution of the total cost after an iteration of any of the neighbourhood structure. On both graphs, it can be noted that the slope is very steep at first. Then, the solution encounters plateaus and the improvements are relatively small. In some ways, these graphs show the importance of allowing delays when dealing with small demand volume.

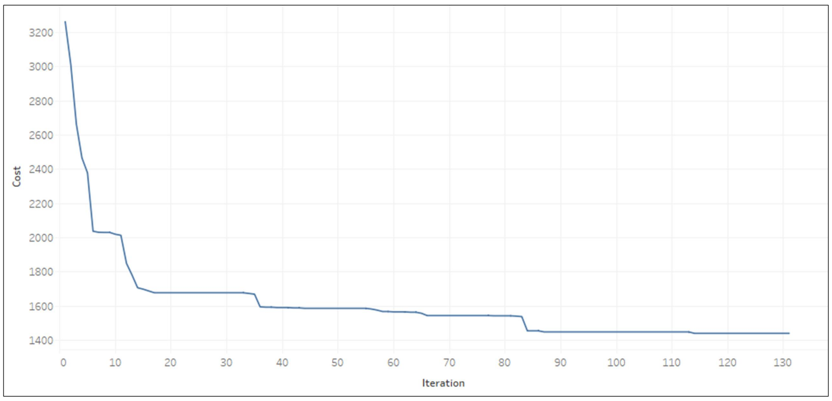

Figure 2: Evolution of the total cost at each neighbourhood structure iteration

c. Best solution

This subsection illustrates the result of the best trial of the chosen small instance. It can be easily noticed that the best solution provided by the metaheuristic in ten trials is suboptimal. An obvious indicator that the solution is not optimal is that some arcs cross each other. More precise local change, for example, only changing a single element at a time might lead to better results. However, this represents extra computational time for slight reduction in terms of cost. The graphs illustrate the routing provided by the metaheuristic during the best trial on the small instance.

Operations occur on Tuesday, Wednesday and Friday. On Tuesday, only the satellite on node 4 is open. It serves the customers $\{30, 13, 35, 32, 28, 36\}$. The depot distributes goods to the customers 26 and 6, then to the open satellite. On Wednesday, the satellite on node 3 is used and serves the customers $\{33, 37, 17, 22, 10, 12, 39, 20, 21, 9, 31, 7, 23, 27\}$ in this order. The depot delivers the customers $\{38, 8, 19\}$ and the open satellite. On Friday, the satellite on node 5 is open and the customers $\{7, 34, 29, 24, 15, 18, 25, 40, 31, 16\}$ are delivered in this order by cargo-bikes. The depot serves the customers 11 and 14, then the open satellite. The two firms transport their goods to the depot on Tuesday, Wednesday and Friday. The journey from firms to the depot is the same for the three operating days (Appendix 1). The schemes of the routing for the three days are provided in the next page.

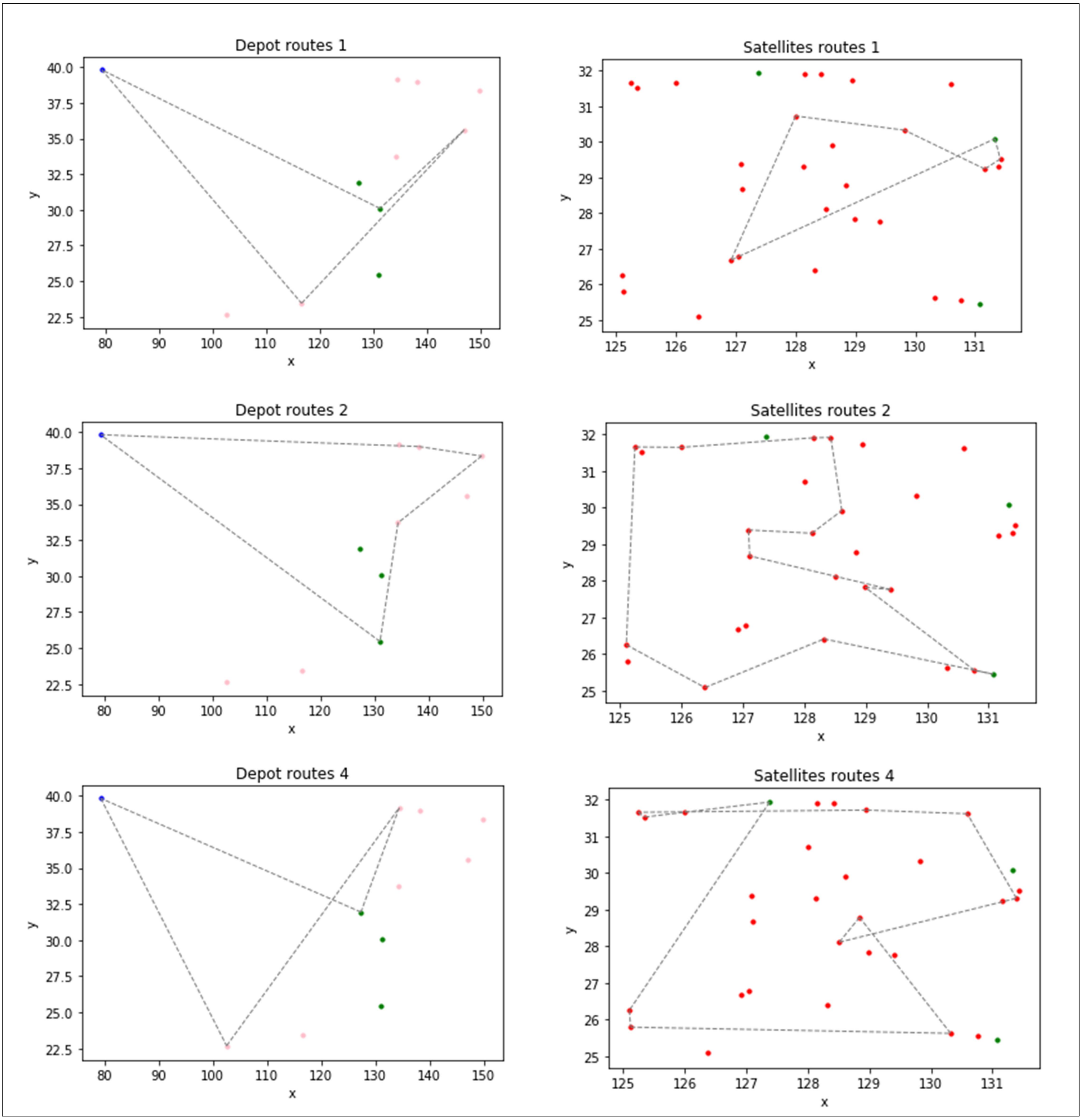

Figure 3: Depot and satellites routing for small instance

In brief, the metaheuristic leads to good solutions on small instances. It is not computationally expensive. Inherently, local search metaheuristics permit to get closer to the optimal solution but they usually get trapped in local optima. In the tests, in fact, the final solution could not be improved in the number of local changes allowed by the heuristic. The metaheuristic was thus stuck and ended up its exploration.

ii. Medium instances

Some tests on randomized medium instances have been realized. The results can be found in the appendix 2. Comparing the end solution and the lower bound is less meaningful for larger instances due to the way the lower bound is constructed. Regarding the computation time, the metaheuristic reaches the local optimum in approximately 5 minutes. The solutions provided seem decent.

The metaheuristic performs well according to the following graph. It shows the progression of the heuristic by retrieving the total cost at the end of each iteration of each neighbourhood structure successively.

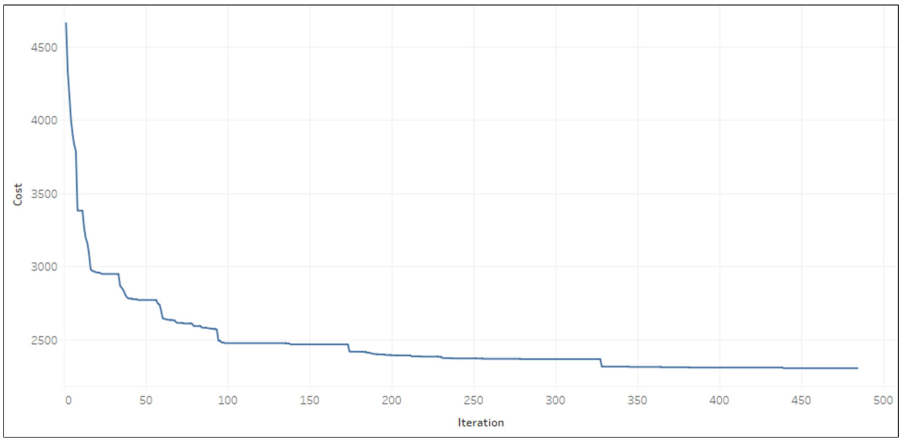

Figure 14: Evolution of the cost at each neighbourhood iteration

Multiple trials on a single instance

Multiple runs have been performed on the same medium instances in order to examine the results provided by the metaheuristic. The randomized medium instance tested is composed of 4 firms, 1 depot, 6 potential satellites' locations, 80 customers (64 bike-customers and 16 van-customers). A planning horizon of 5 days is considered. The total demand on the planning horizon is of 88 parcels. Four different products can be ordered. The location of the nodes is represented in the graph below. The distances are in kilometres.

	Volume	Weight
Product of firm 0	0.16064628 m^3	6.3 kg
Product of firm 1	0.01884583 m^3	0.5 kg
Product of firm 2	0.1293786 m^3	2.9 kg
Product of firm 3	0.03501126 m^3	5.7 kg

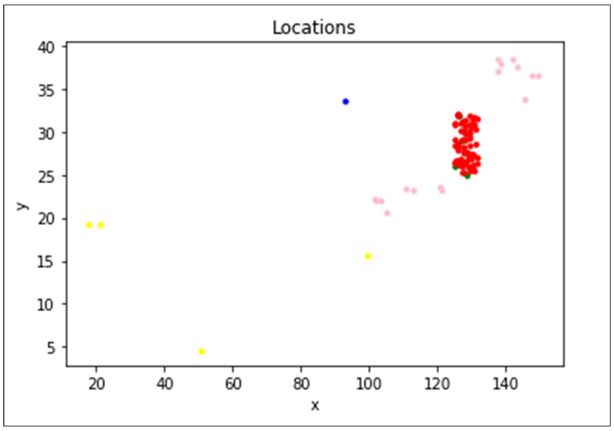

Figure 15: Locations medium instance

The instance chosen is interesting to examine because it takes into account small products and larger and heavier products. In small instances, with relatively small parcels, best solutions are typically the ones in which the parcels are consolidated in a single satellite. For larger instances, even more with bigger products, the heuristic tends to stop on solutions with multiple satellites open at the same period of time. Few local changes will not be sufficient to consolidate all the customers to a single satellite. The solution reached is not optimal but it is effectively a local optimum. The results of the seven trials are provided in the table below. The routing for the planning horizon can be found in the appendix 3. Once again, the tolerance of a one-day delay leads to an important cost reduction. In the best solution of this medium instance, deliveries occur on Tuesday, Thursday and Friday.

trial	time	lower_bound	start_solution	end_solution
1	4:32	1622,9	5295,37	2320,47
2	5:27	1622,9	5244,18	2371,75
3	5:32	1622,9	5265,89	2482,17
4	4:54	1622,9	5224,77	2322,21
5	3:45	1622,9	5242,56	2362,87
6	5:34	1622,9	5286,7	2431,54
7	3:22	1622,9	5256,49	2307.45

Figure 16: Trials on a medium instance

The performances of the metaheuristic on medium instances are less impressive than on small instances. The initial solution which splits the customers on every potential satellite locations is very poor, especially when the number of potential locations is increasing. On realistic data of Liège-Namur area, an adjustment will be tried out to tackle this issue.

4. Solution with and without a one-day delay

An aspect of this master's thesis is to demonstrate the impact of allowing a delay in a multi-echelon distribution network. In terms of cost, it is interesting to compare the difference between the two policies, which are allowing or not backorders. For an instance, the metaheuristic is run once according to each policy. To be accurate, the heuristic will start on the same initial solution. For small and medium instances, the results are recapped in the following table.

small	C	S	initial_solution	no_delay	time_no_delay	delay	time_delay	difference
1	46	3	3370,33	2508,81	00:33	1674,04	00:43	834,77
2	49	3	3282,58	2398,32	00:45	1628,26	00:55	770,06
3	37	3	3140,44	2261,41	00:20	1807,02	00:25	454,39
4	44	3	3289,52	2351,03	00:34	1535,2	00:47	815,83
5	40	3	3169,22	2461,53	00:28	1495,5	00:57	966,03
medium								
1	87	6	5703,25	3448,58	02:29	2387,76	05:46	1060,82
2	75	7	5201,31	3000,72	04:33	2309,02	01:58	691,7
3	88	7	5657,26	3289,71	06:26	2271,37	04:43	1018,34
4	65	6	5145,68	3052,5	03:37	2188,84	05:34	863,66

Figure 17: Results impact backorders

The conclusion is manifest, tolerating a one-day delay leads to a cost reduction, on small and medium instances at least. Regardless of the trial, the difference between the cost with and without backorders is significant. Moreover, it does not cost much extra computation time.

B. Liège-Namur area

The second part of the tests focusses on realistic data based on Liège. The case is treated as a large instance. The construction of the instance is essential because no data of a real-case have been provided in the framework of this master's thesis. Tools to map the locations and the routes will be used. In addition, minor adjustments will be made to provide the best results on larger instances. Then, the solutions provided will be reviewed. A final point will analyse more precisely the impact of the tolerance of a one-day delay on a distribution network which deals with larger demand volume.

1. Instances' construction

i. Analysis of the area

- **Characteristics of large instances**

For the tests on a realistic case, large-size instances are studied. The distribution network is composed of 6 firms, 1 depot, 8 to 15 potential satellites' locations, 100 to 250 customers. Regarding the planning horizon and the products' dimensions, these characteristics are similar to the ones of smaller instances, described in the previous section of this chapter. Concerning the demand, only 5% of extra demand is considered; otherwise a customer has a single order in the time-period.

- **Location**

To test the metaheuristic on a realistic case, the areas where the different facilities could be located must be delineated. The map below shows the global picture. However, a more precise analysis is provided in zooming on each echelon.

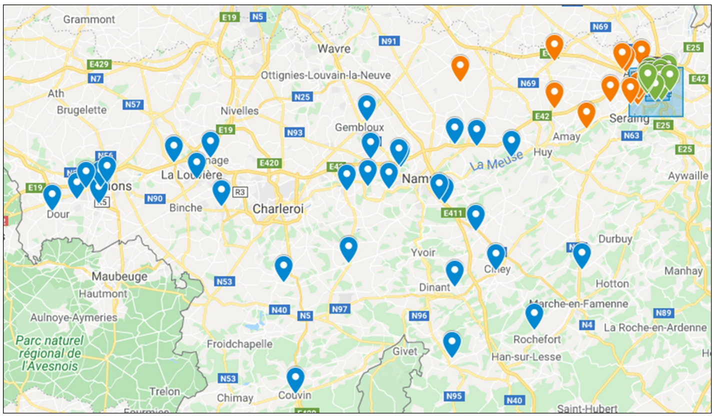

Figure 18: Large instance map

1) Firms

The firms can be located in the Hainaut and Namur provinces. In this region, a research has been made to identify likely locations for firms. In reality, SMEs can be located anywhere, especially when the level of activity of the company is low. However, in the instances constructed, the firms will be located in dedicated industrial zones or economic development areas. 32 economic areas have been selected. Their locations are provided in the appendix 4.

Zones that have been selected cluster some SMEs which focus on craftsmanship and local distribution (IDEA, 2020[85] and BEP, 2019[86], Ville de Mons[87]).

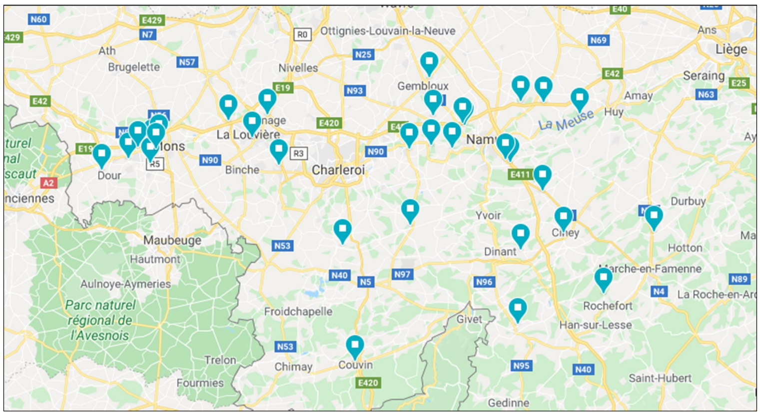

Figure 19: Firms' location

2) Depot

Regarding the location of the depot, a set of potential locations is defined. The depot should be located between Namur and Liège, in Liège province. Similarly to the firms' locations, economic activity zones were targeted to locate the depot. Two criteria were applied to select the industrial area. It must contain at least a company which concentrates its activities on national transport. Additionally, only industrial areas located in the west of Liège were selected. Indeed, it is relevant to locate the depot between the areas were firms are located and the area where customers are located (SPI[88]). 11 economic development areas have been picked (Appendix 5).

[85] Intercommunale de Développement Economique et d'Aménagement du Cœur du Hainaut. (2020). Les parcs d'activité économique. Retrieved from https://www.idea.be/fr/developpement-economique/les-parcs-d-activites-economiques/zoning.html
[86] Bureau Economique de la Province de Namur. (2019, June 18). Les parcs. Retrieved from https://www.bep-entreprises.be/parcs/
[87] Ville de Mons. (n.d.). Parcs d'activités économiques. Retrieved from https://www.mons.be/vivre-a-mons/economie/poles-d-activites/parcs-dactivite-economique
[88] SPI. (n.d.). Zoning. Retrieved from http://www.spi.be/fr/zoning

Figure 20: Depot's location

3) Satellites

Satellites must be located in the city of Liège. 32 locations, mainly off-street car-parks of the city, are selected to potentially accommodate satellites (Ville de Liège, 2020[89]). Out of the 32 locations, 8 to 15 are chosen randomly to be tested in the model. However, from this set of 8 to 15 satellites, some of them will be open and other close. The list of the 32 points can be found in the appendix 6.

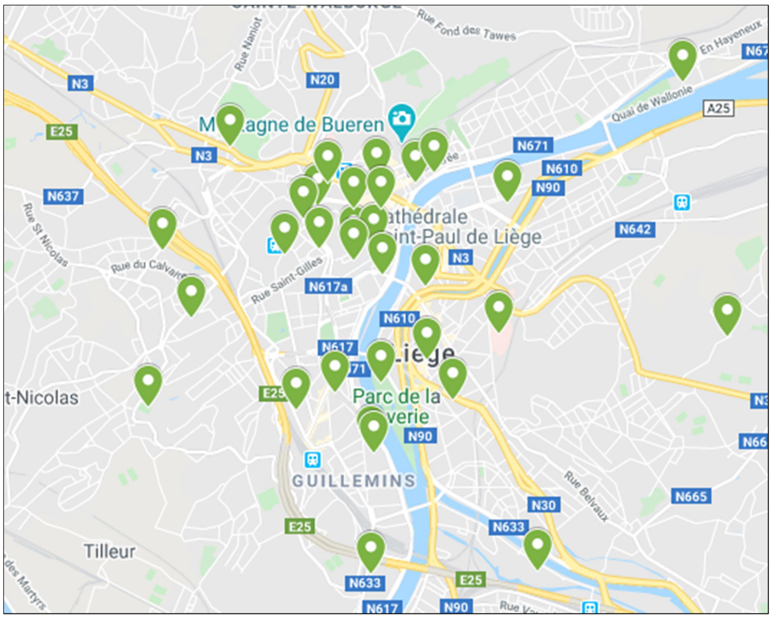

Figure 21: Satellites' location

[89] Ville de Liège. (2020). Stationnement payant hors voirie. Retrieved from https://www.liege.be/fr/vie-communale/services-communaux/mobilite/stationner/voiture/stationnement-payant-hors-voirie

4) Customers

Customers are defined randomly in their respective areas whether they are bike or van customers. The smaller square is dedicated to the city centre, and thus to bike-customers. The larger border is dedicated to van-customers, it is the close suburban area. The range in geographical coordinates is provided in the appendix 7.

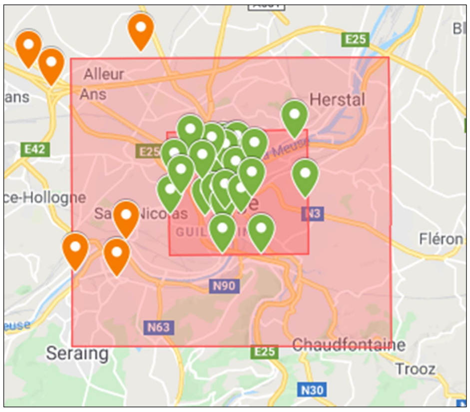

Figure 22: Customers' location

ii. <u>Tools</u>

After some researches on the available tools to provide the most precise routing, the Google API for distance matrix seems appealing at first. However, there are major limitations in this API. A request can only contains up to 25 origins or destinations. Due to the size of the real-case studied, the Google API is not suitable. The distance matrix of the problem will not be based on driving distances; the Euclidean distance will be applied instead. The free Google tool MyMaps have been used to create some of the location's maps.

During the development of the realistic tests, multiple tools, such as GeoPandas, OpenStreetMap API and Basemap, to create maps on Python have been explored. Finally, the tool used to map the locations and the trips is the library Folium. It permits to display attractive maps which can be zoomed.

2. Fine adjustments

i. <u>Merge satellites</u>

In the testing phase on medium-size instances, it has been noticed that the number of satellites open was slightly superior to the expected number of satellites. Therefore, a minor improvement has been implemented to diminish the gap between the number found by the heuristic and the expected number of satellites to be open. When a plateau seems to be reached, concretely, when the solution has not been improved in the previous complete iteration, an additional local change is possible. This local change occurs at the beginning of the iteration. It allows two satellites of the same time period to merge. The journey of a satellite is appended at the end of the routing of another satellite. Thus, in a way, the activities of the two satellites merge. This feature has a relatively minor impact, but it very often permits to improve the end-solution. Moreover, this feature does not compromise the consistency of the metaheuristic developed all along this paper. However, it extends the computation time because the solution has more chance to evolve after reaching a plateau.

ii. Parameters' values

For backorder, similarly as smaller instances, the orders are delayed in the three first iterations of the metaheuristic. Afterwards, this neighbourhood structure is skipped.

	Merge satellites	Backorder	Inter-satellites routing	Intra-satellites routing	Depot routing
Maximum number of moves accepted	1	10	5	10	10
Neighbourhood size	25	25	40	25	25
Maximum number of elements changed	2	10	10	10	6

3. Computation time and evolution of the solution

Due to the size of the instances studied and the computation time required to reach the final solution, the number of tests performed has been limited. Concerning the computation time, it goes from around 10 minutes to almost an hour depending and the instances and on the path followed by the metaheuristic. Compared to the extremely long time an exact method would take to solve such an instance, the computation time required to run the metaheuristic seems reasonable. Some results can be found in the appendix 8.

Regarding the performance of the metaheuristic, for larger instances, the metaheuristic is less reliable. Compared to smaller instances, the risk to end up with a lower quality solution is more significant. Moreover, it requires more live memory and on some materials, the metaheuristic sometimes crashed. In general, the final solution provided by the metaheuristic is totally acceptable for the size of the problem treated.

The following graph illustrates the evolution of the solution for each iteration of a neighbourhood structure. The instance studied is composed of 127 customers and 8 satellites.

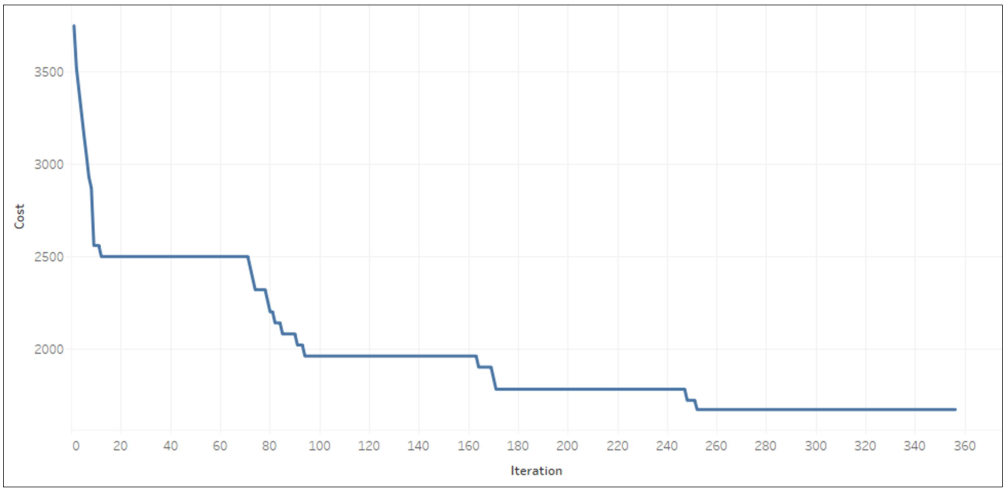

Figure 23: Evolution of the total cost for a large instance on Liège-Namur

4. Example of the output

For the real-case of Liège, it was too time expensive to try a multi-start strategy. However, the results of a trial will be exhibited in this section. An example of the routing for a given day is provided below. Obviously, the program also outputs the routing as vectors. The instance studied is composed of 168 customers and 13 potential satellites' locations. The final solution has been found in almost an hour. The total cost is 2154.58€. On the graphs, the routing of Wednesday is showed.

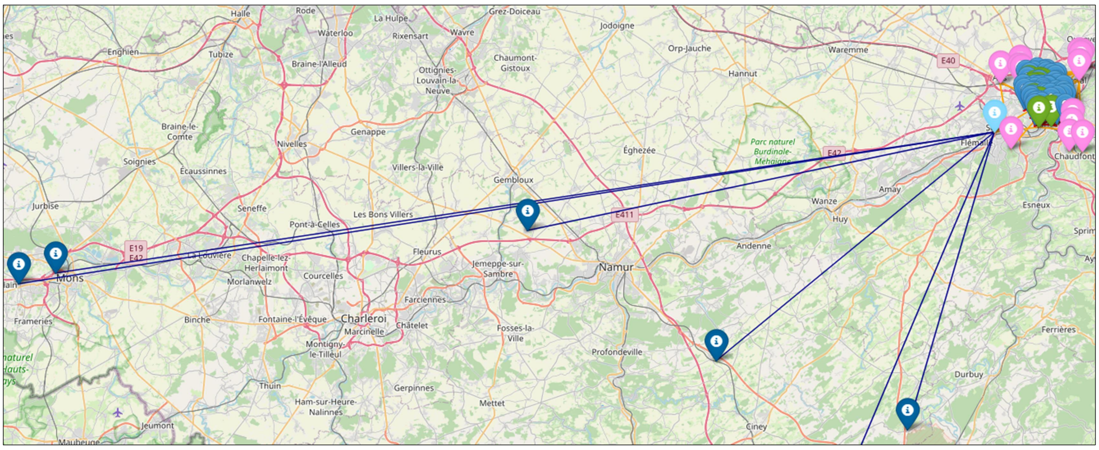

Figure 24: Example of the global routing for a given day

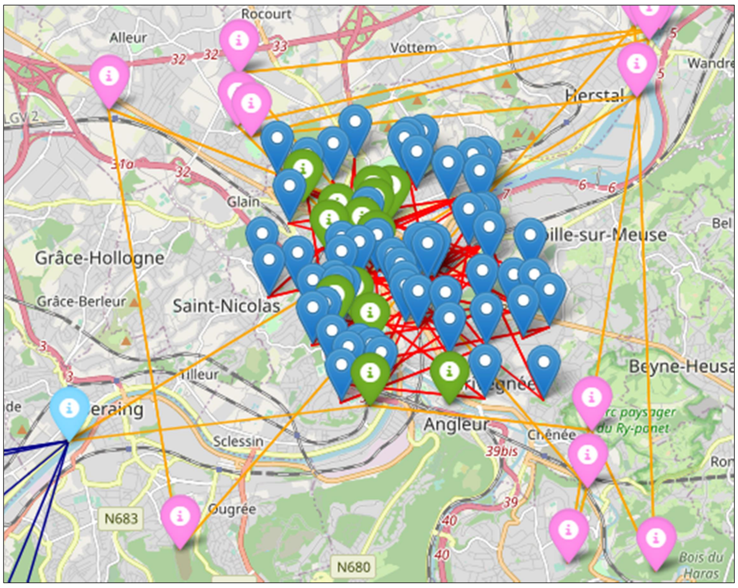

Figure 25: Zoom on the depot routing

Due to the size of the instance, the representation of the map looks like an intricate web. Nevertheless, it is possible to zoom on the part of the map we want to analyse. Moreover, the routing of a specific satellite can easily be isolated in the Python program.

5. Solutions with and without a one-day delay

The impact of the delay's tolerance has been evaluated in the testing phase on small to medium size instances. It is still important to ascertain that the conclusions stated for smaller instances are valid for larger instances. Indeed, on larger instances, the impact of consolidation could be less significant because of the higher demand volume. For large instances, to some extent, economies of scale are already achievable. Nevertheless, in relation to the instances' size and the capacities of the distribution network, even with 250 customers in a week, the network is not at its maximal capacity. There is thus an opportunity to increase the level of consolidation thanks to the permission of a delay. The tests on realistic data over Liège-Namur area confirm the preliminary observations. A one-day delay contributes to a decrease of the cost. Moreover, consolidation has a positive impact on greenhouse gas emissions as well as on congestion. Logically, if the goods are batched, less vehicles and satellites are needed. Consequently, the distance travelled is smaller, namely less trips are required to satisfy the demand. The results of a few tests are given in the table.

C	S	initial_solution	no_delay	time_no_delay	delay	time_delay	difference
128	10	4334,6	2019,04	19:05	1550,7	12:32	468,34
207	8	3818,18	2087,3	24:38	1607,38	32:34	479,92
205	15	5896,12	2686,26	44:21	2087,42	49:50	598,84

Figure 26: Comparison solutions with and without a delay

Chapter 7: Project Management

A. Theory

Many theories over Project Management are developed in the literature and applied in organizations. Indeed, project management often refers to team projects among organisations (Meredith, Mantel & Shafer, 2017[90]). Given its extent, a research thesis is typically carried out outside the structure of an organisation. In addition, the circumstances in which this master's thesis has been written have made any team work almost unfeasible.

"A project can be thought of as the allocation of resources directed toward a specific objective following a planned, organized approach" (Lientz & Rea, 2007[91]). According to this definition, a research thesis is clearly a project. In this case, it is very self-directed. Regardless of the size of the project or of the people involved, a project needs to be properly managed (Munns & Bjeirmi, 1996[92]).

B. Methodology

The first step was to define the scope of the research thesis. The scope is not completely static; especially it must evolve when the circumstances in which the research is realized change. It has also been adjusted according to the resources available, mainly skills and data. Another important aspect of the project management is the timing and planning. Planning the execution of the research provides a wide view of the development of the project. The submission's deadline was the major imperative. However, all along the project, personal intermediate deadlines have been set. These intermediate dates served as check points to review the work that has been done and the future of the project. In this master's thesis, the monitoring of the progress was essential. Indeed, the metaheuristic has been built with a continuous improvement approach. I have tried to be critical towards the project and also the metaheuristic itself in order to challenge my ideas and improve them. A research thesis is a

[90] Meredith, J. R., Mantel Jr, S. J., & Shafer, S. M. (2017). *Project management: a managerial approach*. John Wiley & Sons.
[91] Lientz, B., & Rea, K. (2007). *Project management for the 21st century*. Routledge.
[92] Munns, A. K., & Bjeirmi, B. F. (1996). The role of project management in achieving project success. *International journal of project management*, *14*(2), 81-87.

whole project and not just an answer to a research question. The complete process of the project is therefore worthy of being demonstrated.

C. Challenges

The writing of a master's thesis is undoubtedly challenging for every students. Still, I would like to briefly mention the challenges faced during the project development. This research thesis was supposed to be coupled with an internship of minimum ten weeks at the Centre for Mathematical Modelling of the University of Chile. To a certain extent, the research thesis and the internship were related. At least, the internship and thesis perspectives were common. My expectations for this internship were high. I was eager to learn more over the field of optimization and modelling, to be enriched by the insights of co-workers on the subject. Also, I had a strong interest in improving my mathematical skills. Unfortunately, due to the social crisis in Chile, the internship has been cancelled and the project was a bit reoriented. The timing to find an alternative internship equally meaningful was not optimal. Finally, my internship was on a totally opposite matter. The main difficulty was that I did not benefit from a significant internship in my research's field. In retrospect, I really think that the skills that I would have developed in the CMM were essential to boost the mathematical and programming parts of this research thesis.

This note on the context is relevant to understand the framework of the project. However, the goal is not to demean the quality of the work done. On the contrary, despite the ups and downs, the project has been well conducted. This research thesis has led to the development of self-taught skills and moral qualities, such as resilience and determination.

Chapter 8: Conclusion

Multi-Echelon distribution networks are relatively new in the literature related to vehicle routing problems. The positive impacts of these networks have already been demonstrated. The performance of a Two-Echelon network is superior to the one of a Single-Echelon network (Cuda et al., 2015). The central aim of this master's thesis was to analyse the performance of a dynamic Multi-Echelon distribution network which allows a one-day delay versus the same network without the possibility to delay orders. The observations leave no ambiguities; delaying some orders improve the overall performance of the distribution network. In this report, the aspect of the performance studied was mainly the total cost incurred by the network. The cost reduction is provided by a higher level of consolidation, which refers to a smaller distance travelled to satisfy the demand, consequently to less vehicles required to deliver goods (Mancini, 2013). In the literature and within organizations, it has been known for years that consolidation and also cooperation is the key to improve urban transportation (Crainic et al., 2009 and Hall, 1987[93]).

The conclusions drawn in this report have been based on a computerized method. This choice seems relevant knowing that, according to Toth and Vigo (2002), 5 to 20% of the total transportation cost could be saved thanks to computerized methods. Implementing a heuristic was necessary to provide numerical results on the research question. The performances of the metaheuristic are satisfactory. Nonetheless, the local search based metaheuristic proposed in this master's thesis may be outperformed by applying a different strategy or a different type of heuristics. As far as possible, the metaheuristic developed has been reviewed and continuously improved.

In addition, building a Multi-Echelon distribution network enables to better understand the actual difficulties and constraints faced in urban distribution systems. The Vehicle Routing Problem is known to be NP-hard. But it is not the only problem that needs to be solved in urban distribution network. Nowadays, the pressure on carriers is increasing. They have to adapt to new regulations regarding transport but also to social laws, while still trying to reduce their cost as much as possible. The e-commerce, the low emission zones, the increasing climate awareness, to name but a few, are matters that force the transport industry to evolve.

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[93] Hall, R. W. (1987). Consolidation strategy: inventory, vehicles and terminals. *Journal of business logistics*, *8*(2), 57.

The positive impacts of a Multi-Echelon distribution network allowing a delay are not solely economic but also environmental and social. Additionally, the model studied in this master's thesis includes greener freight vehicles within the limits of rationality. The environmental impact of the network is reduced in terms of emissions thanks to consolidation and electric vehicles. Consequently, the living conditions in cities are improved, namely regarding health issues related to pollution and congestion. It directly affects urban residents but also commuters who work on the city centre or people who perform economical and commercial activities in urban areas. The overall attractiveness of a city is enhanced by innovative distribution networks (Tamayo, Gaudron & de La Fortelle, 2017[94]).

It is still necessary to mention the drawbacks and the limits of these types of distribution networks. They can require high setting costs, especially when the switch from a traditional distribution network to this multi-echelon network is made in a short time. Renewing a fleet is costly; therefore the cost must be spread over the years to assure the financial stability of carriers. Often, the decisions to turn a fleet green emerge from regulations. The carriers must anticipate changes in regulations to start the necessary adjustments at an early stage (Patier & Toilier, 2018[95]). Unexpected policies can potentially exit small carriers from the market (Dablanc, Cruz & Montenon, 2018). A way to prevent from this issue is to develop public-private partnerships between carriers and local authorities. These partnerships can also strengthen the cooperation between carriers, public authorities but even with some other stakeholders such as SMEs or citizen associations (Taniguchi, 2014). It should be noted that developing a multi-echelon distribution network involves a high level of cooperation between the stakeholders.

The network proposed mainly relies on cargo-bikes for the last-mile delivery. Deliveries on bikes are more demanding for the staff than deliveries in traditional vehicles. The legal framework of bike-deliverers is blurred in some companies. The sector suffers from social precariousness. The profession of bike-deliverer should be considered as tedious. Given its nature, the job cannot be performed during a whole career. Driving a cargo-bike requires a certain physical condition. Moreover, weather conditions can make the job very exhausting. The risk of accidents is also relatively important for bike-deliverers.

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[94] Tamayo, S., Gaudron, A., & de La Fortelle, A. (2017, June). Loading/unloading spaces location and evaluation: an approach through real data.
[95] Patier, D., & Toilier, F. (2018). Urban Logistics Spaces: What Models, What Uses and What Role for Public Authorities?. *City Logistics 2: Modeling and Planning Initiatives*, 1-21.

To conclude, the model designed is very appealing and generates many positive outcomes for cities. In practice, the network should be implemented without neglecting negative externalities, notably towards small carriers and deliverers.

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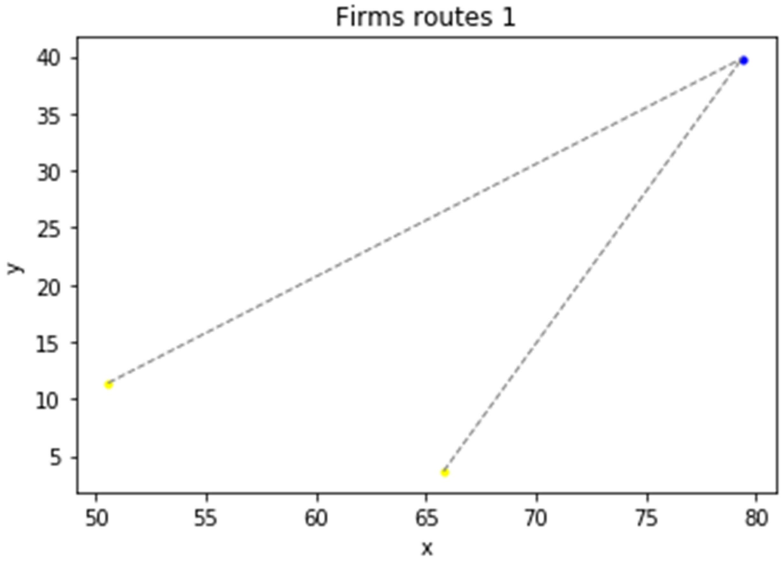
Appendices

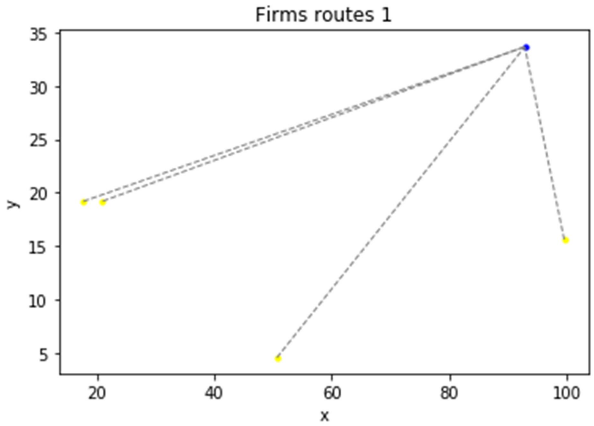
Appendix 1

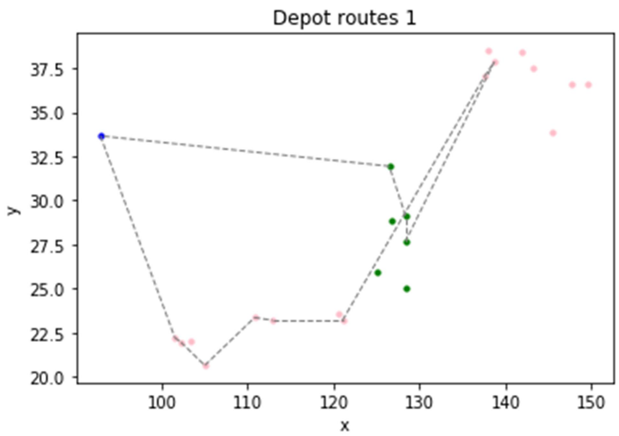


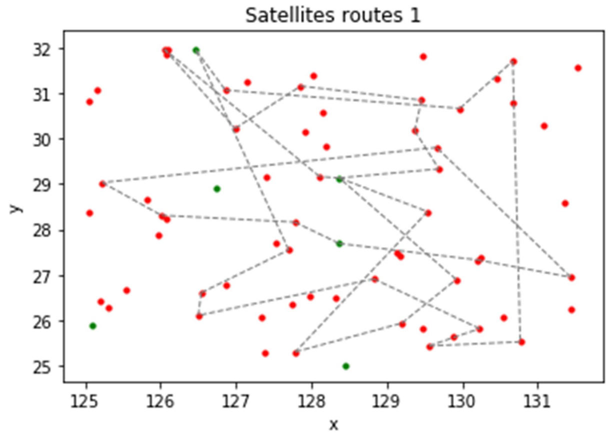
Appendix 2

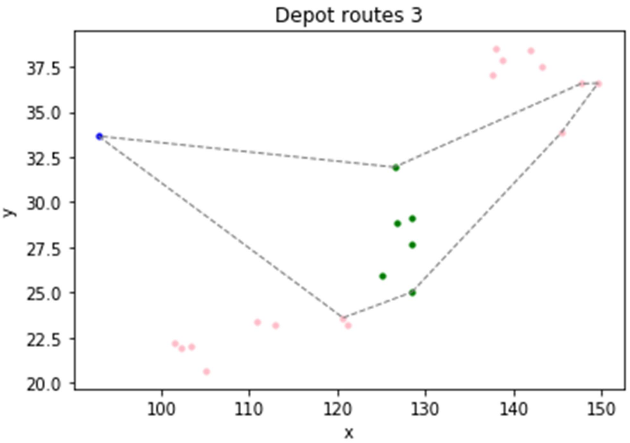
trial	C	S	lower_bound	solution	time
1	78	6	1542,99	2037,48	04:05
2	55	5	1471,86	1856,06	01:37
3	71	5	1528,53	2070,16	02:51
4	77	6	1346,3	2180,6	02:53
5	63	6	1583,58	2050,63	02:50
6	80	4	1487,45	2162,09	02:17
7	97	4	1422,71	2069,07	03:47

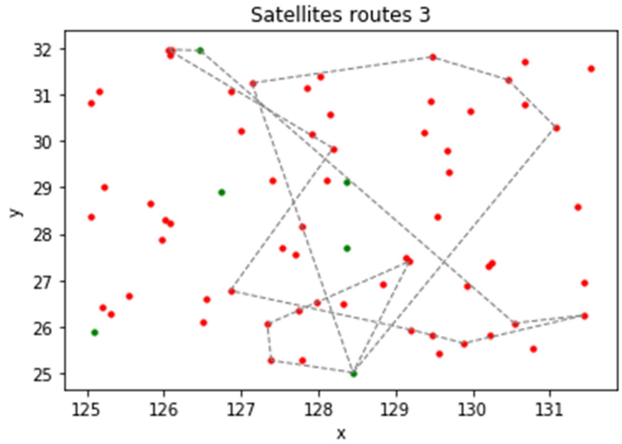
Appendix 3

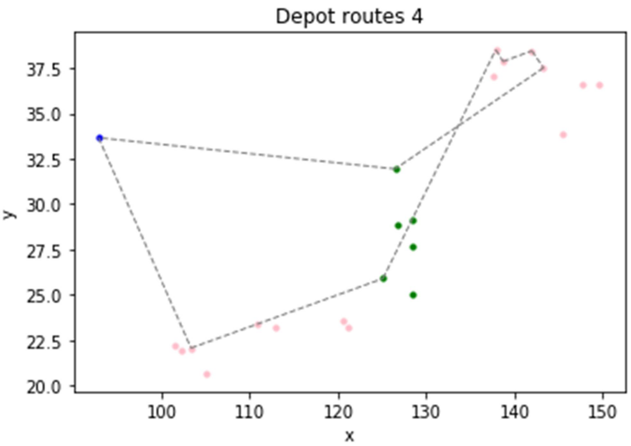


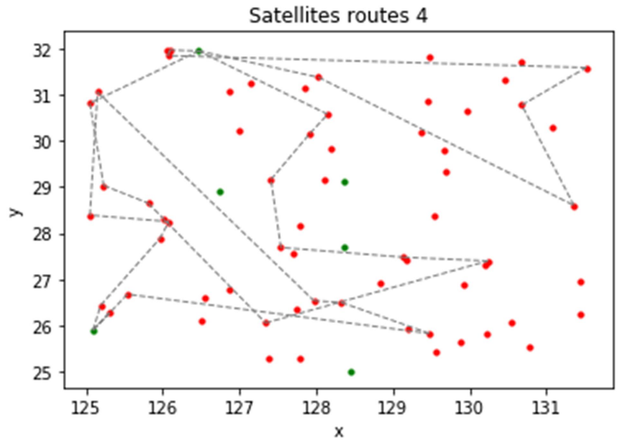

Depot routes 1
x
y


Satellites routes 1
x
y


Depot routes 3
x
y


Satellites routes 3
x
y


Depot routes 4
x
y


Satellites routes 4
x
y

Appendix 4

industrial zone	location
Mons-Cuesmes	50.446315, 3.919696
Crealys	50.505470, 4.717458
Anderlues	50.414352, 4.271715
Colfontaine-Vanneaux	50.426986, 3.838230
Dour Belle-Vue	50.405630, 3.762890
Frameries Crachet	50.418758, 3.903465
Jemappes-Puits 28	50.451029, 3.907492
La Louvière Gare du Sud	50.465825, 4.195570
Le Roeulx	50.497761, 4.128237
Manage Faubourg	50.507064, 4.238925
Initialis	50.459790, 3.927687
Quaregnon	50.448660, 3.865329
Assesse	50.366602, 5.033488
Auvelais	50.444115, 4.648378
Baillonville Nord	50.292635, 5.353713
Beauraing	50.122508, 4.961786
Chastrès	50.268412, 4.457543
Ciney	50.290448, 5.095262
Ecolys	50.488729, 4.808505
Fernelmont	50.532305, 4.971512
Floreffe 10	50.446137, 4.772433
Gembloux-Sauvenière	50.575928, 4.707984
Hamois	50.419651, 4.940816
Mariembourg	50.053407, 4.493620
Mécalys	50.529694, 5.036708
Mettet	50.304736, 4.652894
Mornimont	50.259456, 4.970623
Namur-Nord-Rhisnes	50.492765, 4.803833
Namur-Sud-Naninne	50.425601, 4.925246
Rochefort	50.177741, 5.209987
Sainte-Eugénie	50.508667, 5.141646
Sorinnes	50.451705, 4.711300

Appendix 5

industrial zone	location
Alleur	50.681211, 5.531616
Liège Logistics	50.669721, 5.485739
Amay	50.599821, 5.271506
Arbre Saint-Michel	50.612457, 5.438532
Seraing	50.607954, 5.519565
Saint-Nicolas	50.620378, 5.523964
Waremme	50.691510, 5.271262
Jemeppe	50.610030, 5.497994
Hannut	50.650806, 4.987852
Hermalle-sous-Huy	50.562812, 5.365504
Awans	50.675539, 5.474221

Appendix 6

parking	location
Cathédrale	50.640558, 5.571411
Saint-Lambert	50.645614, 5.574179
Charles Magnette	50.640690, 5.573763
Guillemins P2	50.625379, 5.573530
Guillemins P3	50.628223, 5.564528
Médiacité	50.632000, 5.580146
Cité	50.645469, 5.578742
Saint-Georges	50.646190, 5.580990
Neujean	50.643730, 5.567159
Kennedy	50.638450, 5.574958
Sauvenière	50.642761, 5.565384
Anneau d'Or	50.640432, 5.567399
Opéra	50.643426, 5.571394
Saint-Paul	50.639588, 5.571471
Saint-Denis	50.643503, 5.574664
Cadran	50.645442, 5.568280
Aquarium	50.637647, 5.580050
Légia	50.648119, 5.556686
Avenue Blonden	50.629505, 5.569251
Palais des Congrès	50.630345, 5.574692
Belle-Ile	50.615989, 5.593376
Musée TEC	50.628956, 5.583348
Astrid	50.653046, 5.610811
Burenville	50.640289, 5.548583
Jonfosse	50.640025, 5.563171
Bavière	50.643859, 5.589751
Longdoz	50.634030, 5.588779
Robermont	50.633731, 5.615991
Val-Benoit	50.615788, 5.573426
Skatepark Cointe	50.628490, 5.546848
Château Massart	50.635173, 5.552041

Appendix 7

NW	50.6796939, 5.4962138
NE	50.680129, 5.660322
SW	50.585619, 5.4965571
SE	50.585183, 5.6616953
NW	50.6556929, 5.5454944
NE	50.6565635, 5.6182789
SW	50.6150819, 5.5466961
SE	50.6155176, 5.6191372

Appendix 8

trial	C	S	lower_bound	solution	time
1	127	8	954,0	1676,44	11:06
2	194	12	1045,78	1906,4	59:17
3	168	13	993,96	2154,58	36:03

Table of contents

Executive summary

Nowadays, congestion and pollution are challenging urban transportation systems. Low emission zones and e-commerce force distribution networks to become more flexible and efficient. The concept of City Logistics has been developed in the literature to encompass these issues.

The well-known Vehicle Routing Problem and its variants such as the Multi-Echelon Vehicle Routing Problem offer prospects for improvement in City Logistics. An overview of the literature over the specific case of the Multi-Echelon VRP is provided in this paper. Based on the existing models, a new model is presented in this research thesis: the Multi-Echelon Multi-Satellite Multi-Product Capacitated Vehicle Routing Problem with one-day delay allowed. For the purpose of submitting a sustainable distribution network, a predominantly green freight is chosen to operate in the city and its suburban area.

A local search based metaheuristic is developed to solve the model. Theoretical aspects of the Steepest Descent metaheuristic are discussed. The metaheuristic proposed differs from the classic version in the way neighbourhood structures are applied. A first version of the metaheuristic is tested and assessed. Additional features are added to improve the quality of the final solution given by the metaheuristic.

Thanks to this solving method, conclusions can be drawn over the impact of the tolerance of a one-day delay. Even for large instances, offering the possibility to delay some orders leads to a significant cost reduction. Consolidation has a great impact on the cost, especially when the network deals with small parcels and small demand volumes.

The model and the metaheuristic built are then tested on realistic data based on Liège-Namur area. The choice of the location for the different facilities is explained. Maps and representations of the output of the metaheuristic are provided. The performances of the solving method are evaluated. Finally, conclusions are stated on the overall research.