Executive summary

On the one hand, cities tend to reduce congestion and air pollution. On the other hand, e-commerce is growing fast which increases the demand for home deliveries and puts a strain on last-mile logistics. A common ground needs to be found for these two contradictory facts. *What-if parcel deliveries could happen without any additional vehicles driving into the city ?*

This is the question to which this thesis attends to answer by proposing a joined passenger and parcel transport system. Inspired by the *Physical Internet*, a set of connected containers will be moved through the city public transport services from a depot at the edge to a stop in the city center. There, they will be stored in a locker terminal where customers will be able to open it and get their parcels. This system will thus use the idle capacity outside peak-hours of the already planned public transport trips to move parcels around.

This thesis aims to model such a network and propose an operational framework. Based on the city of Brussels, it will locate the depots, hubs and lockers such as creating an efficient network to deliver these parcels on time. It will also test such system with the schedule of Brussels public transport operator and by simulating parcel demands in Brussels.

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1 Introduction

1.1 Motivation

Following the Climate Action Summit of 2016, the World Bank brought together transport stakeholders to define and achieve sustainable mobility. From this, four characteristics and priorities came out: universal access, efficiency, safety and green mobility. (World Bank, 2017)

Concerning green mobility and efficiency, the European Commission (2014) published a report to explain their transport policies and highlighted some challenges that will have to be faced in the coming years:

- Congestion is estimated to cost 1% of the European GDP on top of the social and environmental impact it has on society;
- The transport sector is depending mostly on oil (96%). Volatility of the market and future sourcing difficulties make it essential to find alternative means of transport;
- Greenhouse gas emissions have to be cut and transport is responsible for 25% of the EU's emissions;
- The efficiency of transportation needs to increase. Logistics should be improved but integration and unification of available transport means and networks are also essential to optimize capacity and use;
- The EU should work for a better infrastructure: build missing link and better integrate what is available;

Additionally, the trend for urbanization and the growing demand for transport (freight transport will grow by 80% by 2050) are accentuating the need to find a solution for these challenges. Optimizing the logistics, switching to alternative transport means (or fuel) and combining different transport modes by creating common standards seems crucial.

Another big challenge is induced by e-commerce. In Europe, the selling and delivery of physical goods concern more than 50% of e-commerce businesses. This growth of e-commerce has led to an increase of freight traffic in office and residential areas with negative impact on air pollution, noise and congestion. These negative externalities are now directly affecting people ! The wish for an always faster delivery put even more strain on the last-mile logistic: consolidation become more difficult and costs are therefore increasing. Delivery failures are also enforcing these issues.

For a sustainable city logistics, partnerships between private and public entities are key. Policy makers could help in the following areas: 1) adopting joint delivery systems in order to consolidate goods of competitive carriers; 2) making public places available for the development of parcels lockers; 3) promoting the use of cargo-bikes, etc. (van den Bossche, Maes, Vanelslander, Macário, and Reis (2018) ; Perboli and Rosano (2019) ; Taniguchi (2014))

Today, we are entering a fourth revolution which is characterized by technology and digitalization. This revolution is evolving fast and has a global impact across entire systems (Schwab, 2017). Thanks to these technological and digital innovation, the *internet-of-things* is becoming a reality: the objects are communicating. Radio-Frequency Identification (RFID) tags are already used to optimize the supply chains by sharing four main types of information: what, where, when and why. (Tu, Lim, & Yang, 2018) This revolution is giving us new opportunities to rethink our current system and to deal with the many challenges we are now facing.

Following these new possibilities and from the observation that our physical objects are transported but also stored, produced, supplied and used in an unsustainable way, Montreuil (2011) developed the idea of the *physical internet.* Inspired by the digital internet, the physical internet aims to reshape the logistic of physical object as " *an open, global and multimodal logistic system founded on universal, physical, digital, operational, business and legal interconnectivity enabled through world standard encapsulation, protocols and interfaces*" (Crainic and Montreuil 2016, p.388). The Alliance for Logistics Innovation Through Collaboration in Europe (alice) (2014) [1] has created a roadmap to fully implement the physical internet by 2050. Divided in 5 working groups, one of them is focussing on urban logistics and the urban freight deliveries and returns. Their aim is to reach efficient and automated distribution systems by 2030.

1.2 Research question

This thesis proposes a solution to face these city logistic challenges by using the existing public transport infrastructure for the delivery of parcels !

Inspired by the physical internet, the idea will be to consolidated parcels into containers and load them with trolleys on tramways and metros from a depot at the edge of the city to a station close to or chosen by the consumer. In these stations, the consumers will be able to open the containers with a unique code and get their parcels, similarly to the functioning of Automated Parcels Lockers (APL).

Since the transport of passenger is a priority for urban planners, such a system should guarantee a fast delivery of the parcels while keeping passenger schedule time undisturbed. A model to locate such lockers will be built in this thesis with the city of Brussels and its public transport (STIB-MIVB) as a case study. Then, based on the current passenger schedules of STIB, a scheduling model will be built to allocate and consolidate the demand such as moving a parcel from a depot at the edge of the city to a locker in the city center.

This thesis will first, in a review of the literature, define the concepts related to the physical internet, city logistics and freight transportation. Then, it will look at the optimization modeling literature and its application in shared passenger and freight transports. In a second part, a locker location model will be built and test on the STIB network. Additionally, a scheduling model will be solved to assign parcels to metros and trams trips.

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[1] This research group aims at giving a strategy for logistic and supply chain innovation in Europe. In their roadmaps, they give suggestion and time frame for further researches on the subject. They coordinate the researches on the physical internet and their objective is to reach a fully implemented physical internet by 2050.

1.3 Limitations

This thesis aims to show one way of applying the physical internet in cities. It still relies on strong technical assumptions such as the creation of connected and automated containers and trolleys but also their availability at a decent cost.

Without these assumptions, relying on persons to move the object could be too costly, timely and unreliable such that it may disturb the passenger's schedules. Such a system will thus require new infrastructures and the associated investment which won't be discussed in detail in this thesis. Moreover, this system should be further adapted to account for the reverse logistic of these containers. This could be associated to the return of e-commerces good such as reducing the empty running.

2 Literature review

2.1 The physical internet

2.1.1 Physical and digital drivers

In 2004, Gershenfeld, Kirkorian, and Cohen, emit the idea of using the internet to connect various devices instead of only networks. They wanted to extend the internet from the computer hardware to a basic daily object like a light bulb. That's how the concept of the *Internet-of-Things* was born.

The Internet-of-Things (IoT) is defined as "*a dynamic global network infrastructure with self configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities, use intelligent interfaces, and are seamlessly integrated into the information network*" (Vermesan et al. 2011 , p.10).

The huge development of the internet, artificial intelligence and machine learning along with cheap, small and efficient captors are allowing a better integration of digital technologies. The progress in robotics has led to robot applications across a wide range of sectors to perform a wide range of tasks. Robots are becoming more flexible and adaptable. The development of sensors are connecting the robots to their environment which they can understand and respond to. With the IoT, knowledge can be enhanced by the valuable information given by these new interconnections and robots are now capable to directly access data. (Schwab, 2017)

2.1.2 The digital internet analogy

The digital internet at its creation was inspired by transportation logistics. In the digital internet network, communication is divided into packets that will follow a path or route through the network, passing by packets switches and going from the sending end system to the receiving end system.

These communications are just similar to a good that will go on a transport mean (packets), move through a network of roads and railways (communications links) and pass by different hubs and warehouses (packets switches) with the aim of reaching its final destination (end system). (Kurose & Ross, 2012)

In the digital internet, the path is dynamic and determined in real-time, while in transportation logistics physical constraints put a strain on the path decision: planification in advance, longer lead time, close access to hubs and warehouses, etc. Montreuil (2011) has identified all these constraints as the *grand challenge* logistics is facing.

He pointed out that the digital world also used to face a similar challenge: isolated large computers have been transformed into a huge amount of interconnected personal devices which are sharing information to some open access networks. While the digital internet was created taking its inspiration from the logistics, it is now suggested to reverse this thought and use this efficient internet to improve logistics. This rethinking of logistics is what Montreuil, inspired by the title of an article published in The Economist (2006), has named the *physical internet.*

The physical internet aim is to reach "*universal interconnectivity [which] enables to connect any node to any other node*" (Sarraj, Ballot, Pan, & Montreuil, 2014, p.1209).

The digital internet became the most known interconnected and resilient network due to its fragmented structure that has the same topology at each level. This fragmentation is limiting the size of the infrastructure which makes it easier to transfer data.

The digital internet is composed of a high number of *Autonomous System* (AS) that are independently managed. AS may be in competition within the same geographical area but they can also be divided in sub-networks depending of their area which can again be subdivided further down until the host system. At each level, the AS are interconnected through border routers and protocols while the flow inside each AS is managed by internal routers. It is only at the highest level that all the systems become interconnected and form a global digital network. (Sarraj et al., 2014)

2.1.3 The physical internet architecture

To apply this architecture to the physical internet (PI, π), the current logistic situation must be taken into account. This concerns the country internal particularities as well as its cross-border regulations.

Applied to the PI, an autonomous system will be a logistic network ruled by a firm or an organization. Unlike the digital internet, travel distance matters a lot for the physical internet: if different networks are geographically overlapping each other, sharing their network will not be more efficient. The physical AS would have to be divided in areas. This is not yet the case with the current system which is composed of a broad amount of independent companies and their individual logistic networks. Connecting existing networks will require to build new links.

Logistic service providers that have such networks for their client may start to open it to other service providers. These collaborations will lead to "*a network with a variety of logistical entities, which can be highly autonomous and geographically distributed but have the joint operative environment and goals*" (Sarraj et al., 2014, p.1207).

To enable the deployment of the physical internet as a global and interconnected logistic network, physical elements as well as protocols will have to be defined. (Sarraj, Ballot, Pan, Hakimi, & Montreuil, 2013; Montreuil, Meller, & Ballot, 2010; Montreuil, Meller, & Ballot, 2012)

2.1.3.1 π-elements

On the one hand, according to Montreuil et al. (2010), the physical internet (PI, π) will be possible thanks to 3 main types of physical elements: π-containers, π-movers and π-nodes.

Firstly, the objects moved, carried and stored will be standardized into a set of π-containers. This way, the content become encapsulated which will enable the physical internet to only take care of the logistics of a set of π-containers instead of adapting to each good specificity.

The π-containers sizes and shapes should be designed by international standards and with the aim of minimizing storage waste. Each size should be a combination of the other container sizes. They should be modular and interlocking. Landschützer, Ehrentraut, and Jodin (2015) collaborated on a project (MODULUSCHA) to define such containers and elaborate a mechanism to interlock boxes. A study by Meller, Lin, and Ellis (2012) showed that if there is flexibility, the use of such containers won't have negative impact on the shipping volume.

Moreover, each π-containers will have an electronic identifier (RFID type) with smart tags since information and communication are key drivers of the industry 4.0 and the Physical Internet. These data captured by the π-containers, not the encapsulated objects, will enabled a direct interaction with the network. The Internet-of-things is thus an important and needed concept of PI. This is done similarly in the digital internet in which data are packaged into datagrams that contain a routing table with information about their destinations.

Secondly, the way π-containers are moved around should take into account their standardized characteristics. Therefore, the term π-mover account for the set of π-vehicles, π-carriers, π-conveyors and π-handlers which allow and automatize the movement of the π-containers.

Thirdly, location where these π-containers are moved from one π-mover to another are called π-nodes. In such locations, structural changes on the π-containers may also happen. These nodes will all have different characteristics and capabilities that will be taken into account when deciding where the flow of goods will stop. Additionally, π-fixtures, π-nodes, π-devices and π-platforms will ensure the smooth flow of π-containers.

2.1.3.2 π-protocols

On the other hand, to manage the collaboration between the different networks, a set of common and universal protocols should be elaborated: "*the true potential [of PI] will only be reached when agreements on neutral protocols can be reached*" (Ballot, 2017, p. 26).

In the digital internet, routers, via a routing table, are determining the direction that a datagram has to follow. The datagram is then sent from a router to the next router of its routing table. If this router is identified as the host, the datagram has reached its destination. Otherwise, by checking the routing table again, the datagram is sent one step further. The router is able to read on the routing table the final destination address. A datagram is a data packet which is encapsulated within a frame. Each frame may thus contain one or more datagram.

The physical internet transposed this idea of encapsulation into logistics. Merchandise (data packets) will be sent in the forms of containers (datagrams) that will be moved together through transportation means (frame). The physical internet networks will be composed of π-nodes (routers) that will store the containers, sort them and recompose them. These sets of containers will then be sent according to their destination. These π-containers will all have a routing table that can be read at each node and from which their next move is determined with criteria like transport costs, delivery time and CO_2 emissions.

PI is more constrained than the digital internet due to capacity constraints, sorting constraints in the π-hubs, higher costs for each errors, etc. PI also needs to use estimates of future flow while in the digital internet, everything happens in real time. (Sarraj et al., 2014)

Montreuil, Ballot, and Fontane (2012) proposed a division of the PI protocols similar to the seven open layers of the digital internet protocol in which each instances will collaborate vertically and horizontally: 1) the logistics web which is the interface between the users and the π-elements; 2) the encapsulation layer which standardized goods into π-containers; 3) the shipping layer which sets the conditions of the shipment; 4) the routing layer which define the best path; 5) the network layer which assure the interconnectivity 6) the link layer which check the consistency between the physical information and its digital counterpart and finally; 7) the physical layer which deal with all containers movements.

Similarly, Sarraj et al. (2013) conceived a set of protocols for the freight transport sector to encourage collaboration between supply chains and networks. Their paper used a simulation on FMCG in France to test it. Their experiment showed a potential to increase the filling rate by 17% and to reduce carbon dioxide emissions by 60% with a better use of the rail network.

To build the transportation protocol, they identified several steps in the process of shipping goods within the PI: 1) the containerization; 2) the container routing and; 3) their consolidation on transport means.

First, goods need to be loaded in one or several containers. The containers will be loaded such that this is the "best" fit. The containerization of goods consists in choosing the number of containers needed for a shipment as well as their sizes. This is similar to encapsulation in the digital internet. There is different way to look at this problem. The objective may be to minimize the number of containers and thus to encapsulate the shipment in the biggest container available. It could also be to choose small containers such as reducing lead time and stock levels. Finally, we can also chose different sets of container dimensions. The authors decided to maximize the space utilization while minimizing the number of containers.

The second and biggest part of the protocol is the container routing. The protocol will choose the best path to arrive at destination. The path is divided into segments where at the end of each of them, the goods are unloaded in the hubs. When the containers get there, the algorithm will run to find the best available transportation mean to move it to the next hub. Routing problems aim to solve what the literature refers to as the shortest path problem. The authors solved with an extension of the Djikstra's algorithm which is a heuristic method with a short computational time. At each node, the algorithm is looking for the best path from this node to the end destination. Therefore, a well-defined evaluation function is estimating the cost of all possible paths. These costs are computed with regard to monetary, time and environmental parameters.

Third, when a routing is defined for a container, space has to be optimized in the chosen transportation mean. A constraint aims at shipping first the urgent containers. The bin-packing problem is the basis of this algorithm. The algorithm runs with respect to targeted delivery times. The bin-packing problem will first assigned a mean to a container. If this mean is too empty, a new path is searched for this container. If no better solution is found in time, the departure is forced, regardless of the flow level. The protocol is thus consolidating the containers according to common destination. Four different strategies could be chosen from: first fit, first fit decreasing, best fit and best fit decreasing. These depend on the mean we are trying to fill first and wether or not the containers are sorted by decreasing size.

2.1.4 The physical internet potentials and needs

A simulation with data of two french retailers has shown the significant improvement on transport efficiency and sustainability that the physical internet can lead to. (Sarraj et al., 2013)

Besides these apparent efficiencies in terms of time and emissions, a simulation model with a risk avoidance (or risk taking) protocol as shown that the physical internet has also a resilience potential. By simulating a disruption which generates a lost of capacity in the network, Yang, Pan, and Ballot (2017) show that the π-protocols manage to only slightly reflect these impacts on the shipments.

To implement fully the physical internet, the need of horizontal collaboration is one of the key elements. An interview research as shown that the main barriers to be removed are the fear of administrative burden and antitrust fines. (Simmer, Pfoser, Grabner, Schauer, & Putz, 2017)

2.2 City logistics

The last segment of the physical internet will often have to deal with the specificities and complexities of a city. As focus of city governments on freight transport and logistic has been mostly limited to the control of infrastructure uses and to vehicle entries restrictions, most cities are now overwhelmed by a flow of freight vehicles carrying individual tasks.

The concept of city logistics was introduced to better integrate the flow of freight logistics into the city planning. With the physical internet, this integration could go even further and allow the deployment of an hyperconnected city logistic network which aims to design urban transport and logistics in an efficient and sustainable way. (Crainic & Montreuil, 2016)

2.2.1 Definitions of city logistics

The broader goal of city logistics is to decrease the negative externalities of the freight transportation on the city living conditions while not impacting the social and economic activities of the city. These living conditions can be evaluated in terms of congestion, (air and noise) pollutions and safety.

Concretely, consolidation of loads and coordination are the fundamental concepts that will help to achieve these goals. Alternative and innovative ways can also be considered such as the use of greener vehicle or the integration of freight with public transports. Partnerships between private and public actors are also essential; mostly to share information and needs. (Crainic, Ricciardi, and Storchi 2009; Taniguchi, Thompson, and Yamada 2014)

City logistics is often confronted with problems that are more complex than in conventional freight logistics. This is the reason why the Alliance for Logistics Innovation Through Collaboration in Europe (alice) (2014) proposed a specific research roadmap on the urban logistics. They proposed between others to research the possible "*integration of urban freight with public transport on the road infrastructure, but also at the level of the vehicles and at public transport interchanges*" (alice, 2014, p.26).

2.2.2 E-commerces, home deliveries and last mile issues

Demand from e-commerce is increasing due to youngest generations born with the internet that are getting purchasing power and due to older generations that are discovering the convenience of buying online. It is also strengthened by the reduction of the number of brick and mortar stores caused by online competition, the launch of online groceries shopping and the increasing use of smartphones to this aim. (Visser, Nemoto, & Browne, 2014) This also shows the growing trend of purchasing goods online which will undoubtedly keep increasing the number of deliveries at home.

The main logistic challenge, mostly encountered in cities, especially in the case of home deliveries, is often referred in logistics as the *last-mile* issue: the "*final leg in a business-to-consumer delivery service whereby the consignment is delivered to the recipient, either at the recipient's home or at a collection point*" (Gevaers, Van de Voorde, and Vanelslander 2011, p.57). Last-mile is considered the less efficient part of logistics in terms of costs and pollution per delivery. The main problem comes from the difficulty to gather a sufficient volume (*critical mass*) for the deliveries to be cost efficient (Gevaers et al., 2011). Since last-mile is a big share of city logistics, focussing on this problem is crucial to reduce the inefficiencies in the urban freight transport.

E-commerce growth intensifies the multiple city logistic challenges and inefficiencies that come with home deliveries by multiplying the number of deliveries, spreading the delivery points and making the planning more complex (alice, 2014). Even if more e-commerce purchases may lead to more volume and thus more deliveries per trip (i.e., more parcel demands in an area) other kind of problems such as delivery failures, empty reverse trips and the increasing use of vans still arise. Delivery failures happen when the consumer is not present to take delivery of the parcels. The deliveries will often need to happen a second or even third time which leads to more trips, costs and pollution (Visser et al., 2014). On top of that, same-day delivery which is becoming a standard and more demanded service level, is putting a bigger strain on this last mile issue (Morganti, Seidel, Blanquart, Dablanc, & Lenz, 2014).

A couple of solutions have been developed in cities to reduce the negative impact of home deliveries. Policy makers are promoting the use of alternative modes such as electric vehicles and bicycles with the creation of low emissions zones (Taniguchi et al., 2014). In Europe, the last mile segment is often outsourced to traditional courier delivery services. This led searchers to analyze the outsourcing of the last mile to green subcontractors (Perboli & Rosano, 2019) or led to the emergence of crowd logistic platforms (Buldeo Rai, Verlinde, & Macharis, 2018b).

Alternatively, *pickup points* instead of home deliveries has appeared as a solution for a more sustainable and profitable last mile.

2.2.3 Pickup points

To mitigate these disadvantages of home deliveries, e-commerces has been working increasingly with pick-up points. They have the advantage of reducing delivery failures while increasing the consolidation of shipments (Morganti et al. 2014; Weltevreden 2008).

Pickup points can be divided into two categories: service pickup points which are often located in a shop or a post service and unmanned pickup points (Moroz & Polkowski, 2016) such as automated parcel lockers (located in public places) and smart parcel box (installed at the customer's house) (van den Bossche et al., 2018). Unmanned pickup points have the major advantage to be available for the consumers 24/7 which leads to be more likely used by time-constrained households (van den Bossche et al., 2018). However, parcel lockers are less flexible than service pickup points regarding the sizes and shapes of the parcels. (Weltevreden, 2008).

The main issue with both type of pickup point is to modify consumer's behaviors towards switching from home deliveries to parcel collections in pickup points.

Regarding the implementation of unmanned pickup points, Faugère and Montreuil (2018) showed that a modular design for automated parcel lockers could perform as well as a fixed one while being more flexible. Additionally, Dell'Amico and Hadjidimitriou (2012) developed a logistic system, that will ship goods in drawers and later connect them to a station where customers can come to pick them up.

2.2.4 City logistics in Brussels

Some field researches have been made on the city of Brussels by one of its universities (Vrije Universiteit van Brussel). On the logistic side Buldeo Rai, Verlinde, and Macharis (2019) focused their research on the link between logistic service providers (LSP) and city logistics for the distribution of parcels. They used the city of Brussels for their case scenario. Interviews with logistic service providers show that the efficiency of the city distribution was impeded by four main elements: 1) parcel volume; 2) stop density; 3) delivery failure and; 4) urban regulations. What stands out is the use of pick-up points, lockers and other tools that affect consumer's behaviors, as a solution to deal with these issues.

On the consumer side, a quantitative survey among a representative share of the Belgian population showed that price followed by return possibilities are the major attributes when deciding for a type of delivery. Also, half of the respondent find it important that less kilometers are driven for the deliveries of their parcels. While they accept to wait longer or to pick-up the parcels themselves for this reason, they aren't ready to pay for more sustainable delivery options.

With the survey's results, a simulation was made and point out that with return possibilities and free deliveries, a large part of consumers wouldn't be bothered to wait longer for their order or to go pick it up at a nearby location: customers are willing to make trade-offs. Due to a large amount of neutral responses, the searchers made the hypothesis that consumers are not well aware of the last mile impacts of deliveries on sustainability. The customers could thus be influenced to make a greener choice. (Buldeo Rai, Verlinde, & Macharis, 2018a)

Since January 1st, 2018, as many European counterparts, Brussels has banned the most polluting vehicles out of the city to increase the air quality (Brussels Government, n.d.). In addition, the pedestrian zone in the center of Brussels has double its size to 50 hectares in 2015. No vehicles are authorized in this zone with small exception such as the unloading of freight, only until 11.00 am. (Ville de Bruxelles, n.d.) There is thus a willingness to change and improve mobility in Brussels. The usual way to deliver goods, with trucks and vans, may be getting more complicate in a near future.

Bpost, the Belgian mail delivering company, has launched Cubee in 2017. It is an open and independent network of parcel delivery. It consists of different lockers where online consumers can go to pick-up or return their goods 24/7 thanks to a code. (La Libre Belgique, 2017)

2.3 Optimization models

Optimization models have been built to help the decision process. Decision can be made at strategic, tactical and operational levels.

2.3.1 Strategic decisions

2.3.1.1 Facility location models

Strategic decisions start with location decisions: the location of facilities to serve a certain demand across a region. Several models have been developed in the literature. The location is usually chosen from a set of plausible locations.

Firstly, covering models aim to find just enough facility locations such that all the demand is within a certain distance of at least one of these facilities. Secondly, a variant of these covering models is the fixed charge model which aims to minimize costs by allocating to each candidate facility site a fixed cost which will be incurred if it is chosen as a location. Besides fixed costs, shipment costs related to the distance between the customer and the facility can also incur. The models can also be extended to account for multiple-commodities or multiple nodes (e.g. by passing through a distribution center). (Daskin, Snyder, & Berger, 2005) Thirdly, center models will locate a fix number of facilities such as minimizing the distance. Finally, median models aim to minimize the total weighted distance by locating a decided amount of facilities. These latter are often used in freight distribution problems. (Crainic & Laporte, 1997)

Other classifications exist such as the one in the review of Farahani, Asgari, Heidari, Hosseininia, and Goh (2012) about covering problems from the facility location literature. They classified the models into two main groups: 1) set covering problems which aims are to minimize the costs while satisfying a certain service level and; 2) maximal covering location problems which focus on maximizing the coverage while being limited by a fixed amount of facilities. From their review, some researches stand out as being of interest to solve this thesis locker location problem.

To begin with, the demand location can be expressed in several ways. Jia, Ordóñez, and Dessouky (2007) used the population density to aggregate demand points at their centroid. This geographical representation as computational advantages, but it may lead to errors and should thus be used with enough supporting evidences (A. T. Murray & O'Kelly, 2002). In addition, the authors propose to give different quantity-of-coverage to the demand points according to their population density and developed therefore different heuristics.

Then, Nozick (2001) developed a model that minimize costs (as a fixed charge model does) while allowing some uncovered demand. This has been done by introducing an upper bound on the total uncovered demand. Berman and Krass (2002) also worked on partial covering by introducing a coverage level function depending on the distance.

Moreover, the geometric particularities were taken deeper into account by several searchers. Church (1984) uses euclidian and rectilinear distance to solve maximal and partial covering problems. The rectilinear distance is calculated by taking the absolute value of the differences between the two coordinates that characterize a point. While with euclidian distances the coverage boundary has a circular form, it has a diamond-shape with rectilinear distances. Rectilinear distances in p-median and center location problem are further discussed by Beaumont (1981). Church (1984) also proposed to change the number P of facilities and take a decision by looking at how it impacts the coverage-effectiveness.

Furthermore, A. Murray, O'Kelly, and Church (2008) focussed on fully covering several areas with circular coverage coming from different facilities. They analyzed different geographic representations. Between others, point-representation is an often used one to address total coverage. However, it often does not manage to actually ensure total coverage. The statistical bias of point representation is often referred to as the modifiable areal unit problem (MAUP). Therefore, the authors proposed to iterate until total coverage is reached by adding the centroid of each uncovered-areas (called gap) to the set of area-points at each iteration.

Encouraged by the possibilities offered by GIS, the authors also proposed area-representation to address coverage. The idea is to divide the region to cover in smaller polygons to assure total coverage of each area. Besides, the authors defined that coverage was provided only if the whole area is covered but they also proposed the use of other norms such as covering only percentage of the polygon to defined an area as covered. The authors also highlighted the essential a posteriori analysis to ensure sufficient coverage.

MAUP can be reduce by using the less aggregated data available. With geographic information systems (GIS), it is possible to look at overlapping areas and partially covered ones. Taking this into account, A. Murray (2005) introduced a binary variable tracking partial coverage into the standard set-covering model.

2.3.1.2 Network design problem

Another strategic decision comes from the network design problem. Similarly to location problem, the aim is here to decide between a set of links, the ones to use for the flow of goods. The shortest path spanning problem (SSTP) is the easiest one and can be solved with a simple Greedy algorithm. (Crainic & Laporte, 1997) It is formulated hereunder (eq. 1):

$$minimize \qquad \sum_{i<j} c_{i,j} x_{i,j}$$

$$\begin{aligned} \text{subject to} \qquad & \sum_{v_i \in S,\, v_j \in V \backslash S \; or \; v_i \in V \backslash S,\, v_j \in S} x_{i,j} \geq 1 \\ & x_{i,j} = \{0,1\} \qquad \forall (v_i, v_j) \in E \end{aligned} \tag{1}$$

where $c_{i,j}$ is the cost to use the link that connects the nodes i and j, $x_{i,j}$ is equal to 1 if the edge (v_i, v_j) belongs to the SSTP, V is a set of potential vertex (v_i) and E is the set of all potential edges.

Models have also been developed in the literature to integrate routing and location problems. Due to the merger of two NP hard problems with different decisions time horizon, they are difficult to solve and aren't thus much used. (Daskin et al., 2005)

2.3.2 Tactical decisions

At the tactical level, planning problems need to be solved. Tactical planning is crucial to create a transportation plan that will guide the daily operations. It always involves a trade-off between operating costs and service quality. Crainic and Laporte (1997) divided such problems in two categories: 1) service network design problems which focus on long distance movement of goods and; 2) vehicle routing problems (VRP) which deal with several pickup or delivery operations on a generally short distance. In the scope of this thesis, the planning will consist of the design of delivery routes to move parcels from some depots to multiple lockers.

2.3.2.1 Service network design problems

In long-distance problems, sorting and consolidation happen together at freight terminals. The decision implies a trade-off between operating costs and service quality. The main service network design problems deal with an existing system infrastructure for which choices have to be made concerning line operations and terminal policies. These decisions are often based on network simulations or on optimization models. While simulation requires a lot of data inputs and running time, optimization models are faster and thus best suited for a frequent use in an ever changing system. (Crainic & Laporte, 1997)

2.3.2.2 Vehicle routing problems

This category of problems happen on smaller geographical area and are thus best suited for city logistic. VRP "*involve the design of pick-up or delivery routes from one or more central depots to a set of geographically scattered customers*" (Crainic and Laporte 1997, p.425). Since lot's of different questions must be addressed while solving VRP, lot's of different models and solutions exist. Consolidation is central to such systems implying a vehicle movement to transport goods from an origin to a destination. (Crainic & Laporte, 1997)

2.3.3 Operational decisions

At the operational level, when strategic and tactical decisions have been made, problems like service scheduling, empty vehicles repositioning, crew scheduling and resources allocation should be looked into. These decisions ensure that the logistic plan made previously is adapted to the daily operations. (Crainic & Laporte, 1997) Due to the need of real time and field data coming from a real implementation of the system, this decision level is out of the scope of this thesis.

2.4 Public transportation models

2.4.1 Shared passenger and freight transports

Several searchers have looked into the potential of mixing urban freight transport with passenger's transport. The main findings are summarized in this section.

Behiri, Belmokhtar-Berraf, and Chu (2018) identified six main operating issues while integrating urban freight into passenger trains:

1. Goods needs to be stored temporarily close to the gate while waiting for the train and therefore a space needs to be found.
2. Similarly, an area should also be planned for the unloading. These first two issues are bin-packing problems.
3. Train timetable should fit the distribution needs. Planning might have to be adapted according to freight demand and the impact on passenger's transport should be analyzed.
4. The load should be optimally stored in the car such as reducing the future unloading time.
5. The upstream flow should be regulated according to peak hours in passenger transportation. This may be done by balancing the price with different lead times.

6. Finally, the freight transport should be dispatched and scheduled in order to minimize the waiting time. The waiting time is here defined as the time a package wait at the source station before being loaded in the first train.

Additionally, the authors formulated a freight rail transport scheduling problem as a mixed-integer. In their case, they considered a complete sharing of the physical elements (vehicles, rails and stations). Since passenger and freight transport will often operate simultaneously, their operating time will also be shared. Due to regulation constraints, the authors decided that some cars at the end of the train will be entirely dedicated to freight while the front will be for passengers journey. For simplification, they considered a single rail line problem.

Fatnassi, Chaouachi, and Klibi (2015) proposed to share personal and freight rapid transit. This mode of transport use urban rail to move small quantities from a source station straight to a destination thanks to a well interconnected rail network. Assuming that the design was already decided and implemented, they focused on an operational model and on the transport problem with the objective of minimizing empty runnings and waiting time. With time window, they will specifies when the network is available for freight, person or both. In peak hours, it could be dedicated only for passengers while in off-peak hours, smaller time window should alternate between freight and person. Nights could for example, be dedicated only to freight transports.

Masson et al. (2017) developed a model to transport goods through public buses on a single bus line from a consolidation center to bus stops where a city freighter will collect the goods and deal with the last mile. Their main assumption is that the goods will use the buses sparse capacity without affecting the passengers. First, the distribution centre takes care of reception, sorting and loading into buses in an asynchronous way: only when reception and sorting operations are terminated may the loading starts. Loading operations take place in an adequate container system and is constrained by a maximum capacity to keep the service-level for passenger unchanged and such that they can be unloaded in each station sufficiently fast. Then, at each station, a city freighter will be there to unload the bus and deliver the good to its final customers. This city freighter will face usual last-mile issues. Finally, the authors translate all this to a vehicle routing inspired model.

Zhao et al. (2018) designed a metro-integrated logistics system for intra-city deliveries in Shanghai. First, they divided the city in sub-areas in which p hubs will need to be situated. Then, they evaluated the importance of each metro stations with indices from complex network theories: 1) degree centrality - how many connections does the node has in comparison to the maximum number of connections in the network; 2) betweenness centrality - how frequently a node is in between two other nodes; 3) closeness centrality - how close is a node from the center of the network and; 4) eigenvectors centrality - how important are the neighboring nodes of a node. Afterwards, they balanced these indices by assigning them weights. The importance of each indices with pairwise comparisons was established by a panel of experts. Then, they used a three-scale method of analytic hierarchy process to compute the weights. The equation for each of these indices are represented in table 1. Finally, they solved a location model which aims to minimize the delivery travel distances. Analytical hierarchy processes, generally used a 1-9 scale for such decisions (Franek & Kresta, 2014, Vaidya & Kumar, 2006).

Degree centrality	Betweenness centrality	Closeness centrality	Eigenvector centrality
$DC_i = \frac{K_i}{N-1}$	$BC_i = \sum_{i \neq j \neq r} \frac{k_{j,r}(i)}{k_{j,r}}$	$CC_i = \frac{N-1}{\sum_{j=1}^{N} d_{i,j}}$	$EC_i = \frac{\sum_{ij} A_{i,j} EC_j}{\lambda}$
K_i is the degree of node i, the number of nodes that i is directly connected to. N is the total number of nodes in the network $k_{j,r}$ is the number of path from j to r and $k_j r(i)$ are the ones passing through node i $d_{i,j}$ is the shortest distance from node i to node j $A_{i,j}$ is the adjacent matrix of the network, node j is node i neighbours λ is a constant that reflects that not all nodes are equal.			

Table 1: Node importance indices according to Zhao et al. (2018) and clarified by Newman (2016)

2.4.2 Network theory applied to public transports

How could this network theory be applied further to the public transport context ?

Shanmukhappa, Ho, and Tse (2018) used the network theory to analyze the spatiality of transports networks. He proposed to model a bus transport network by using super-nodes.

Super-nodes are defined by combining the stops that are geographically close. He proposed a threshold of 100 m which is a walkable distance. Practically, super-nodes correspond to stops that deserve the same place and are typically located on each side of the road. The authors advance that this combination make the structural behavior easier to understand, help in the determination of transfer possibilities and with the determination of nodes significances. Above that, it reduces the redundancies in the network and fasten the computational process. In addition to the centrality as defined by Zhao et al. (2018), the authors introduced the concepts of hub and authority centralities: "*a hub is a node that connects to many other nodes in the network and an authority is a node which is pointed by many hubs in the network* "(Shanmukhappa et al., 2018, p.307).

Hadas (2013) used google transit data to assess the connectivity in public transport. The author presented a methodology to extract, store and analyze public transport data with GIS (geographic information system) techniques. First, he added and connected the stops to the network. Then, he built routes by locating the shortest path based on the stops sequences that are find in the `trips` file. Afterwards, based on the schedules departure, he calculated headways and frequencies. Finally, he used these spatial and temporal data to analyze the network connectivity.

Psaltoglou and Calle (2018) first identify critical nodes using degree and betweenness centralities. Then, with data on frequencies (F_l), velocity (V_l), vehicle capacity (C_l) and distance ($D_{l,n}$), the authors computed the connectivity index of the nodes. This is defined as: "*the sum of all connecting powers of all the lines (links) crossing the node*" (Psaltoglou & Calle, 2018, p.25) with the equation 2 that expresses the out or in-bound connecting power of a link. H_l is the daily hours of operations on the line 1 and a, β and γ are scaling factors for their respective parameters. Since the pre-processing of the data may take time, the authors propose to only do it for nodes that already seems critical based on centrality and betweenness. In addition, the authors considered the temporal dimension of critical node by using data about urban activities density.

$$P_l = a(C_l * \frac{60}{F_l} * H_l) * \beta V_l * \gamma D_{l,n} \tag{2}$$

3 Methodology

This thesis aims at creating a network design model for the deliveries of parcels through urban public transport. A functional physical internet network is assumed to exist to make the operational activities feasible. In this section, we will explain how the delivery process will happen before introducing the methodology to design such network.

3.1 Operational process

This process is illustrated in figure 1.

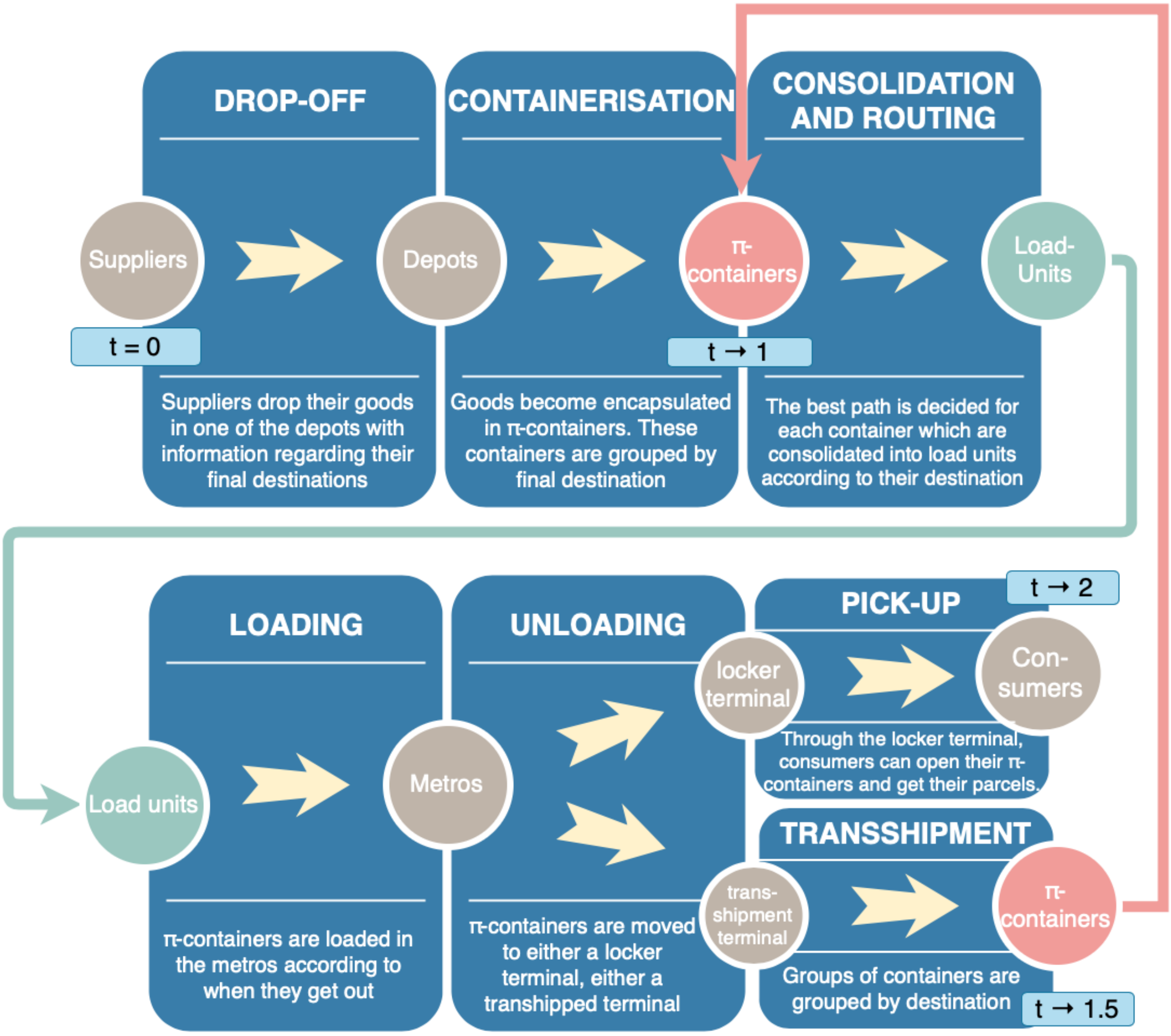
Suppliers will deliver the goods in one of the depots where it will be put in π-containers. These π-containers are boxes which encapsulate the goods to be delivered. These boxes can be attached easily to one another. They will contain an RFID tag to give them the ability to communicate. Only with the right smartphone signal can the boxes be unclipped or opened. In these depots, after the containerization, will the consolidation and the routing happen : the containers will be grouped and clipped together according to their destination.

Before its first trip, in the depot, a tram or metro (here after both named metro) will be loaded with containers according to needs and capacities. These containers will be locked to the metro to prevent any theft or movement.

When the metro arrives in a locker-station, automation or an employee with a smart-device will be able to unlock the π-containers and bring them to the smart locker-terminal. There, customers will open the containers with their smartphone or with a code on the locker-terminal, to finally get their goods.

If a transshipment is needed, the goods will get out at a transshipment station together with the goods for which it is the final destination. They will then be brought to the terminal where consolidation will happen again. When all of this-period containers have arrived to the transshipment-station, they will be sent together to the next metro. There, the same process happen again until the containers have reached their final destination.

To enable this system, a design problem will first be solved: depots at the edge of the system will be chosen, transshipment stations will be identified and finally locker terminals will be located. Then, a planning model will be created which assure the delivery of the containers in time. Finally, the design of this network made based on the Brussels public transport schedules will be tested with randomly generated parcels demand.



Suppliers drop their goods in one of the depots with information regarding their final destinations

Goods become encapsulated in π-containers. These containers are grouped by final destination

The best path is decided for each container which are consolidated into load units according to their destination

Through the locker terminal, consumers can open their π-containers and get their parcels.

π-containers are loaded in the metros according to when they get out

π-containers are moved to either a locker terminal, either a transhipped terminal

Groups of containers are grouped by destination

Figure 1: Operational process

3.2 Network design model

To send parcels through public transport, the network will need to be build based on the data from the used public transport network, available in the format of the global transit feed identification system (gtfs) created by Google (2019). Other data on the city characteristics such as its population in each districts will also be needed.

With all these data, the first step will be to simplify the public transport network using the super-node representation developed by Shanmukhappa et al. (2018) and extract them from the gtfs file as suggested by Hadas (2013). The network can then be build by adding to the super-nodes, the edges corresponding to each routes.

When the network is built, network connectivity can be analyzed. This will help to identify hubs location and prioritize some locker locations over others. The most used indices in the literature which are degree centrality and betweenness centralities (Zhao et al. 2018; Zhao et al. 2018; Psaltoglou and Calle 2018) will be used along with closeness centrality and eigenvectors centrality. Since each of them doesn't have the same importance for our choice of location, weights for each indices will be calculated by using pairwise comparisons and a 1-9 scale based analytical hierarchy process. This final centrality index will help to identify one or several hubs that are important nodes in the network while connecting both depots. When these hubs are decided, the set of potential lockers will be build such that each locker can be reached by a depot in no more than one transshipment.

In a second part, the locker location model will be solved. The nodes selected above will form the set of potential locker locations. This model will be a fixed charge model (Daskin et al., 2005) that allow some uncovered demand (Nozick, 2001). The coverage will be computed for several districts which demands are represented as a centroid point and their quantity-of-coverage will differ according to their populations (Jia et al., 2007). Taking relatively small districts will reduce the MAUP problem (A. Murray, 2005). The coverage will be calculated with euclidian distances but the choice of an appropriate distance that customers will be willing to walk should take this approximation into account. For each node, their indices will be used to compute the cost of its impolementation. These indices should reflect the preference of having one node as a locker instead of another one.

Additionally, the cost to built a hub will be null such that our model will undoubtedly choose it as a locker location.

The network will then be further designed by allocating to each chosen locker the public transport trips in which their parcels could be handled to arrive directly or through a hub.

Finally, a simulation of this parcel transportation model will be made based on an estimate of the demand for parcels across the Brussels region. Parcels will be allocated to one of the selected trips such as maximizing filling rate while respecting a certain capacity. Furthermore, the choice of a planning period will be made such that a half-a-day delivery can be guaranteed to the contractor.

4 Analysis

4.1 Data explanation and preprocessing

4.1.1 The public transport network

4.1.1.1 Background informations on Brussels public transport

The principal public transport operator in Brussels is *Société des transports inter-bruxellois* (STIB-MIVB). STIB aims at "*improving mobility in Brussels and the quality of life of its citizens*" (STIB-MIVB, 2019a). Its network is composed of 4 metro-, 17 tram- and 50 bus-lines. It operates 24/7 and on approximately 650 km across the Brussels region and its suburbs, serving 2,200 stops. (STIB-MIVB, 2019b) In 2017, trams and metros accounted together for 75% of the journeys (STIB-MIVB, 2017). Focusing only on this two similar modes of transport will thus be significant.

Wishing to "*keep Brussels moving*", STIB, with its open data project which aims to trigger innovative solutions, has shared all the information used by customers to travel in their network (STIB-MIVB, 2019c). The data are shared in a gtfs folder. Global Transit Feed Specification (gtfs) is "*a common format for public transportation schedules and associated geographic information*" (Google, 2019). Along with scheduling information, useful data on the design of the network can be retrieved from this gtfs folder. The data are separated in different files that are related to each others as can be seen on figure 2. The coordinates follow the WGS84 reference system.

4.1.1.2 Transformation of the gtfs database

The structure of the relational database is illustrated in the figure 2. Due to the size of this folder, only some data will be retrieved in the code (appendix A3.1). The following changes have been made:

- `calendar_date`: The strategic decisions are based on an usual day with a standard schedule. Therefore, this file, which was created to account for exceptions, isn't relevant here.
- `calendar`: The file accounts for a 30-day period. Since the basic trips happen everyday, we will retrieve only the element for one usual day: the 11th of March 2019 (20190311).
- `routes`: Our system will focus only on tram (route_type = 0) and metro routes (route_type=1).
- `trips`: Only the trips related to the services (calendar) and routes selected above will be retrieved.
- `shapes`: This file will be used only for illustration purposes.
- `stop_times`: The timeframe will be reduced to the period between 10:00:00 and 12:00:00. Looking only at two not-peak hours should be enough to give us all information regarding frequent routes. This will reduce the instances in the `stop_times` file from more than 4 millions to less than half a million.
- `stops`: Only the stops related to the selected trips will be kept.

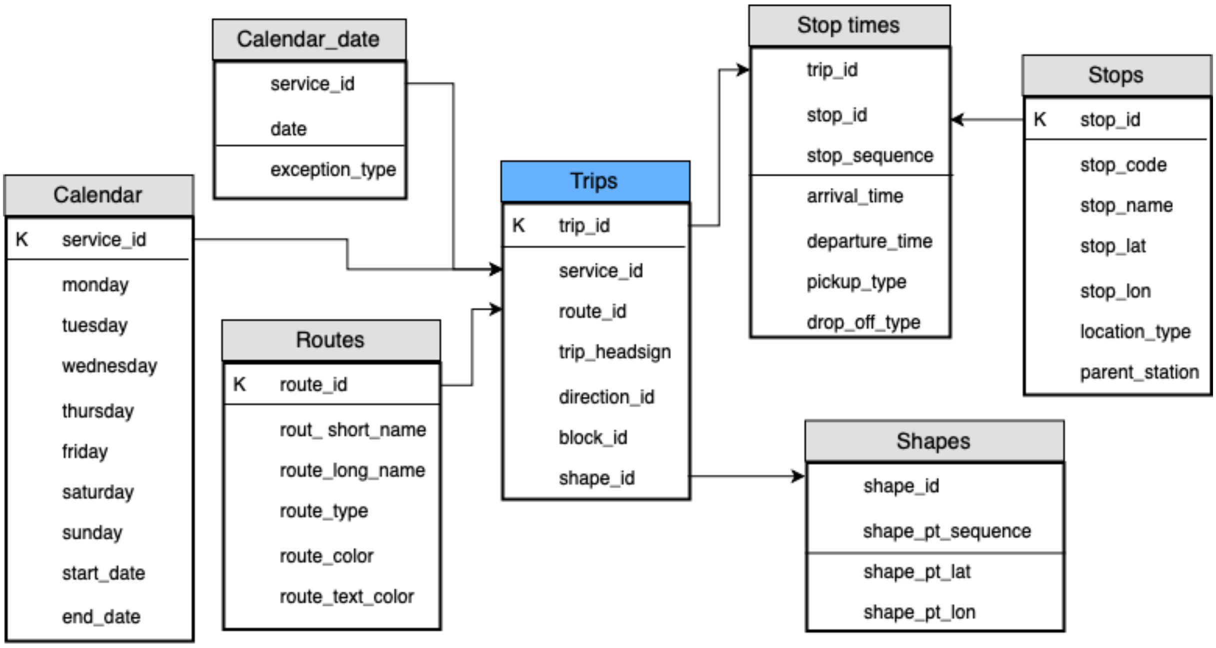


Figure 2: Entity relations for the STIB (gtfs) database

4.1.2 Depot locations

Freight flows can enter Brussels through multiple axes. Brussels mobility has counted the entries and exits of trucks and delivery vans on a usual weekday at 25 strategic points on the edge of Brussels. It appears, without surprise, that delivery vans are well represented and three locations stand out: on one hand, *boulevard industriel* in the South that connects to the E19 (Paris-Mons) and on the other hand, the entries on the A3 and the A12 in the North that connects to the E40 (Leuven-Liège) and to Antwerp. This study also shows that this traffic is spread across the day while car traffic has two peaks: one around 8.00am and one around 05.00pm. (Strale, Lebeau, Hubert, & Macharis, 2015)

Knowing how freights prefer to access Brussels, the depots should be located to satisfy these North and South entries. STIB owns several tram depots from which two seems to be the best candidates due to their size and due to their location nearby these main axes: the *Maroni* depot in the South and the *Haren* depot in the North.

Trams stay there overnight and travel empty afterwards until their starting stop. We may assumed that trams starting their trips at *Stalle* (line 4), *Drogenbos Chateau* (lines 32 and 82) and *Van Haelen* (line 51) were parked in the nearby Maroni depot. The Haren depot is likely to store trams that will start their journey at the following nearby stops: *Da Vinci* (line 32 and 55) and *Euro Control* (line 62). All these stops will be referred to as *depot stops* and are illustrated along with the STIB metro and tram network on figure 3.

With an interconnected logistics network enabled by the PI in mind, the Brussels port shouldn't be forgotten as a potential depot. The terminal *avant-port* handles most of the freight transport (Strale et al., 2015). Combined with the *Van Praet* tram-stops nearby it could be a plausible depot place and intermodal hub. While difficult to implement at the moment, barge delivery could be applicable in a near future (Buldeo Rai et al., 2019).

4.1.3 Estimation of the demand for parcels

According to Cárdenas, Beckers, and Vanelslander (2017), 0.33 deliveries per 1,000 inhabitants occur daily in Belgian urban areas. Population density data along with geographical boundaries of 145 districts that cover the Brussels region can thus be used to express the demand for parcels in Brussels. These data are retrieved from the *Monitoring des quartiers (2016).* The geographical data are expressed with Belgian reference system (EPSG:31370) which is in metric units. From these 145 districts, only the 118 residential districts are relevant because the other districts (green space, cemeteries and industrial area) have a low population density. These residential districts account together for the areas where 99.7% of Brussels population live.

The demand for parcels in each district ($h_i = 0.33 * (\text{population in i})/1000$) will be used in the location model to prioritize highly populated districts since the total coverage will have to be higher than a given treshold. Additionally, each district will be represented by its centroid point. A district will be considered as covered if its centroid lies inside the coverage area of a locker (i.e., if the distance between the centroid and the locker is inferior to the willingness to walk) As highlighted in the literature review, the use of a point-representation may lead to uncovered areas. Nevertheless, since our dataset is divided in a high number of districts, each with relatively small areas, the additional distance this representation may lead to will be small enough to be acceptable. We may therefore assume that potential customers will still be willing to walk it. The districts along with their centroids are illustrated in figure 4. Only the residential district centroids are represented.

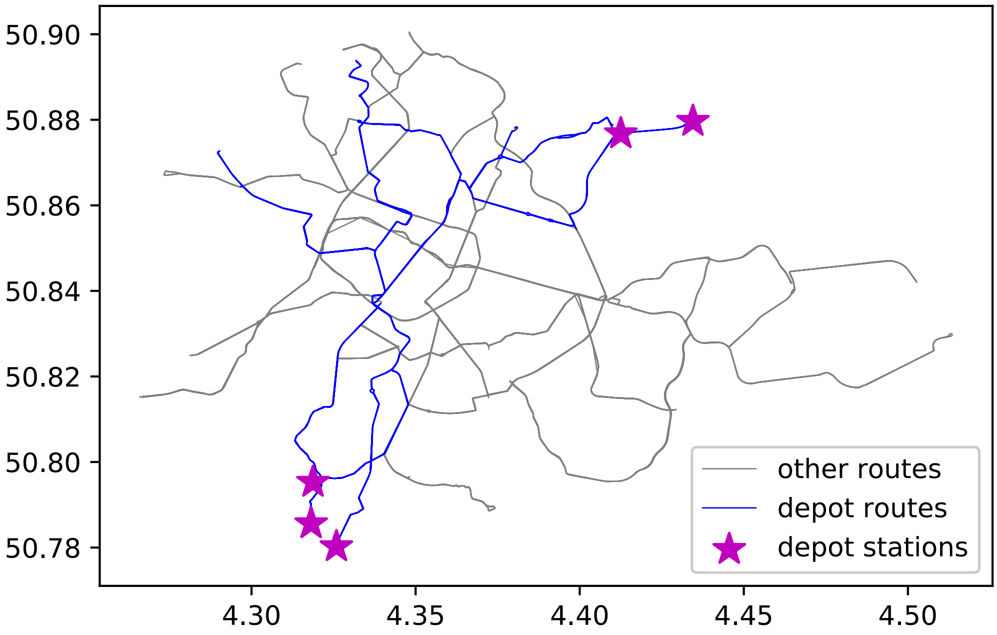


Figure 3: The STIB network and the depot stations

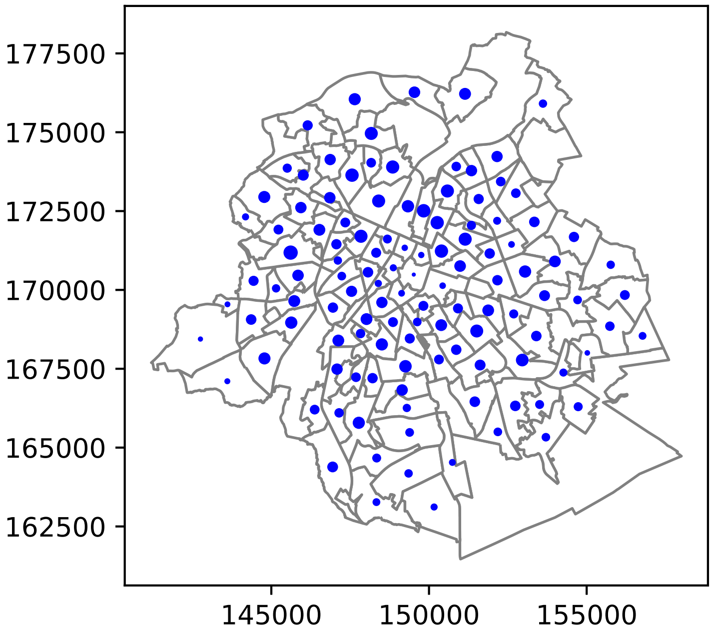


Figure 4: Brussels residential districts and their centroid reflecting the demand

4.2 Potential locker locations

Automated parcel lockers storing π-containers should be built at some metro stops. They are the connection point between the customers and the logistic network. Each metro stop does not have the same weight as a candidate. Therefore, centrality indices from complex network theory will be built to account for the importance of each node in the network. With this classification, a unique index will be built. It will play the role of a cost for the locker location model. This section will explain how the data were generated to be used in the locker locations problem. The code used is explained in appendix A3.2.

Before the first computations, stops will be grouped in super-nodes according to their proximity (Shanmukhappa et al., 2018). In the gtfs data file, this corresponds to stops having the same name but different `stop_id`. Then, the edge between each node will have to be computed. Therefore, information about each trip will be needed. The stop sequence for each route will also help to define the edges.

4.2.1 Centrality indices

Indices from network theory will be used to estimate the importance of each stops. The most known and used centrality indices are classified by importance bellow. They can be calculated in python with the `NetworkX` package.

- Degree centrality: the bigger is this index, the more direct neighbors does this node have. It also means that multiple metro-lines are passing by this node. People are thus more likely to go out of their transport mean at this stop.
- Closeness centrality: the closer is this node to the center, the bigger will this index be. If people do not especially live in the center of the network, workspace, shops and other activities are likely to be situated close to there.
- Betweenness centrality: if this node is in the middle of lot's of path, then people will likely pass through it. They may not have planned to stop there, this is why this index is less important than the degree centrality.

- Eigenvectors centrality: this index reflects the importance of the nodes situated close-by. In our context, the locker should preferably be situated in the important locker instead of close to it. Therefore, this index will be the least valued.

These four indices of centrality doesn't have the same weight in the decision process. Therefore, we will use an analytical hierarchy process to define these weights. First, the indices will be pairwise compared. Then, this matrix will be normalized and finally, weight will be calculated. The results can be seen in table 2 and were computed with excel (appendix A9)

	DC	BC	CC	EC
DC	0,64 (1)	0,16 (1/4)	0,13 (1/5)	0,07 (1/9)
BC	0,75 (4)	0,19 (1)	0,04 (1/5)	0,03 (1/7)
CC	0,45 (5)	0,45 (5)	0,09 (1)	0,02 (1/5)
EC	0,41 (9)	0,32 (7)	0,23 (5)	0,05 (1)
Total	2,24	1,11	0,48	0,16
Weight	0,56	0,28	0,12	0,04

normalization (scale-value)

Table 2: Pair-wise comparison on a scale of 1 to 9, normalization and weights for the centralization indices

4.2.2 Transshipment hub location

By using only the routes connected to the depot, 80 % coverage within 2km isn't possible (cfr. appendix A8): the use of transshipment hubs is crucial. For the operational process to stay manageable, transshipment should happen at most once. Therefore, the transshipment hubs should be identified before defining the set of potential locker locations. This latter will be restricted to the stations that can be reached by the transshipment hubs.

Table 3 shows the 5 stops on the depot line that have the highest importance in terms of centrality as computed above. It also shows the centrality index of the three stations that are connecting both depots. From these results, *Rogier* stands out as a potential hub since it is connecting both depots and is the second highest in terms of centrality. *Gare du Nord* is connecting the same routes as *Rogier*. It is therefore not an interesting station to choose as a second hub. Since *Cimetière de Jette* is connected to both depots and is reaching different routes than *Rogier*, it seems an ideal location for a second hub. By looking at the map 5, we can clearly see that *Rogier* and *Cimetière de Jette* are connecting a different set of stations.

	Centrality index	DC	BC	CC	EC	Routes	N. depot 4, 82, 51	S. depot 32*, 55, 62
Station connecting at least one depot (top 5)								
Gare du Midi	0.0986	0.015	0.279	0.093	0.027	2, 3 4, 6 (32), 51, 81, 82	yes	*After 8pm
Rogier	0.0884	0.012	0.206	0.094	0.321	2, 3, 4, 25, (32), 55	yes	yes
Gare de l'ouest	0.0879	0.145	0.245	0.086	0.015	1, 2, 4, 6, 82	yes	no
Porte de Hal	0.0855	0.009	0.245	0.093	0.016	2, 3, 4, 6, 51	yes	no
De Brouckere	0.0717	0.012	0.161	0.094	0.218	1, 3, 4, 5	yes	no
Stations connecting both depots (all)								
Rogier	0.0884	0.012	0.206	0.094	0.321	3, 4, 55, 25, 2, 6, (32)	yes	yes
Gare du Nord	0.0442	0.006	0.084	0.088	0.169	3, 4, 25, 55	yes	yes
Cimetière de Jette	0.0240	0.018	0.019	0.064	0.027	19, 51, 62, 93	yes	yes

Table 3: Centrality indices for the most central potential hub locations and their connecting routes

4.2.3 Potential locker locations

Now that the hub have been chosen, the set of potential locker locations can be reduced to all the stations that are on one of the hubs routes. The other ones on a depot route cannot be reached by both depots with one or less transshipment. From the 335 super-nodes, 123 still stand as candidates for the implementation of a locker terminal (fig. 5). All of these can be reached from both depots through maximum one transshipment.

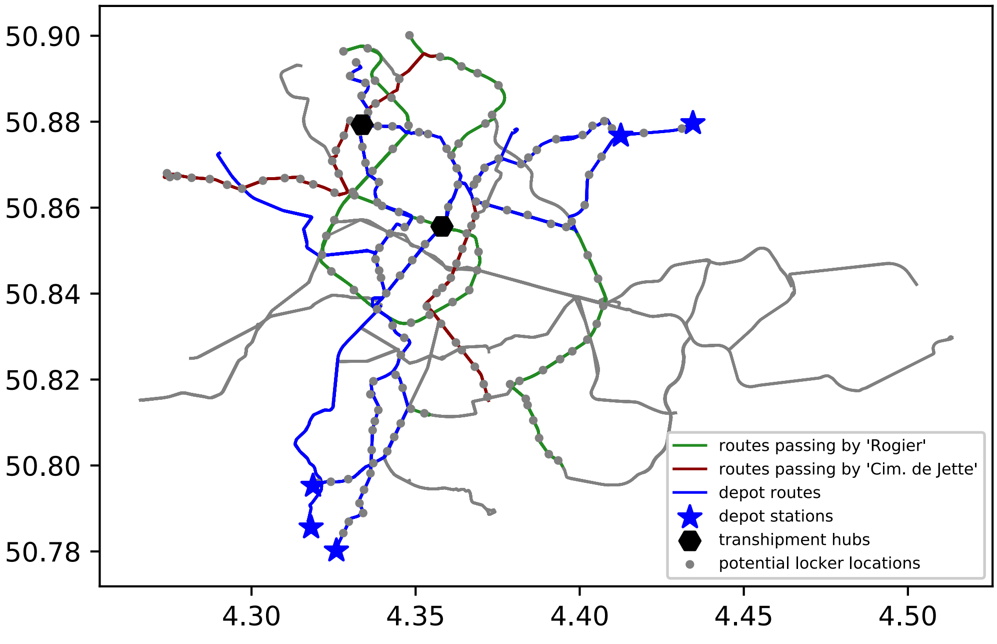


Figure 5: Potential locker locations

4.3 Locker location model

4.3.1 Model

To find a solution to the locker location problem, we will iterate a fixed charge location model adapted from Daskin et al. (2005) over several coverage rates and with different walking distances (R). The most plausible solution will be selected: a solution that has a realistic number of lockers, a sufficient coverage and a distance R that customers will be willing to walk.

The model that will be used is written below. Variables, sets and parameters are defined on table 4. The objective function (3) minimizes the total costs of implementing locker terminals (i.e., favor the most important one according to their centrality index). The equation 4 along with the constraint 5 ensure that the minimal coverage rate is achieved. The next one (eq. 6) ensures that no demand is allocated to a closed or too far away locker terminal. The last constraint (eq. 7) defines our allocation variables as binary.

$$min \qquad \sum_{j=1}^{J} c_j x_j \tag{3}$$

such that

$$b * \sum_{i=1}^{I} h_i \qquad \leq \qquad \sum_{i=1}^{I} \sum_{j=1}^{J} \quad (h_i * y_{i,j}) \tag{4}$$

$$\sum_{i=1}^{I} y_i \qquad \leq \qquad 1 \tag{5}$$

$$y_{i,j} - x_j * z_{i,j} \qquad \leq \quad 0 \qquad \forall i, j \tag{6}$$

$$y_i, x_j \in \{0, 1\} \qquad \forall i, j \tag{7}$$

	Sets
i = 1,...,I	set of parcels/clients locations.
j = 1,...,J	set of potential locker locations.
	Variables
x_j	lockers allocation : 1 if a locker is open in location j, 0 otherwise.
$y_{i,j}$	demand allocation: 1 if the aggregated demand i is assigned to the locker j.
	Parameters
$z_{i,j}$	coverage parameter : 1 if demand at location i is covered by the locker terminal situated in j, 0 otherwise.
h_i	demand parameter : demand for parcels aggregated at node i
b	the minimum coverage rate required.
c_j	cost to put a locker in station j defined as the opposite of the centrality index.

Table 4: Sets, parameters and variables for the locker location model

This model has been solved using the Python(3.7)-based open-source optimization modeling package: Pyomo (5.6.2) (Hart, Watson, & Woodruff, 2011 ; Hart et al., 2017) and the solver cplex (12.9) of IBM. The main python file can be find in appendix A3.

First, the distance between each centroid point and each locker has been computed. Then, the binary parameter $z_{i,j}$ that accounts for the coverage was built according to the distance previously calculated and the maximum willingness to walk (R). Besides, the cost to implement each locker c_j is computed with the importance obtained in section 4.2.1 as follow : $c_j = 1 - Index_{centrality}$. Additionally, the parameter of the demand in each location has been computed as explained in section 4.1.3. Afterwards, a `.dat` file is written with the coverage matrix, the cost parameters, the demand parameters and both sets.

These data are then used along with a second python file written in the pyomo language (appendix A2) to solve the model using cplex and through the following line in an osx-64 terminal:

```
pyomo solve LocationModel.py LocationModel.dat --solver=cplex
     --save-result results/results_name.json --json
```

The data were then extracted from the `result.json` file and analyzed in the same `Main.py` file.

4.3.2 Results

Within an euclidian distance of 2 km, the model located 11 lockers for a coverage of 90%. Within this distance, 100% coverage wasn't possible and a lower distance couldn't guarantee a 90% coverage. Nevertheless, a 2 km euclidian distance is small enough and 90% coverage is sufficient. The results are summarized in the table 5 and illustrated on figure 6. The table contain the name and centrality index of each locker along with a binary parameter that reflects the depots and hubs it can be reached by.

Locker location	Depot Nord	Depot Sud	ROGIER	CIM. DE JETTE	Centrality index
BOONDAEL GARE	0	0	1	0	0.015
CIM. DE JETTE	1	1	0	1	0.024
DELACROIX	0	0	1	0	0.057
GARE DU MIDI	0	1	1	1	0.099
HEROS	0	1	1	0	0.052
MEISER	1	0	1	1	0.045
MONTGOMERY	0	0	1	0	0.096
ROGIER	1	1	1	0	0.088
SCHWEITZER	0	1	0	1	0.029
STEPHANIE	0	0	0	1	0.047
VAN PRAET	0	0	1	0	0.017

The binary values indicate if a locker can be reached directly by a depot or a hub

Table 5: Results of the facility location model with two transshipment hubs.

Besides, the model has also been solved for the cases with only one of the identified transshipment hubs. For an euclidian distance R of 2km, 90% coverage was infeasible. However, for the hub 1 (Rogier), the model managed to locate 12 lockers with an 88% coverage (and 2km distance). This solution might be interesting to limit operational costs due to the use of only one transshipment station but it has one more locker than the original solution (table 6). Concerning the second hub (*Cimetière de Jette*), it wasn't possible to achieve an 80% coverage for a 2km radius.

We can notice that for this last result plotted on the figure 7, one of the locker (North-West) is pretty close to the localization of the potential hub *Cimetière de Jette*. Therefore, since it can be reached by both depots, the model has been run one last time with the addition of this stop to the set of potential lockers for the one transshipment hub case. The result with 88% coverage are shown on figure 8. By adding this locker, we can reduce the total number of lockers to the one we had in the two-hub case while keeping the same minimum coverage rate as in the one hub case which is close to the 90% of the first case.

Cimetière de Jette has also a higher centrality index than the stop *Heysel* but a smaller than the stop *Simonis* that both were in the previous result.

We can also notice on figure 8 that two lockers on the South-West are located quite close. The locker *Delacroix* has been selected because it could covered the district *Veyde - Aurore*. As can be seen in the figure 9 and the table 8, this district is the only one that Delacroix is covering that isn't already covered by another district. This district's centroid is at 1.996km of the locker Delacroix and at 2.21 km of the *Gare de l'Ouest*. Additionally, this latter has a higher centrality index and is covering 2 district that no one else covers. Excluding the *Delacroix* locker will thus not impact the real coverage that much since the locker *Gare de l'Ouest* will probably absorb part of its potential demand. This last case will thus be the cheapest option: only one hub and 10 lockers.

The final decision for a parcel delivery network should be made according to the allocated budget and field information such as the true passenger flow should be further analyzed before discarding a station.

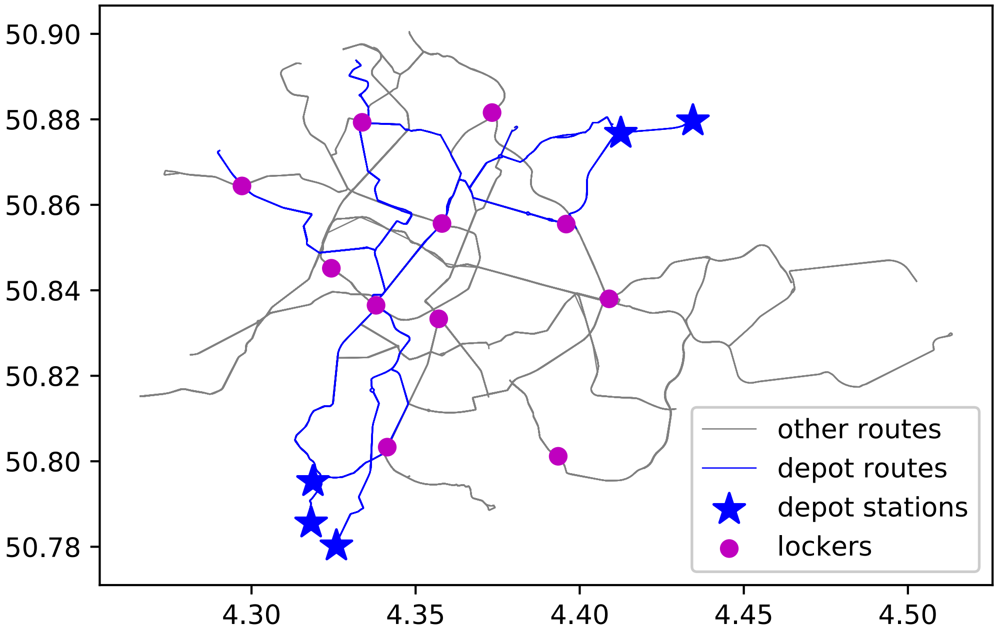


Figure 6: Results of the location model with two transshipment hubs

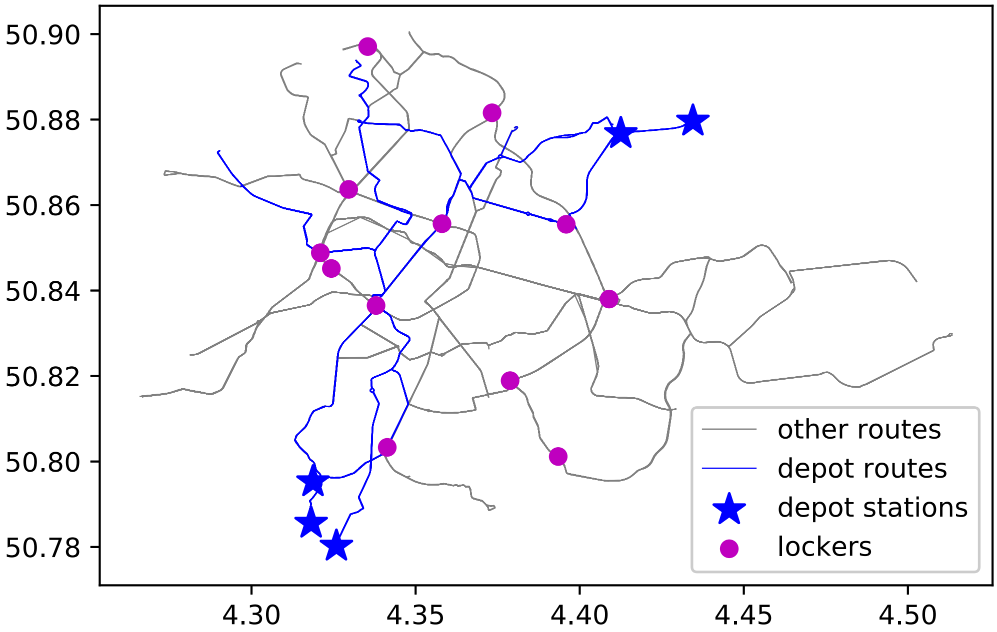


Figure 7: Result of the location model with Rogier as unique transshipment hub

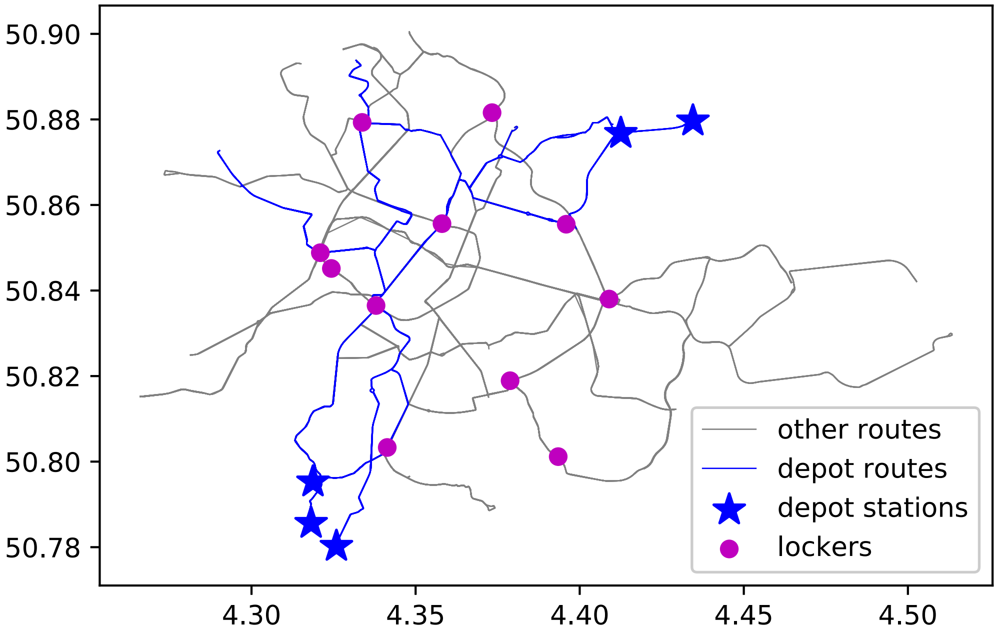
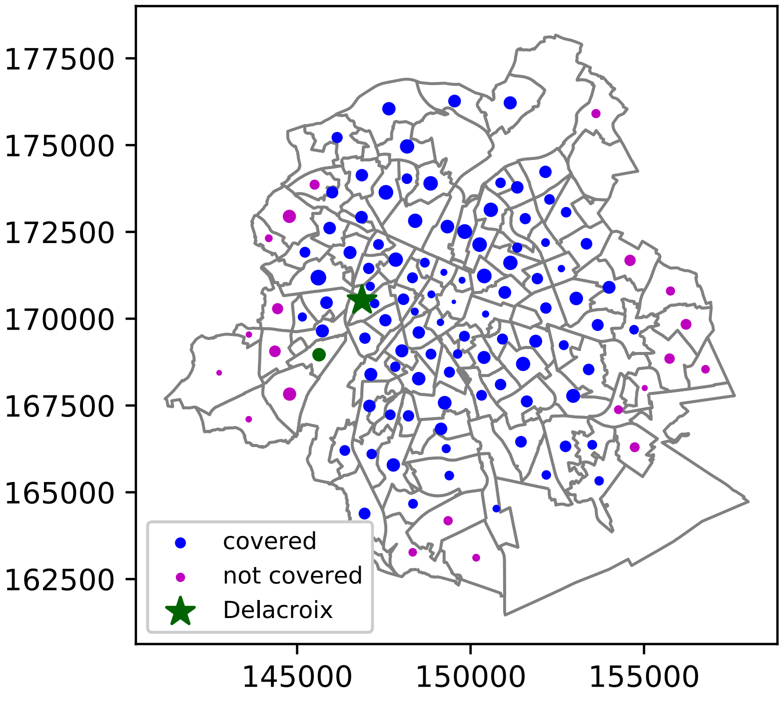


Figure 8: Result of the location model with Rogier as unique transshipment hub and with the addition of *Cim. de Jette* to the set of potential locations

Locker location	Depot Nord	Depot Sud	ROGIER	CIM. DE JETTE	Centrality index
GARE DE L'OUEST'	0	1	1	0	0.088
BOONDAEL GARE	0	0	1	0	0.015
BUYL	0	0	1	0	0.036
DELACROIX	0	0	1	0	0.057
GARE DU MIDI	0	1	1	1	0.099
HEROS	0	1	1	0	0.052
HEYSEL	0	0	1	0	0.014
MEISER	1	0	1	1	0.045
MONTGOMERY	0	0	1	0	0.096
ROGIER	1	1	1	0	0.088
SIMONIS	0	0	1	1	0.067
VAN PRAET	0	0	1	0	0.017

The binary values indicate if a locker can be reached directly by a depot or a hub

Table 6: Results of the location model with the stop *Rogier* as a unique transshipment hub



The green mark is the district that won't be covered if the locker Delacroix is excluded

Figure 9: Coverage of Brussels districts for the single hub case

Locker location	Depot Nord	Depot Sud	ROGIER	(CIM. DE JETTE)	Centrality index
GARE DE L'OUEST'	0	1	1	0	0.088
BOONDAEL GARE	0	0	1	0	0.015
BUYL	0	0	1	0	0.036
CIM. DE JETTE	1	1	0	1	0.024
DELACROIX	0	0	1	0	0.057
GARE DU MIDI	0	1	1	1	0.099
HEROS	0	1	1	0	0.052
MEISER	1	0	1	1	0.045
MONTGOMERY	0	0	1	0	0.096
ROGIER	1	1	1	0	0.088
VAN PRAET	0	0	1	0	0.017

The binary values indicate if a locker can be reached directly by a depot or a hub

Table 7: Results of the facility location model with *Rogier* as a unique hub and with the addition of the stop *Cimetière de Jette* in the set of potential locations

Districts			Lockers			
code	name	population	ROGIER	GARE DU MIDI	GARE DE L'OUEST	DELACROIX
2	Dansaert	3357	1	1	1	1
8	Marolles	12680	0	1	0	1
9	Stalingrad	3522	1	1	1	1
10	Anneessens	10449	1	1	1	1
11	Cureghem Bara	12222	0	1	1	1
12	Cureghem Vétérinaire	9915	0	1	1	1
13	Cureghem Rosée	6145	0	1	1	1
14	Duchesse	5485	0	1	1	1
15	Gare de l'ouest	9853	0	0	1	1
16	Molenbeek Historique	18347	1	0	1	1
17	Koekelberg	8693	1	0	1	1
48	Porte de Hal	14198	0	1	0	1
52	Veeweyde - Aurore	15679	0	0	0	1
58	Anderlecht - Centre - Wayez	14448	0	0	1	1
59	Scheut	13145	0	0	1	1
60	Buffon	5453	0	0	1	1
62	Machtens	22703	0	0	1	1
63	Karreveld	14195	0	0	1	1

Table 8: Coverage of the station Delacroix compared to the other stations in its area.

4.4 Network design problem

For this network design, we decided to select the cheapest configuration: a unique hub and 10 lockers. With these results, paths and trips should be selected to reach these lockers at the least possible costs. The cost should reflect the flow of passenger, the time it takes and the transshipment.

Since our locker location problem was solved with a set of potential locations that will need at most one transshipment, the aim will be to identify which paths could be taken and through which transport routes. The table 7, that synthesizes the results of the location problem, already give us the routing possibilities. The value 1 means that the locker in the row can be reached by the depot or hub in the column. Four lockers will have to receive their goods through the transshipment hub. According to where the parcel arrived in the network, the possible paths for them will be limited to the ones:

- from the Northern depot through the transshipment hub *Rogier* to the locker (2 routes); or
- from the Southern depot through the transshipment hub *Rogier* to the locker (2 routes).

Three lockers could get their parcels through the hub or, if it comes from the Southern depot, they could get it without transhipment. The opposite case applies for one of the lockers (*Meiser*). Depending again of where the parcel arrived in the network, the choice of paths is thus limited to the ones:

- from the Northern (Southern) depot through the transshipment hub *Rogier* to the locker (2 routes);
- from the Southern (Northern) depot through the transshipment hub *Rogier* to the locker (2 routes); or
- from the Southern (Northern) depot directly to the locker (1 route).

Finally, the locker terminal located at *Cim. de Jette* will have to get its parcels directly from the depot. The possible path a parcels for this locker might take are thus the ones:

- from the Northern depot directly to the locker (1 route); or
- from the Southern depot directly to the locker (1 route).

Using the code in appendix A4, the possible metro trips have been identified. The results are summarized in table 9 with, for each locker, the name of the routes it can take along with their frequencies. These trips were identified only for a morning period out of peak hours (between 10.00 and 12.00). The same process can be applied to the afternoon as well to allow two shipments per day and guarantee, for the last-mile, a *half-day* delivery to the main contractor.

Locker locations	depot North	depot South	Rogier
ROGIER (hub)	55 (12)	4 (6)	-
GARE DE L'OUEST	-	82 (18)	2, 6 (12)
BOONDAEL GARE	-	-	25 (3)
BUYL	-	-	25 (4)
CIM. DE JETTE	62 (16)	51 (14)	-
GARE DU MIDI	-	4, 51, 82 (46)	2, 3, 4, 6 (27)
HEROS	-	4 (16)	4 (5)
MEISER	62 (8)	-	25 (22)
MONTGOMERY	-	-	25 (5)
VAN PRAET	-	-	3 (6)

The value in each cell represent the name of the metro lines with the total number of trips inside brackets. The trips from a depot to the hub happen between 10am and 11am, from a hub to a locker happen between 11am and 12am and from a depot to a hub happen between 10am and 12am.

Table 9: Paths to handle the parcels through STIB metro schedules

Before deciding which parcels to allocate to which mode and at which time, which will be done along with a simulation in the next section, we need here to prioritize some trips over some others. A frame will be built with the code in appendix (A3.3) for each path with the following information: trip id, starting point, arriving point, arriving time, departure time. In addition, the number of time a same trip could be used as a path will be added. With this informations, we will ordered the frame by departure time (the earlier it leaves, the better) and by the number of different lockers one same trip can reach (better consolidation). These paths may have to be recomputed regularly to be always updated according to STIB daily schedules. Now, all needed information for this parcel delivery network are created: it is just waiting for parcels to handle.

4.5 Planning

4.5.1 Operational process

When the network is fully designed, an efficient protocol should be built to allocate each parcels to a trip. This will allow to test the system with some random sample datas.

We assume that we have two periods t per day: one in the morning, the other one in the afternoon. Objects dropped in period t should arrive at their destination locker before the beginning of the next period (t+1). Each period is again divided in two phases. In the first one, transportation starts from the depot. In the second one, transportation starts from the transshipment station. This means that each station should be reachable by a depot through the use of maximum two transportation means to ensure a delivery the same day. This was verified at the end of the strategic phase and was ensure in the setting of the potential locations.

When parameters, indices and variables have been decided, the planning might start. Before the beginning of each period t+1, parcels that have enter the depot in period t are encapsulated into π-containers. They are then stored with other containers that have the same locker terminal as destination. These containers will be locked together into load units. When a maximum capacity is reached, a new load unit is created. Since routes to reach each lockers have been identified in the previous phase, the containers can also be grouped together with containers using the same route and stopping at the same transshipment station.

When the period t+1 starts, routing has to be organized to send all these load units to their final or transshipment station. At this point, we will have clear informations about each parcels to be send: where they come from and where they need to go along with the number of load units to transport. Each load unit will be moved around on a trolley that correspond to the number of item that can be taken out of the metros without disturbing the passenger's journeys. The objective will be to minimize the number of different metros to be loaded while being constrained by the number of time a metro can unload trolley without delaying the metros. The loading of the trolleys will of course be done such that the first to get out aren't blocked by other load units. Since loading will happen before a metro starts a new trips, loading time won't be an issue here.

Arriving at their destination or transshipment station, the load units will be moved to the lockers. Final destination containers should notified the customers of their availability. Transshipped containers should be placed with other containers that have the same final destination (if there is some coming from another depot) to create a new load unit. For the transshipped goods, they will arrive in the transshipment-terminal at the end of period t+1. There, consolidation will happen as it happened in the depot. It is only in period t+1.5, when all containers that have left their depot in period t have reached the transshipment-station that the trip will start to their final destination. This is too ensure a better consolidation, reduce the number of trips and handling as well as allowing for a same day delivery.

4.5.2 Application

Some assumptions will be made to be able to test this process. First, each containers will have the same size and we assume that parcels arriving at the depot are meeting the size requirement. Then, trolley will have a capacity of 3 superposed row of 4 containers each: 12 containers can be unloaded in each station. Each trolley contains the parcels of one locker terminal such that the unloading can be fast enough.

It should be noticed in the matrix created previously that there is a maximum of three lockers that have the possibility to share a trip. We assumed that by unloading a maximum of three times, there is no risks of disturbing the metro schedule. This means that a maximum of 36 containers can be transported in each trips.

Using Cárdenas et al. (2017) estimations, we will test on an half-day period our transport scheme for half of Brussels daily estimated parcel deliveries. We will randomly assigned to all these parcels an initial depot and a final locker. For each parcel, the locker will be randomly chosen from a set close to its district centroid.

When we have these input, we may run the code (appendix A4.1) that will allocate each parcel to one or two STIB trips depending on their initial depot. The priority is put on the allocation of trips that will go directly from the depot to the locker. Nevertheless, this is often not possible and the parcels will then have to go through the hub. In addition, a trip leaving early is prioritised over a trip leaving later.

4.5.3 Results

The script was run for 176 parcels. The results are summarized in table 10 and the full results can be found in appendix A10. Each parcel will enter the system in one of the depot before 10am and will arrive at the destination locker before 12am. From these, 83 parcels reached directly their lockers while 93 transshipped through the hub. For the Northern depot, 34 parcels were sent directly while 53 went through the hub. For the Southern depot, 49 went directly and 40 went through the hub. *Rogier* was the most chosen locker so its centrality in the city reflects the public transport network centrality. *Boondael Gare* was the least chosen: only 7 parcels had to reach it. Nevertheless, since this latter is a train station as well, it could also appeal a public coming from outside of the city which wasn't taken into account in this simulation.

These results show that the capacity is sufficient to transport parcel through the metro. With close to a 100 parcels passing through Rogier, the schedule used here may have to be slightly adapted. We may add a buffer time for consolidation and hub operations between the first half period and the second one. Additionally, since people may take several days to get their parcels, each locker terminal should be sufficiently big and their size should be decided through further simulations and tests.

Locker location	Allocated parcels	directly*	with a transshipment
ROGIER	23	23 (N & S)	0
GARE DE L'OUEST	22	9 (S)	13
MEISER	22	12 (N)	10
CIM. DE JETTE	21	21 (N & S)	0
MONTGOMERY	21	0	21
HEROS	17	8 (S)	9
GARE DU MIDI	16	10 (S)	6
BUYL	15	0	15
VAN PRAET	12	0	12
BOONDAEL GARE	7	0	7
Total	176	83 (34 N & 49 S)	93 (53 N & 40 S)

*direct deliveries coming from the Northern depot (N) or the Southern depot (S).

Table 10: Results of the allocation of parcels to trips

5 Conclusion

5.1 Managerial findings

In this thesis, a full system to move parcels through a city, from a depot at the edge to its center where people live has been developed. This system uses existing transport capacities, which leads to no additional negative externalities such as pollution.

For the city of Brussels, a network was build for which approximately 88% of the demand will be within a 2km radius of a locker. This network necessitates the implementation of 10 lockers, two depots and only one central hub.

In addition to model the network to transport such parcels, the operational process to move these parcels within a half-a-day period was developed. The results on the city of Brussels show that the capacity of the public transport will be sufficient to assure a fast last-mile delivery. The STIB along with an optional parcel delivery subcontractor could deal with the last mile of main logistic provider services. Therefore, this system could be an alternative to home deliveries and van transportations that will allow to solve the last-mile issue or at least reduce its externalities.

5.2 Theoretical contributions

This thesis contributes to the location model literature by applying a fixed charge model with minimal coverage to a public transportation network. Additionally, the network theory and its concept of centrality was used to define the importance of nodes and generate the cost parameter of the location model.

Besides, the code developed for this thesis used a global transit file which is a common format generated by most public transport operators. Therefore, the process developed here could be easily adapted to other cities that are facing different or similar challenges. The process to identify depots, hubs and locker locations can be replicated and its operational model can be applicable, with slight modifications, to most cities.

5.3 Critics

All of these results need to be confronted with actual field experimentations. With real on site data, other indices such as the connectivity index proposed by Psaltoglou and Calle (2018) could be defined. These will allow to create a more precise segmentation of the potential lockers and lead to more accurate results. Additional physical or legal constraints for the stops may also exclude some locations from the set of potential lockers. Besides, instead of using only the centrality as a factor of the costs, costs could also be calculated with the operational and fixed costs that a locker implementation will actually induce.

This thesis also made strong assumptions about technical issues that π-elements should be able to deal with. Of course, the Physical Internet is not yet a reality and a solution for these technicalities should thus be found before being able to implement this system. It was for example simplified here with only one parcel size. The model could be further developed to account for larger parcels encaspulated in multiple interlocked containers.

Furthermore, the costs to adapt the transport mode together with the financial costs to build and run the lockers, hub and depots were not deeply taken into account in this work.

Nevertheless, this thesis gives a first insight of the potential to integrate parcel deliveries into passenger transport. Due to the global format of the gtfs file, this framework could be applicable to cities way larger than Brussels for which the need of such systems may be even more present.

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