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Optimizing the location selection of Urban Consolidation Centers with sustainability considerations in the City of Bordeaux

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Highlights

- A two level multi-commodity network flow and location selection model is formulated to optimize the overall cost of the network including transport costs and urban consolidation centers (UCC) costs.
- The operation of the UCCs is modelled in terms of capacity and flow consolidation.
- Realistic data sets from the city of Bordeaux are used: delivery demands, distances matrix and location of main city logistics entities. The breakdown of transport costs and the costs setting is based on national French road committee .
- The optimal combination of deliveries via UCCs and direct deliveries significantly improves the total transport cost including the social cost of CO2 emissions, compared to direct delivery scenario.
- The design of a distribution network where the total capacity of the UCCs is balanced against the total demand for deliveries is sufficient to achieve the best overall cost.

Abstract The delivery of parcels in city centers is nowadays a topical issue and a major challenge for the local authorities. In this paper, we tackle the parcels distribution network in the city of Bordeaux. This city is at the very beginning of the process of moving from direct deliveries towards city center, to a more rational organization based on joint deliveries. We focus on the potential contributions of a two-tier distribution system made up of warehouses, proximity logistics spaces and intermediate depots so-called urban consolidation centers (UCCs). We seek to optimize the costs of the distribution network (i.e. transport and UCCs) and the selection of UCCs, while assessing the impact in terms of sustainable development by measuring CO₂ emissions. We analyze and compare different scenarios using different deliveries' variants (with or without UCCs), different total UCCs capacities and different truck speeds. The findings demonstrate the benefits of using UCCs for city center distribution. The reductions in total cost and CO₂ are most significant when the size of the UCCs is balanced with the total deliveries demands.

Keywords: city logistics; freight distribution network; urban consolidation centers; network flow problem; linear programming

1. Introduction

City logistics concerns with the flow of goods and commodities in conurbations, their transport, their delivery to the final destination, as well as the management of return flows. It involves or affects multiple actors with sometimes contradictory objectives: economic agents, public institutions, inhabitants. Today, city logistics is a major concern that attempts to respond to the challenges of sustainable development and quality of life in the cities (Taniguchi et al., 2016). This is all the more important in the current context of the constant increase in deliveries generated due to broadening of e-commerce and the emergence of phenomena such as pandemics.

In this article, we focus on the city logistics in Bordeaux. The city center of Bordeaux is characterized by a scarce amount of land. Since 2000 the urban policy in Bordeaux has set up pedestrian zones in the city center with restricted access (LTZ: limited traffic zone) in certain time slots (i.e. from 7 to 11 a.m.) for vehicles less than 7.5 tons. However, these restrictions are poorly respected since these limited traffic zones create strong tensions on deliveries in the city center generating congestions at the opening hours.

In this context, new solutions are being sought for the delivery of goods in city center. The new trend in city logistics is the implementation of urban consolidation centers (UCC) to improve the last mile deliveries. This UCC operates the last mile delivery towards the shops in the city center, and it also offers a reverse logistics service for shops as well some remote storage. The goods are transported from the carriers' warehouses to the UCCs where the consolidation takes place. The transport between the UCC and the final customers (shops) is handled by the UCC itself. This avoids the trucks entering the city center and losing time due to congestion and parking difficulties. The deliveries to end customers are made with trucks that meet the latest emission standards or with small electric vehicles or cargo bikes.

A previous study (CUBa, 2012; CUBb, 2012) on the setting up of a UCC, north of Bordeaux concluded that such a UCC would not be profitable in the medium term when the volumes captured by the UCCs are low. In 2019, given the sharp increase in the volume of parcels to be transported and the changing environmental constraints, a UCC was installed in this same northern area of the Bordeaux in the area of the old docks. This UCC, which currently handles a marginal volume of parcels, is nevertheless operated by a company named Urby¹, which is setting up such UCCs in several French cities. Two other actions have been launched recently: one is the logistic hotel of Laposte group also located in the north of Bordeaux, which provides various services including that of UCC; the second is a UCC in the west side, on the right

¹ <https://www.urby.fr/>

bank of the Garonne river. The volumes of parcels deliveries insured via all those UCCs are still marginal to date.

The objective of this research is to bridge the gap between academic work on UCCs and freight transport practices in a context of strong evolution of urban policies and transported volumes. The aim is to propose an generic evaluation method based on a Mixed_Integer Programming (MIP) model to test scenarios implementing UCCs compared to the classical distribution scenario (i.e. without UCCs). This allows firstly to better evaluate the potential benefit of these uses in terms of overall cost and CO2 emission impact. Secondly, it allows for the determination of the best configuration of the distribution network with respect to certain design or use choices such as the capacity and the number of the UCCs and the delivery modes.

The originality of this work is threefold. Firstly, a two level multi-commodity network flow and location selection model is formulated to optimize the cost of the network including transport costs and urban consolidation centers (UCC) costs: the operation of the UCCs is modelled in terms of capacity and flow consolidation; the breakdown of transport costs and the costs setting is based on the French national² road committee. Second, the proposed model focuses on the mid-term and long-term planning of the parcels flows for the last mile delivery considering existing UCCs. Lastly, our work is based on real freight transport data from the city of Bordeaux relating to delivery demands, distances and location of main city logistics entities. To our knowledge, there is no such work in literature combining these methodological aspects with a real world experimental context. As a result, on the one hand our study bridges the gap between pure academic studies and pilot projects with UCCs, and on the other hand it also fills the gap between short-term vehicle routing oriented problems and long term planning of parcels delivery in city centers.

The next section presents a literature review. The third section defines the problem and describes the Bordeaux case study as well as the collected input data. Lastly, we report the experiments carried out for the parcels distribution in Bordeaux. A conclusion ends the paper.

2. Literature Review

According to the statements of the introductory section and in line with the current developments in city logistics in Bordeaux, we focus in this paper on impact measurement of using intermediate depots with potential consolidation in the distribution network.

2.1. Basis terminology

Some basis terms about intermediary depots in city logistics was defined in Boudouin (2012). The author proposed a typology of different facilities (i.e. Urban Logistics Space) to ease the sharing of space and infrastructures to meet the needs of optimizing deliveries in city logistics. This classification which has been refined by Patier and Toilier (2018), distinguishes six categories according to the geographical position of the facilities in the distribution chain from producer to consumer. In this paper, we consider two of these specific types of facilities: the UCCs located on the outskirts of the city center, which ensure the consolidation of goods and occupy a fairly large space; and the PLSs (Proximity Logistics Space) located in the city center, which allow vehicles to be parked and offer temporary storage space. Notice that the consolidation of flows is carried out in the UCCs, whereas the PLSs are simple transshipment areas without consolidation.

2.2. UCCs: research studies versus pilot projects

² <https://www.cnr.fr/en>

UCCs play a major role in city logistics (Browne et al., 2011; Allen et al., 2012; De Marco et al., 2018) and provide the benefits of a shared freight service (Paddeu, 2017). They are a means of reducing inconveniences such as congestion caused by increased traffic but also by access restrictions for trucks in certain streets, which generate additional costs for carriers. They also reduce noise and environmental problems, which are negative externalities that degrade the quality of life of city center residents. This broad field can be broken down into two branches, depending on whether they are academic studies or actual projects.

On the one hand, there are numerous academic studies showing the advantages of UCCs (Taniguchi and Heijden, 2000). These works are based on either multi-agent approaches (Firdausiyah et al., 2019), or simulation-oriented approaches (Rabe et al., 2018; Van Heeswijk et al., 2019), or on game theory in order to address the stakeholders' perspective of the last mile delivery (Hezarkhani et al., 2019; Ciardiello et al., 2021). In addition, some studies have highlighted the role and the potential advantages of UCCs for reducing inconvenience (Allen et al., 2014; Battaia et al., 2014; Browne et al., 2007; Cherrett et al., 2012; Van Duin et al., 2012). Yang et al. (2016) proposed a method based on fuzzy analytic hierarchy process in order to analyze different distribution modes including a so-called mutual distribution mode, similar to a joint deliveries system of UCCs.

On the other hand, there are some UCC pilot projects that have been reporting concern in the cities of New York (Panero et al., 2011), London (Clarke et al., 2017), Gothenburg (Katsela, 2019) and Nijmegen (Van Rooijen and Quak, 2010). This latest project focuses more on receivers than on trucks. The mixed success of the UCCs which has been analyzed in (Verlinde, 2012; Holguín-Veras et al., 2020; Giampoldaki, et al., 2021), is mainly due to various obstacles such as an increased cost or space restriction in the city center. Lindawati (2014) focuses on collaboration among last mile delivery stakeholders by analyzing existing barriers. Public subsidies are also a critical factor in the sustainability of UCCs, as it is discussed by many authors (Kin et al., 2016; Nocera et al., 2017, Akgün et al. 2020). The literature review of UCCs proposed by (Björklund and Johansson, 2018) highlights the lack of papers on existing initiatives, and the deficiency of studies measuring the impact on the distribution system, particularly in terms of environmental indicators. However, some studies try to fill this gap. Janjevic and Ndiaye's (2017) proposed a framework for evaluating the financial viability of UCCs and applied it to a UCC in Brussels. Paddeu (2021) put forward an operational model made up of indicators to evaluate UCCs in terms of cost, time, quality, productivity and environmental sustainability; this model was tested on two case studies. Isa et al. (2021) analysed the socio-environmental impact of UCCs based on the welfare economics.

2.3. Distribution planning models for city logistics

Crainic (2000) introduced the so-called generic Service Network Design problem in distribution systems focusing on short-term scheduling and management of resources on a two-tier distribution system. In this paper we mainly focus on both mid-term and long-term planning problems (i.e. strategic decision level): the overall evaluation of trucks' flow in the network and the selection of intermediary depots (UCCs or PLSs). Regarding long-term planning, Dupas et al. (2020) use multi-commodity network flow models (Ahuja et al., 1993) to assess city logistics networks. Farvolden et al. (1993) and Barnhart and Sheffi (1993) used these models for less than truckload (LTL) transportation problems. Regarding the location selection topic, Mepparambath et al. (2021) proposed a theoretical framework for measuring the impact of the location of a UCC on the total number of trips; two hypotheses were tested depending on whether the UCC is located within or outside the retail district. Rao et al. (2015) tackled a location selection problem integrating economic, environmental, and social dimensions of sustainability and they proposed a fuzzy multi-attribute group decision-making method. Li et al. (2018) studied a similar problem and proposed a mixed-integer linear programming model minimizing an aggregated objective function integrating economical environmental and socio-economical costs. Gan et al. (2018) developed a so-called eco-facility location mixed-integer program encompassing the operating and the design network costs and the

greenhouse gas emissions; a swarm metaheuristic is used to optimize the model on a case study in the city of Shenzhen. Gonzalez-Feliu and Salanova (2014) developed a simulation based decision support method to analyze the interaction between the land use of the UCCs and the transport cost; this method is illustrated on a case study in the city of Lyon. De Carvalho et al. (2020) proposed a hierarchical decision structure based on multiple criteria decision analysis to support the best location of UCCs in city centers. Saragih et al. (2018) suggested a mathematical model for allocating retailers and suppliers to opened UCCs for a multi-products distribution supply chain. Some authors tackled both strategic (i.e. location) and operational issues (i.e. vehicle routing). Ouhader and El kyal (2017) extended the generic two-echelon location routing problem (2E-LRP) (Drexl and Schneider, 2015; Prodhon and Prins, 2014) in order to assess the CO₂ emissions of different collaborative scenarios between shippers. Simoni et al. (2018) studied the location of UCCs coupled with the multi-depot vehicle routing problem; they used metaheuristics to minimize two alternative objectives (i.e. transport or emission costs) in the case of a heterogeneous vehicles fleet.

Common to the papers mentioned in this section is the use of intermediate depots in a multi-tiered distribution system. Of these, we have selected the subset that explicitly includes the implementation of UCCs on the area of a city. Table 1 characterizes these using the following criteria: level of transport planning, location and costs of UCCs, environmental costs, social costs, experimental data and, modeling / solving approach. This summary highlights some of the shortcomings of academic work in this area such as addressing the medium and long-term aspects of planning, assessing environmental and social economic costs and, exploit very large real data set from urban distribution networks

Table 1. UCCs-based distribution planning models

<u>Authors</u>	<u>planning term</u>	<u>UCCs location</u>	<u>UCCs costs</u>	<u>emission costs</u>	<u>social costs</u>	<u>experimental data</u>	<u>modelling / solving</u>
De Carvalho et al. (2020)	m-t	yes	no	no	no	r-w	dm
Dupas et al. (2020)	m-t	no	no	yes	no	r-w	mip
Gonzalez-Feliu and Salanova (2014)	m-t ; l-t	yes	no	no	no	r-w	sim
Mepparambath et al. (2021)	l-t	yes	no	no	no	r-w	math
Ouhader and El kyal (2017)	s-t ; m-t	yes	yes	yes	yes	rand	mip
Rao et al. (2015)	m-t	yes	no	yes	yes	rand	dm
Saragih et al. (2018)	s-t ; m-t	yes	yes	no	yes	rand	dm
Simoni et al. (2018)	s-t ; m-t	no	yes	yes	no	rand	mip
This paper	m-t ; l-t	yes	yes	yes	yes	r-w	mip

Legend					
l-t	long-term	rand	random	dm	decision making
m-t	mid-term	r-w	real-world	math	mathematical
s-t	short-term			mip	mixed integer programming
				sim	simulation

In summary, our work aims at addressing some of the weaknesses mentioned regarding UCCs academic studies. We focus on the whole distribution system that encompasses intermediary depots (i.e. UCCs and PLSs) ; we optimize the overall cost (i.e. transport and UCCs) and evaluate CO₂ emissions and their socio-economic impact in the city of Bordeaux. This evaluation is based on the multi-commodity network flow model presented in section 3.2.3.

3. Problem Definition and Modelling

3.1. Problem Definition

The distribution network under consideration is a two-tier network with potential use of intermediate depots (UCCs). The final destination points for the parcels are PLSs located close to busy shopping streets

in the city center. It should be noted that the last part of the parcel transport between a PLS and a shop (final customer) is not considered in our approach. In fact, the last leg of delivery is carried out by soft delivery means (electric, cargo-bike, etc.) over very short distances and therefore has a proportionally low impact on the network's performance.

The main entities of the parcel transport network are shown on the map of the Bordeaux conurbation in Figure 1; which are as following:

- Six UCCs can be used for the consolidation of parcels before their delivery to the PLSs. They are distributed around the intra-boulevards area to serve the deliveries within the city center of Bordeaux. The first three UCCs are located in the north (U: Urby and LH: Logistic Hotel) and in the north-west (T: Triporteurs). They are existing UCCs that are currently in use but only marginally in terms of parcels volume. We also assume three hypothetical UCCs, which could be part of a future UCCs network. The UCC MIN in the south is located close to the "Marché d'Intérêt National" which is a market dedicated to the distribution of food in the whole Bordeaux region. Two UCCs fairly close to the city center, located in the south-east (TS: Talence-station) and in the east (MS: Merignac-station) provide connections for goods coming from Bordeaux airport.
- Three PLSs are recipients of the parcels to be delivered. Each PLS serves a particular shopping area in Bordeaux. The Meriadeck PLS is dedicated to distribution in the most important shopping street in Bordeaux (Sainte-Catherine street). PLS Fondaudège is dedicated to distribution in the street of the same name and in the surrounding streets. While PLSs Meriadeck and Fondaudège are already existing in some form, we assumed another PLS Capucins, which is assumed to be dedicated to the delivery of goods around one of the main covered market of the city but also in the direction of Bordeaux's main railway station (Saint-Jean railway station).
- There are 31 warehouses (labelled W1 to W31) owned by existing carrier companies who deliver parcels in the city center.

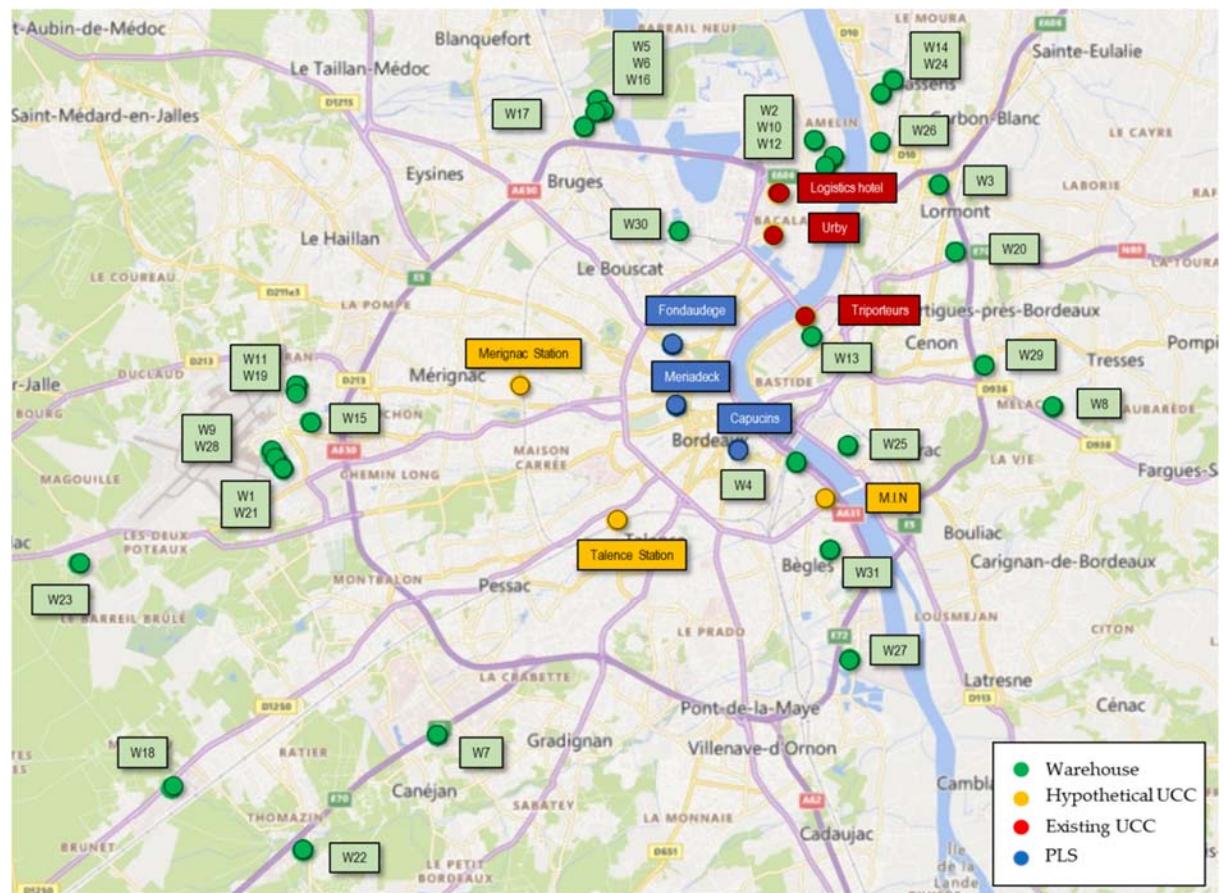


Figure 1. A Bordeaux map extract with proximity logistics spaces (PLS: blue mark), urban consolidation centers (UCC: orange or red mark), and warehouses (W: green mark).

3.2. Methodology

To evaluate the performance of the Bordeaux distribution network and compare different distribution modes we use a network flow optimization model. In this section, we describe the particularities of the Bordeaux case study describing the graph of the transport network and the main features of the optimization model.

3.2.1. Network Graph

Figure 2 shows a simplified graph of the transport network. It contains three sets of nodes corresponding to the three types of network entities: warehouses, UCCs, PLSs. In this figure, PLSs are at the top, warehouses are at the bottom of the graph and UCCs are in the middle layer between PLSs and warehouses (light grey area). The arcs in the graph are partitioned into three sets: i) the arcs between warehouses and PLSs, which represent direct links (blue lines) between the source and destination of the parcels; ii) the arcs between warehouses and UCCs, and between UCCs and PLSs (both in dotted red lines) representing links via UCCs; iii) and the bidirectional arcs between UCCs (dotted green lines), which make inter-UCC flow exchange possible. For the sake of simplicity and in order not to overload the figure, the arcs represented in the figure are restricted to the arcs related to a particular warehouse (warehouse #18) and to a specific UCC (Merignac station UCC) with the exception of all other arcs.

This figure also shows the breakdown between both distribution levels: level L1 (Warehouse-UCC and inter-UCC) and level L2 (warehouse-PLS)

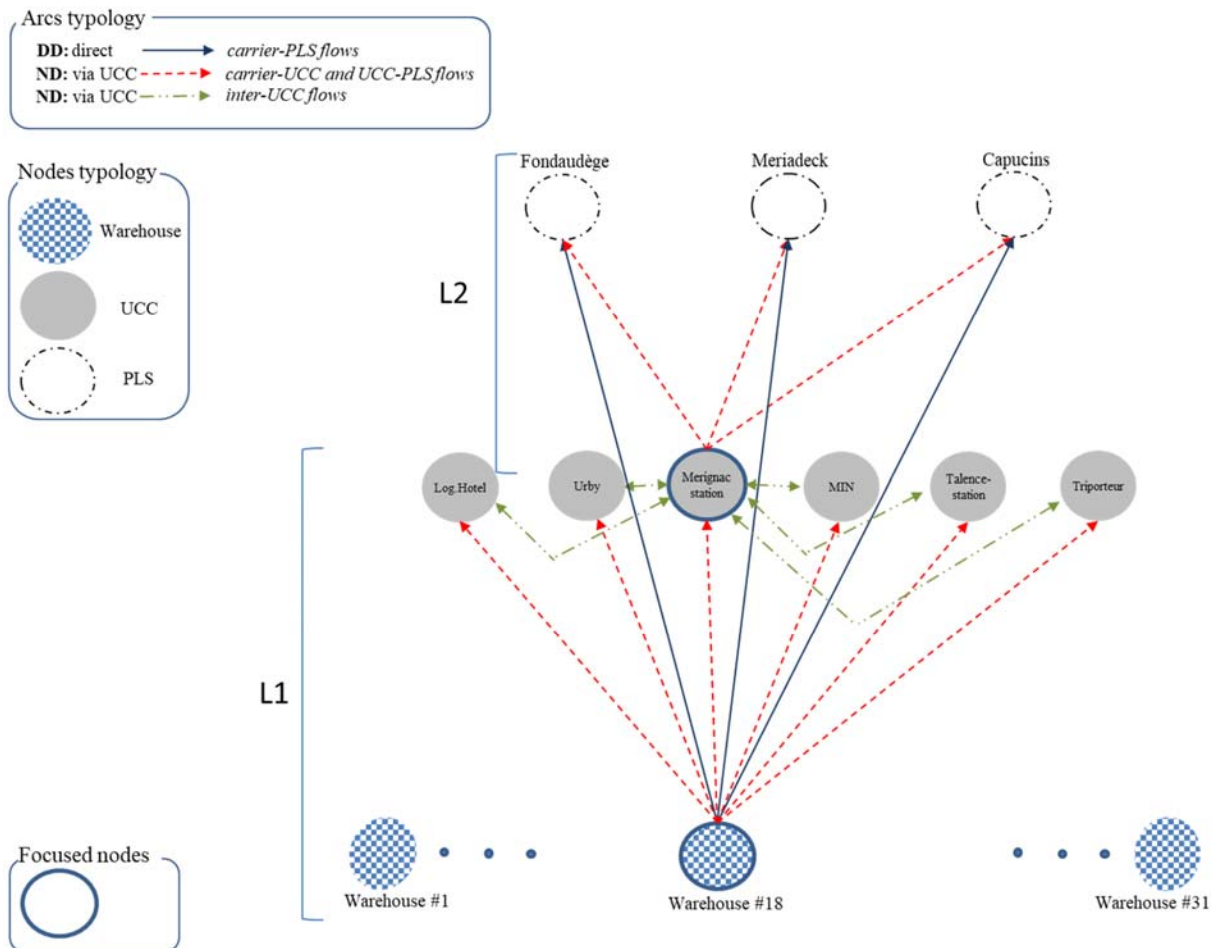


Figure 2. Network graph: simplified view focusing on two nodes (UCC-Merignac and Warehouse #18)

The opening or closing of certain arcs in this graph let us study three variants of the distribution network.

- The first network variant only contains warehouses and PLSs with the related arcs. In this network, the trucks make direct deliveries from their depots to the PLSs; this variant is labelled DD (Direct Delivery).
- The second network variant is made up of warehouses, PLSs and UCCs with the related arcs. In this variant, the trucks make deliveries via UCCs, potentially using inter-UCC arcs; it is labelled ND (Non Direct Delivery). Notice that PLSs and UCCs are shared by all the transportation companies.
- The last variant is the additive combination of the two previous ones and it contains all arcs and all nodes of the graph; it is labelled HD (Hybrid Delivery).

It should be noted that there are no arcs between warehouses, because although consolidation at a warehouse is theoretically possible, it is not permitted, particularly for reasons of liability and insurance of parcels.

3.2.2. Assumptions

In order to evaluate the performance of several distribution variants we have developed a mathematical model based on the following assumptions:

- The distribution of parcels from the warehouses to the PLSs via UCCs is based on a two-level distribution system. The third leg between the PLS and the final customer is not taken into account in our study. This assumption is based on the following observations: (i) the distance of this third leg is very short compared to the two previous legs as the final customers are within a perimeter of less than one kilometer around the PLS; (ii) this third leg represents a constant cost component whether existing (DD) or future (ND, HD) deliveries modes; so that, all deliveries are destined for PLSs, which allow for a fair comparison of their relative performance.
- The UCCs can be used for temporary storage and therefore have limited capacity in our model. The PLSs are not used for temporary storage as it is assumed that the collection at the PLS is in just-in-time for delivery to the end customer, therefore PLSs have no limited capacities.
- The trucks make one or more round-trips during the working day: the outward trip is loaded (full round-trips or incomplete round-trips) and the return is supposed to be empty since in practice these flows are very limited.
- The overall evaluation of the transport flows is carried on a one-day time period (i.e. working day). The parcels flow is supposed to be constant on this working day without any variations of flows over time (i.e. static environment).
- The performance evaluation is based on the transportation costs and the UCC operations costs. The transportation costs are derived from the French national road committee² and they include the travel costs (e.g. distance), the daily costs (e.g. hiring of trucks) and the hourly costs (e.g. driver wages). The UCCs costs include the opening cost of UCCs and the cost of handling the parcels at the UCCs.
- The municipal authorities of the city of Bordeaux impose several restrictions, some of which are being reinforced. This leads us to make the following additional assumptions: i) access for HGV (Heavy Goods Vehicle) trucks is prohibited in the city center; this access is restricted to LCV (LCV: Light Commercial Vehicles); ii) a strict 30 km/h speed limit in the city center (level L2: intra-boulevard zone) voted recently is being implemented to reduce congestion in downtown Bordeaux; iii) vehicles traffic flow can be restricted on certain downtown roads to reduce the negative impacts of freight transport in certain parts of the city.

3.2.3. Model

The problem is modeled as a multi-commodity network flow (MCNF). It aims to minimize the overall costs made up of the transportation costs of all trucks on the network and the operating costs of the UCCs. Each delivery demand is considered as a commodity in a multi-commodity network flow model (Ahuja et al., 1993). This demand corresponds to the quantity of parcels to be transported from the warehouse (i.e. source node) to a PLS (i.e. destination node). This delivery can be done directly or through the UCCs depending on the experimental conditions set. The model makes decisions to open or close UCCs based on the costs of opening the UCCs and the costs of handling each parcel at the UCC.

The formulation is based on a directed graph (labelled $G = (V, A)$) representing the distribution network. Set V consists of three disjoint subsets of nodes: U corresponds to the UCCs, W to the warehouses and P to the PLSs ($V = U \cup W \cup P$). Set A consists of four disjoint subsets of arcs: $A_0 = W \times P$, $A_1 = W \times U$, $A'_1 = \{(u_1, u_2) \in U^2 : u_1 \neq u_2\}$, $A_2 = U \times P$, ($A_0 \cup A_1 \cup A'_1 \cup A_2 = A$). The delivery demand labelled $supply_{k,i}$ is positive at the warehouse (i.e. node $i \in W$), is negative at the PLS (i.e. node $i \in P$) and null at the UCC (i.e. node $i \in U$).

Notice that the L1 level of the transport network corresponds to the graph $G1=(V1, A1 \cup A'1)$ with $V1 = W \cup U$ and the L2 level corresponds to the graph $G2=\{V2, A2\}$ with $V2 = U \cup P$. Notice also that the truck-related parameters ($TruckCap_{i,j}$, $TruckSpeed_{i,j}$, $TruckKMCost_{i,j}$, $TruckDailyCost_{i,j}$ and $TruckHourlyCost_{i,j}$) have constant values on all arcs taken by the same type of trucks (LCV or HGV) assigned to the same level.

The parameters, decision variables and constraints of the formulation are given below.

Parameters and Sets

$suc(i)$	set of successors of node $i \in V$
$pre(i)$	set of predecessors of node $i \in V$
K	set of demands $k, k \in K$
$supply_{k,i}$	delivery k , at the node $i, i \in V, k \in K$
$Cap_{i,j}$	capacity of arc $(i,j), i \in V, j \in V$
$Dist_{i,j}$	travel distance of the round-trip on arc $(i,j), i \in V, j \in V$
$TruckCap_{i,j}$	capacity of trucks on arc $(i,j), i \in V, j \in V$
$TruckSpeed_{i,j}$	truck mean speed (km/h) on arc $(i,j), i \in V, j \in V$
$TruckKMCost_{i,j}$	truck cost per km on arc $(i,j), i \in V, j \in V$
$TruckDailyCost_{i,j}$	truck cost per day on arc $(i,j), i \in V, j \in V$
$TruckHourlyCost_{i,j}$	truck cost per hour on arc $(i,j), i \in V, j \in V$
$UCCOpenCost_j$	opening cost of UCC $j, j \in U$
$UCCHandleCost_j$	UCC handling cost of a parcel of UCC $j, j \in U$
$CapUCC_j$	capacity of UCC $j, j \in U$
DTM	driving time (see Appendix A –Table 8)

Variables

Variables $x_{i,j,k}$ and y_u are core variables defining the parcels flow on each arcs and the open UCCs respectively. Variables $nbt_{i,j}$, $nbtUT_{i,j}$ and $nbpUT_{i,j}$ calculate the corresponding number of round-trips (full and incomplete) and also the remaining number of parcels in incomplete trucks.

$nbt_{i,j}$	number of full round-trips on arc (i,j)
$nbtUT_{i,j}$	number of partial (incomplete) round-trips on arc (i,j)
$nbpUT_{i,j}$	number of parcels in an incomplete round-trips on arc (i,j)
$x_{i,j,k}$	integer number of parcels of demand k on arc (i,j)
y_j	binary number equals 1 if UCC located on node j is open, else 0 (UCC not open)

Constraints and Objective Function

The model includes the classical constraints of a network flow model: flows balance on each node and flows limitation due to the capacity of arcs. It also contains additional constraints to model the trucks capacity and to calculate the number of round-trips of trucks. The model enables the pooling of parcels from different warehouses, which can be grouped in the same truck. It takes into account the capacity of the UCCs and allows the number of parcels entering each UCC to be limited. It is made up of the following constraints: Equation (1) defines the objective function minimizing the sum of the costs of: (i) the trucks transportation costs over all the arcs of the graph, (ii) the UCC operation costs. The truck costs for each level

$l \in L$ are made up of the distance costs (*Travel*), the daily costs (*Daily*) and the hourly costs (*Hourly*). The UCC operation costs are the sum of the costs of handling (*UCCHandling*) the parcels and the cost of opening (*UCCOpening*) the UCC. Equation (2) represents the capacity constraint on each arc (i, j) . Equation (3) states the flow balance for each node and for each demand. Equation (4) is the truckload capacity constraint used to calculate the number of full round-trips and the number of parcels in the incomplete round-trips. Equation (5) limits the number of parcels in an incomplete round-trip. Equation (6) calculates the number of incomplete round-trips (i.e. equal to zero or one). Equation (7) forces the UCC entering flow to be zero when the UCC is not open. Equation (8) limits the number of parcels entering each UCC (i.e. UCC capacity). Equation (6) and Equation (7) are linearized in the model implemented in the solver.

$$\text{Min } (\text{Travel} + \text{Daily} + \text{Hourly} + \text{UCCHandling} + \text{UCCOpening}) \quad (1)$$

$$\text{Travel} = \sum_{(i,j) \in A} \text{TruckKMCost}_{i,j} \cdot \text{Dist}_{i,j} \cdot (\text{nbt}_{i,j} + \text{nbtUT}_{i,j}) \quad (1.a)$$

$$\text{Daily} = \sum_{(i,j) \in A} \text{TruckDailyCost}_{i,j} \cdot (\text{Dist}_{i,j} \cdot (\text{nbt}_{i,j} + \text{nbtUT}_{i,j}) / \text{TruckSpeed}_{i,j}) / (\text{DTM}) \quad (1.b)$$

$$\text{Hourly} = \sum_{(i,j) \in A} \text{TruckHourlyCost}_{i,j} \cdot \text{Dist}_{i,j} \cdot (\text{nbt}_{i,j} + \text{nbtUT}_{i,j}) / \text{TruckSpeed}_{i,j} \quad (1.c)$$

$$\text{UCCHandling} = \sum_{(i,j) \in A_1 \cup A'_1, k \in K} x_{i,j,k} \cdot \text{UCCHandleCost}_j \quad (1.d)$$

$$\text{UCCOpening} = \sum_{j \in U} \text{UCCOpenCost}_j \cdot y_j \quad (1.e)$$

$$\sum_{k \in K} x_{i,j,k} \leq \text{Cap}_{i,j} \quad \forall (i,j) \in A \quad (2)$$

$$\sum_{j \in \text{suc}(i)} x_{i,j,k} - \sum_{j \in \text{pre}(i)} x_{j,i,k} = \text{supply}_{k,i} \quad \forall i \in V, \forall k \in K \quad (3)$$

$$\sum_{k \in K} x_{i,j,k} = \text{nbt}_{i,j} \cdot \text{TruckCap}_{i,j} + \text{nbpUT}_{i,j} \quad \forall (i,j) \in A \quad (4)$$

$$\text{nbpUT}_{i,j} \leq \text{TruckCap}_{i,j} - 1 \quad \forall (i,j) \in A \quad (5)$$

$$\text{nbtUT}_{i,j} = \lceil \text{nbpUT}_{i,j} / \text{TruckCap}_{i,j} \rceil \quad \forall (i,j) \in A \quad (6)$$

$$y_{i,j} = 0 \Rightarrow \sum_{k \in K} x_{i,j,k} = 0 \quad \forall (i,j) \in A_1 \cup A'_1 \quad (7)$$

$$\sum_{k \in K} x_{i,j,k} \leq \text{CapUCC}_j \quad \forall (i,j) \in A_1 \cup A'_1 \quad (8)$$

In summary, this model allows for optimizing the selection of UCCs opened and the overall transport cost (transport and UCC) in parcels' distribution. It measures the impacts of different parameters such as truck capacities, truck costs and UCC costs. These impacts lead to variations in the total transportation cost and the total distance of the trucks, which also allows for an assessment of CO2 emission.

4. Numerical Experiment

First, we present the Bordeaux transport survey and its exploitation for the construction of the input data of our model; then we present the experimental scenarios and the performance indicators to evaluate them.

4.1. Pre-existing survey

The EMV survey (Enquête de Marchandises en Ville) of goods transportation in the city of Bordeaux was carried out in 2013 (Toilier et al., 2015). This survey covers a conurbation of 28 municipalities located

on both banks of the River Garonne (Figure 3a). Its population is about 750,000 inhabitants spread over 570 square kilometers. The city of Bordeaux (yellow area - Figure 3a) covers an area of 49 square kilometers, i.e. 9 percent of the conurbation's total area. The number of inhabitants is 244,000, i.e. 32 percent of the conurbation. A series of boulevards (red line - Figure 3b and 3c) surround the most densely populated part of the city on the left bank of the Garonne so-called «Bordeaux intra-boulevards ».

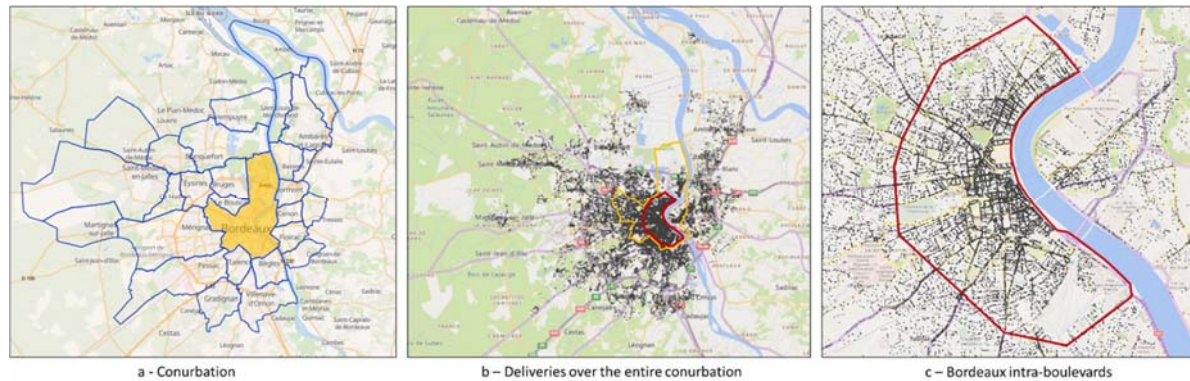


Figure 3. Overview of the Bordeaux conurbation

This survey has allowed to quantify and map the goods transport moves in the agglomeration. A move is precisely defined as the visit of a vehicle in an establishment for delivery and/or pickup of goods. The data collected in this survey includes the location (geographical coordinates) of the pickup and delivery points, the average number of moves over different time horizons (days and week), and some administrative attributes of these points. This survey shows that average number of moves per week inside the Bordeaux conurbation is over 430 000 moves.

In the following section, we focus on a subset of the data from this survey; the reader interested in the full data set is referred to (Toilier et al., 2015).

4.2. Data Set

In this section, we successively present the main input data used in the experimentations: the generation of the deliveries' demand, some costs and capacity parameters and the creation of travel distances' matrix.

4.2.1. Demands

The objective is to generate the demands ($supply_{k,i}$) of the model, from the moves of the EMV database. This construction is made up of four steps:

- **Step 1:** extraction of moves from EMV. Firstly, we select a day of the week from the existing weekly data in the database; we chose Monday as the busiest day in terms of deliveries and it represents around 40% of the weekly deliveries. Secondly, we select the type of moves: we chose the delivery moves, which are the majority compared to the pickup moves and compared to the moves combining delivery and collection.
- **Step 2:** definition of a perimeter around each PLS. This perimeter has a rectangular area of two square kilometers, taking into account that the last part of the transport is carried out by soft modes (bicycle, cargo bike, etc.). As shown in Figure 2, the perimeters of the three PLSs are contiguous and cover an important area (around 50 percent) of Bordeaux intra-boulevards.

- **Step 3:** extraction of all delivery moves whose geographical coordinates are included in the PLS perimeter and assignment to this PLS.

- **Step 4:** estimated number of parcels to be transported for each pair (warehouse, PLS) which is calculated as follows: $PT_i \cdot PM_j \cdot NM$; PT_i be the proportion of the turnover of carrier's warehouse "i" to the total turnover of all carriers, PM_j be the proportion of the number of moves included in the scope of PLS "j" compared to the total number of moves for the three PLS and, NM be the total number of moves.

In summary, there are a total of 12,321 demands per day in total: 3097 demands to PLS Fondaudege, 3842 to PLS Meriadeck and 5382 to PLS Capucins. The locations of demands assigned to each PLS are shown in Figure 4. The full set of all delivery demands is given in appendix B – Table 10 and the geographical position of UCCs is shown in Table 11.



Figure 4. Demands distribution assigned to the PLS

4.2.2. Costs and capacities

The following parameters related to trucks, UCCs and network:

- **Transport costs:** they are taken from the French national road committee² and are given in appendix A – Table 5. These transport costs are broken down into distance costs (i.e. kilometer), daily costs (i.e. truck rental costs), and hourly costs (i.e. driver's salaries).

- **UCCs costs and UCCs capacities:** the opening costs, the handling parcels costs and the capacities of the UCCs are shown in appendix A – Table 6. These costs are averages obtained from a set of real rental prices per square meter for warehouses in the city of Bordeaux.

- **Trucks capacities:** Two types of trucks have been considered. The Light Commercial Vehicles (LCV) have low capacity (i.e., 15 parcels). The higher capacity (i.e., 60 parcels) corresponds to Heavy Goods Vehicle (HGV). The lower capacity is used for direct delivery (DD) and also the link between UCCs and PLSs (Level L2) since these trucks are more suitable for intra-boulevard traffic. The higher capacity trucks are restricted to the links between UCCs and warehouses and on the inter-UCCs links (level L1). The trucks capacities are shown in appendix A - Table 7.

- **Arcs capacities:** They are assumed very large in the experiments presented below so as not to constrain the parcels flow to match the Bordeaux case study. The use of capacity constraints is planned in the future to model traffic restrictions in the city center of Bordeaux as it was done on a similar case study in Tokyo (Dupas et al., 2020).

4.2.3. Distances

The Origin-Destination travel distance matrix is obtained from the OpenStreetmap. Let us recall that these distances represent costs in the optimization model. The dimension of the travel distance matrix equals to 40, which corresponds to the total number of entities (i.e. UCCs, PLSs, warehouses). All real addresses of these entities are geocoded using APIs from the MapQuest³.

4.3. Development of experimental scenarios

Unlike the parameters presented above, which are not variable during the experiments, the input factors have values that change according to the scenario. The following input factors are used:

- **Delivery type:** three values are possible and correspond to the three variants of the transport network (DD, ND, HD). Notice that, in the latter case (HD), the solver decides between direct delivery (DD) and delivery via UCCs (ND) for each delivery.

- **UCCs' total capacity:** three values exist: (i) the total capacity of UCCs' almost equals the total demand of PLSs (EQU); (ii) the total capacity of UCCs' is inferior to the demand of PLSs (INF); (iii) the total capacity of UCCs' far exceed to the demand of PLSs (SUP). These three variants represent successive potential developments that increasingly integrate the use of UCCs in terms of the number of UCCs installed and the volume of packages transferred. Note that the network INF has some similarities with the structure of the current network in Bordeaux city where three UCCs are available (U: Urby, LH: Logistics, T: Triporteurs). However, the network INF is different with regard to the volume of parcels transferred to the UCCs, which is still very low in the current real case (i.e. a very large majority of deliveries is done in direct mode (DD)). Table 6 in appendix A lists the detailed capacity and cost values for each network (INF, EQU, SUP) and each UCC.

- **Trucks mean speed:** Our experimental study aims at evaluating the effects of the speed reduction in Bordeaux (See assumptions in section 3.2.2) by considering two average speed levels on level L2: a high speed (HS: 35 km/h) representing the previous situation, and a low speed (LS: 15 km/h) representing the current situation. The average speed on level L1 is assumed to be fixed (50km/h) because the trips made in this geographical area are not subject to much congestion. Table 7 in appendix A presents the trucks mean speeds.

³ <https://developer.mapquest.com/>

4.4. Performance indicators

4.4.1. Definition of the performance indicators

The performance indicators (PI) used are twofold:

First, we evaluate the transportation activity with the following indicators: the total cumulative distance TD (Equation 9), the number of round-trips NR (Equation 10), the number of trucks NT (Equation 11). We also calculate the number of open UCCs and the flow of parcels through each UCC.

$$TD = \sum_{(i,j) \in A} Dist_{i,j} \cdot (nbt_{i,j} + nbtUT_{i,j}) \quad (9)$$

$$NR = \sum_{(i,j) \in A} (nbt_{i,j} + nbtUT_{i,j}) \quad (10)$$

$$NT = \sum_{(i,j) \in A} (Dist_{i,j} \cdot (nbt_{i,j} + nbtUT_{i,j}) / TruckSpeed_i) / (DTM) \quad (11)$$

Second, we evaluate the emissions calculated in a post-optimization stage. CO₂ is measured according to the methodology recommended by French transport authorities (GES, 2018) using level-1 aggregated data for the emission factor. The parcel flow expressed in ton-kilometers accumulated on all arcs of the network is transformed into CO₂ emissions with the emission factor (Appendix A – Table 9).

4.4.2. Estimation of direct delivery (DD) by level

All indicators (distance, cost, emissions) that relate to direct delivery (DD) have to be broken down into two parts: the part related to city center (area-L2) and the part related to the external part of the city (area-L1). Since the UCCs are located both outside and close to the boulevards that delimit the city center (see Figure 2), a fictitious boundary between two areas L1 and L2 of the city is thus made up of the polygon joining all the UCCs. The estimate of an overall percentage of distance travelled in both areas can therefore be calculated as follows: (i) all direct trips (DD) between each warehouse and each PLS are selected; (ii) the distances of each trip is calculated with Google Maps; (iii) each distance is decomposed into two parts: the distance between the warehouse and the point of intersection of the trip with the boundary formed by the UCCs (area-L1) and the distance between this point of intersection and a PLS (area-L2). According to this estimation, the distance ratio obtained is: 61% for L1 and 39% for L2. The decomposition into two parts (area-L1 and area-L2) of the costs and emissions in relation to direct delivery (DD) is deduced from the distance decomposition mentioned above. Notice also that speed parameters for direct deliveries (DD) are impacted by the speeds on L1 and L2 according to the distance ratio (61% L1, 39% L2) made on each level; the average speeds for DD are therefore respectively 44 km/h in high speed and 36 km/h in low speed scenarios, respectively.

5. Results and Discussion

In this section we present the experimental design results, we conduct comparisons between the scenarios, we analyze the UCC use and the effect of truck loading

5.1. Set of experiments and cost results

A set of scenarios has been experimented with to assess the impact of the input factors on a set of performance indicators related with the city logistics model presented in this paper. Table 2 presents all 10 scenarios and the results obtained in terms of global cost (objective function Equation 1). The last two columns are CO₂ emissions and the estimated social cost of CO₂ calculated assuming an intermediary cost

of CO2 100 euros/ton (Rennert et al., 2022). The optimization model is implemented with the IBM ILOG CPLEX solver. The computation times are limited to 50 seconds for each scenario.

Table 2. List of scenarios and results

N°	Delivery type	UCC's total capacity	Truck mean speed (L2)	Cost (€) (Eq. 1)	CO2 (gr)	Social cost of CO2 (€)
S1	DD	ns*	HS	16,020	347,994	35
S2	DD	ns*	LS	19,032	347,994	35
S3	ND	EQU	HS	16,004	261,963	26
S4	ND	EQU	LS	26,391	262,631	26
S5	HD	EQU	HS	13,562	254,482	25
S6	HD	EQU	LS	18,003	307,110	31
S7	HD	INF	HS	15,578	318,520	32
S8	HD	INF	LS	18,527	336,175	34
S9	HD	SUP	HS	13,691	250,015	25
S10	HD	SUP	LS	18,159	262,631	32

*ns: not significant

We first conduct two comparative analyses: on the one hand, the impact of the type of delivery (DD, ND, HD) in a transport network with balanced UCC capacities (EQU), and on the other hand, the impact of the load-to-capacity ratio of UCCs (EQU, INF, SUP) for the hybrid delivery scenarios (HD). Notice that the direct delivery (DD) corresponds mostly to the existing situation in the city of Bordeaux; it plays the role of a reference for comparison with the other scenarios considered; for this reason the DD scenarios (S1: high speed and S2: low speed) are reported in both parts (Sections 5.1 and 5.2). Then we analyze the utilization rate of the UCCs and the impact of the truck-loading factor, before synthesizing the experimental results.

5.2. Balanced scenarios (EQU)

In this section, we evaluate the delivery that forces mandatory passage to UCCs and prohibits direct delivery. The comparison is made against both direct delivery (DD) and hybrid delivery (HD). The results for the overall UCCs capacity equal to the parcel demand (i.e. scenario EQU) are presented in Figure 5.

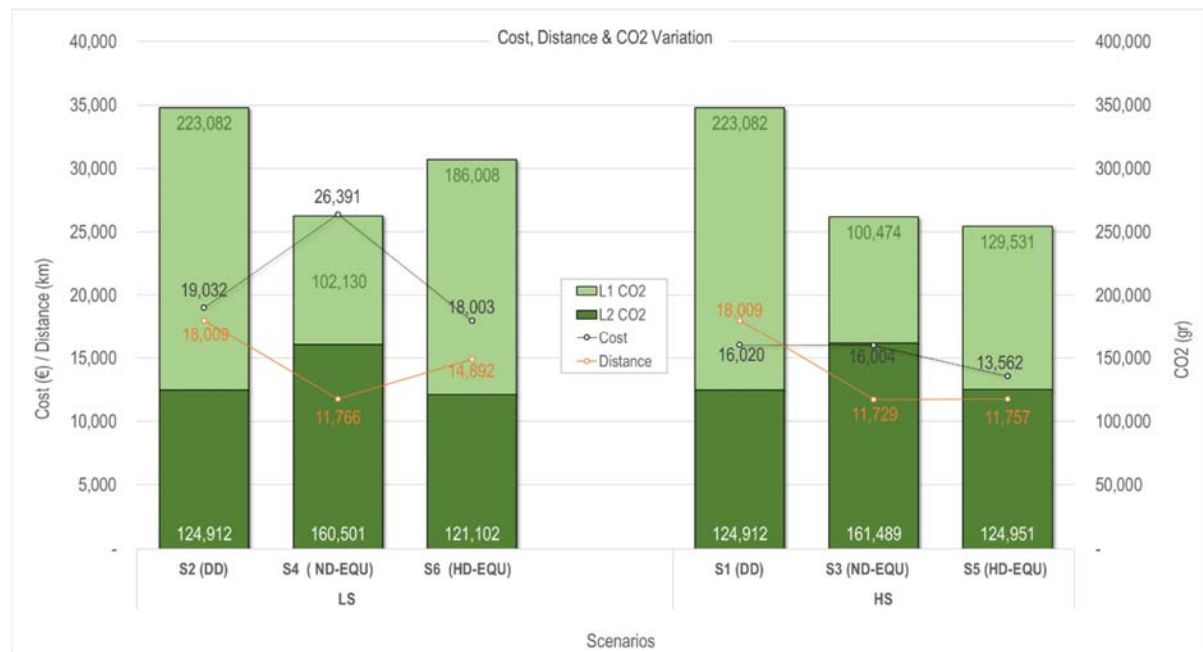


Figure 5. Comparison between direct delivery (DD) and delivery with UCCs (ND) for both speed (LS,HS)

The mandatory use of UCCs (ND) leads to a significant cost increase compared to direct delivery (DD) (from 19032 to 26391 or 39%) at low speed (LS); it does not lead to any significant improvement at high speed (HS) either. Moreover, ND delivery also leads to a cost increase compared to hybrid delivery (HD). This increase is greater for low speed LS (from 18003 to 26391 or 46.6%) than for high speed HS (from 13562 to 16004 or 18.0%). The systematic use of UCCs (ND) therefore leads to additional transport and handling costs that are not compensated for, even though the distance travelled is less than or equal to that of the hybrid case (HD) at low (LS) or high (HS) speed. It should be noted, however, that the reduction in CO2 between direct delivery (DD) and the mandatory use of UCCs (ND) is significant at low speed (LS) (from 262631 to 347994 i.e. 24.5%) and at high speed (HS) (from 261963 to 347994 i.e. 24.7%).

5.3. Hybrid delivery scenarios (HD)

In this section, we use hybrid delivery (HD) and direct delivery (DD) scenarios as the ND scenario was proven to be the worst in previous section. We study the effect of the total capacity of the UCCs (i.e. Balanced (EQU), Lower (INF) and Upper (SUP)), as well as the effect of the speed (Low Speed (LS), High Speed (HS)). Figure 6 shows the 6 scenarios associated with hybrid delivery (HD) and the two direct delivery (DD) scenarios. These experiments are divided into two groups according to the speed of the trucks on the L2 level: the experiments of the right group are carried out with high speed (HS) on the L2 level; the experiments of the left group are carried out at low speed (LS). It must be noticed that the speed on the L1 level remains constant at 50 km/h. For each speed group (HS or LS) the Figure shows direct delivery (DD) and then the three types of capacity (INF, EQU, SUP) of the hybrid delivery (HD).

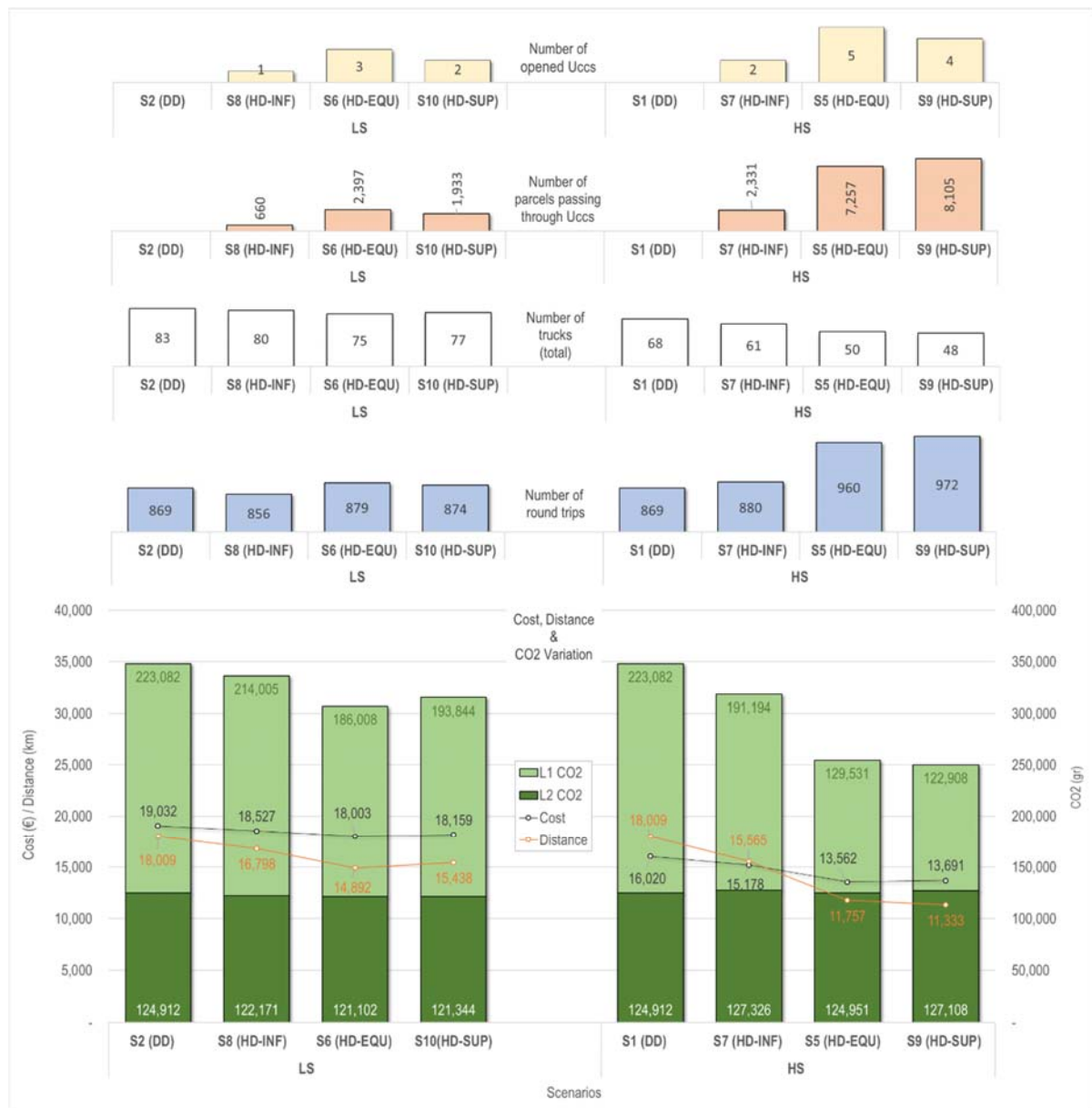


Figure 6. Comparison of 8 scenarios

Figure 6 (lower part) shows that hybrid delivery (HD) reduces cost, distance and CO2 emissions compared to direct delivery (DD). This is observed for both speed levels (HS and LS) and for all three capacity of UCCs (INF, EQU, SUP).

The percentages of reduction from DD to HD are reported in Table 3 (calculated as $100 \times (DD - HD) / DD$). For each indicator, the UCCs capacity level that generates the greatest reduction is indicated by a bold value. This table highlights that: EQU capacity level is associated with the highest number of best values (4 occurrences in bold); INF capacity never offers the best performance; SUP capacity with high speed (HS) is better in two cases than EQU capacity but the differences with EQU are quite small. The poor performance

of INF scenario shows the importance of planning for a comprehensive system of UCCs, whereas one can find many studies in literature just focus on evaluation of an individual UCC project/pilot and thus end in sceptical conclusions about it. For a given pair (indicator, UCCs capacity), the comparison between the results for high speed (HS) and low speed (LS) always shows a better reduction for high speed (HS).

Table 3. Reduction percentage between HD and DD

		Total capacity of the UCCs		
Mean speed	PI	INF	EQU	SUP
HS	total cost	5.30%	15.30%	14.50%
	distance	13.60%	34.70%	37.10%
	co2	8.50%	26.90%	28.20%
LS	total cost	2.70%	5.40%	4.60%
	distance	6.70%	17.30%	14.00%
	co2	3.40%	11.70%	9.40%

Figure 6 (upper part) also shows that the number of open UCCs is always higher with high speed (HS) compared to low speed (LS). For instance, for the balanced capacity (EQU), five UCCs are open at high speed compared to only three UCCs at low speed (LS). As a corollary, the volume of parcels transiting through the UCCs is also greater at high speed. For the EQU network, the percentage of parcels transiting through UCCs is 58.9% (7,257/12,321) with high speed HS and 19.5% (2,397/12,321) with low speed LS. In addition, Figure 6 (middle section) shows that for two identical scenarios differing only in average speed, the number of vehicles is always lower at high speed than at low speed; conversely, the number of round-trips is higher. For example, for both HD-EQU scenarios, at low speed (LS) the number of trucks is 75, while at high speed (HS) it is 50; the number of round-trips increases from 879 to 960. This reflects a more efficient use of trucks at high speed.

Notice that CO₂ emissions at level L2 (i.e. city center) are not significantly reduced by the use of UCCs (see Figure 6). However, the CO₂ emissions at L2 for UCCs with balanced capacity (EQU) are among the lowest; the lowest CO₂ emission is obtained at low speed (LS).

For hybrid delivery (HD), the selection of the EQU capacity coupled with a high speed (HS) therefore brings the best reduction (15.3%) of the total cost which is defined as the sum of the cost (Eq1.) and the social cost of CO₂. It also brings a significant reduction in distance (34.7%) and CO₂ (26.9%).

5.4. Analysis of UCCs use

We elaborate on the general analysis carried out in the paragraph of previous section regarding the number of UCCs used for the high speed (HS) case. For this purpose, the warehouses were grouped into six geographical areas according to their location. These areas are bounded by the main radial roads from the city center and by the river Garonne which is a natural boundary. The six sectors have been named as follows: N: North, NE: North-East, E: East, S: South, SW: South-West, W: West.

For the scenario under consideration (EQU-HS), the parcels percentage from each geographic area and routed via a UCC is reported in Table 4. This rate, labelled PP, is calculated as the number of parcels passing through the UCC in that sector divided by the total number of parcels passing through it. Additional indicators mentioned in Table 4 are the utilization rate of UCCs by each sector (rightmost column of Table 4) labelled UUR that indicates the percentage of parcels passing through UCCs in relation to the total flow (including via UCCs and direct delivery DD); and the capacity utilization rate of each UCC (last line of Table 4) labelled CUR.

Table 4. Activity rates of UCCs (PP and CUR) and sectors (UUR)

PP (Parcels percentage)		UCC					
		U	LH	T	MIN	TS	MS
Geographical area	N	41%	0%	90%	0%	24%	0%
	NE	56%	0%	8%	70%	0%	0%
	E	3%	0%	2%	15%	0%	0%
	S	0%	0%	0%	0%	0%	0%
	SW	0%	0%	0%	15%	56%	0%
	W	0%	0%	0%	0%	23%	100%

CUR (Capacity Utilization Rate)		UCC					
		U	LH	T	MIN	TS	MS
		100%	0%	100%	98%	100%	100%

		UUR (UCCs Utilization Rate)
		Geographical area
	N	73%
	NE	68%
	E	40%
	S	0%
	SW	100%
	W	54%

The map in Figure 7 summarizes the values of these indicators as well as the density of warehouses (WD) in a given area (i.e. number of warehouses in this area divided by the total number of warehouses) and the percentage of delivery demands originating from that sector compared to the total number of demands (PPF).

This Figure highlights the following points:

- Approximately three quarters of the parcels flow originates in the N, NE and W sectors (i.e. $PPF=23+18+32=73\%$) where half of the UCCs are concentrated (i.e. three UCCs out of a total of 6). A close examination of Table 4 shows that the Merignac-station UCC (MS) has very high PP rate in the western area (W) as well as the Triporteurs UCC (T) in the northern area (N). Therefore, UCC MS is in geographical adequacy with the needs of the warehouses of the western area (W); UCC Triporteurs (T) is very useful for the warehouses of the North area because it belongs to the border between the N and NE areas.
- UCCs opened in the concerned scenario (EQU-HS) (i.e., U, T, MIN, TS, MS) are used to their maximum capacity (indicated by high CUR) to meet the cost minimisation objective whereas the UCC Logistic Hotel (LH) is not open.

- The UCCs utilization rate (UUR) varies widely. A particular interesting case was the warehouses in the south (S), which never used the UCCs (UUR equals 0%). It shows that, for this sector, the UCC does not allow for cost savings due to the location of the warehouses in relation to the UCC.

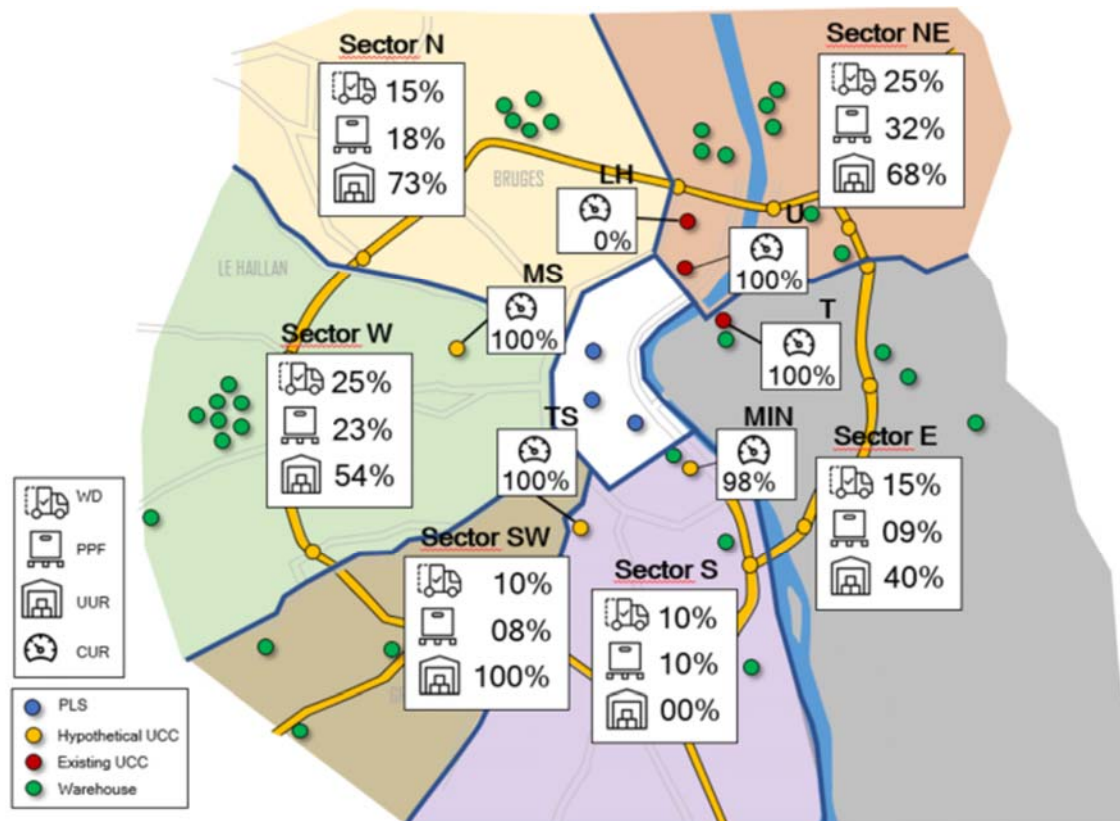


Figure 7. Analysis of activity by area

5.5. Effects of load factor

An additional analysis was performed to measure the effect of truck loading (labelled LF: Load Factor). This factor corresponds to the percentage of capacity utilization of the trucks that operate on the direct links. For example, a load factor of 60% means that the truck capacity is effectively reduced by 40%. Figure 8 represents the distribution of the number of parcels transported in the direct flow and the flow through the UCCs for a given load factor. The figure shows that if the load factor is low, the optimized solution clearly favours delivery via UCCs, whereas for a high load factor the share of direct flow increases. The experiments reported in previous sections use a 100% LF and therefore, the benefits of UCCs reported in the previous sections represent the minimum values which would be increased in a real-life operating context in which the trucks are never 100% full.

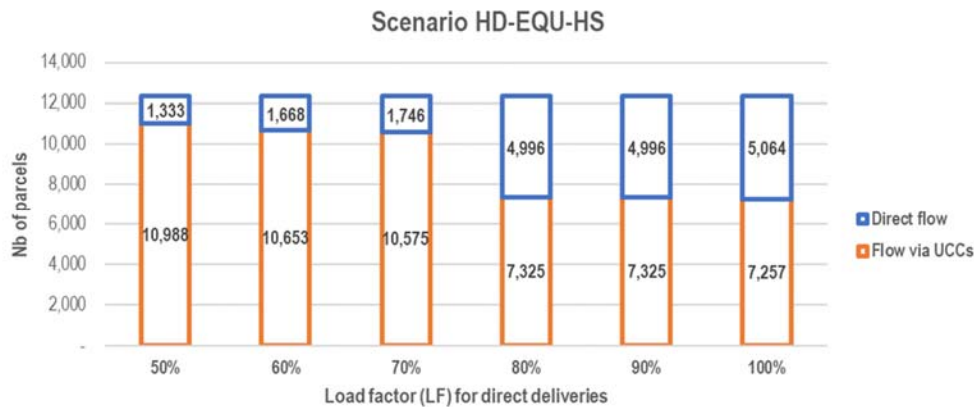


Figure 8. Impact of the direct link load factor on the flow distribution

5.6. Discussion of experimental results

In this section, we discuss the results obtained with regard to the needs of city logistics in Bordeaux and the potential developments in the Bordeaux conurbation. Notice again that the use of UCCs in the city of Bordeaux is in a start-up phase because the existing UCCs absorb a very small volume of the parcel flow converging towards the city center. By comparing the existing situation (i.e. the reference situation) which is similar to the DD network, with the future scenarios, our study highlights several important conclusions: UCCs have been shown to provide an advantage for city center distribution for the transport network where the total capacity of all UCCs is balanced (EQU) with hybrid delivery (HD) operation. Indeed, this scenario improves the overall performance on all three criteria (total cost, distance and CO₂) compared to direct deliveries (DD). This general result is particularly important because it shows that two types of stakeholders can be concurrently satisfied: on the one hand, the carriers (i.e. cost and distance reduction) and, on the other hand, the residents of the city centre (i.e. CO₂ reduction and social cost of CO₂). Notice that, the interest of UCCs with hybrid delivery (HD) is reduced when the average speed on the L2 level is reduced, as foreseen by the new urban regulation in 2022, which can be a challenge for the city authorities. Similarly, although the experiments show that the use of UCCs can significantly reduce total CO₂ emissions, the reduction of emissions at the L2 (city center) level is not obvious. However, the introduction of zero emission vehicles such as Light Electric Freight Vehicles at level L2 would significantly reduce CO₂ emissions in city center (i.e. level L2). In the end, although there are some limitations in the gains achieved, the resulting hybrid transport network (HD-EQU) leads to a more environmentally friendly system.

- It has been shown that it is relevant to search for a compromise (HD) between a system of direct deliveries without UCCs (DD) and a system where all parcels pass through UCCs (ND). Our results highlight that the mandatory use of UCCs (ND) leads to a worse performance than with the hybrid mode (HD). Therefore, it does not seem appropriate to eliminate direct routes in favour of exclusive use of UCCs. Indeed, in the ND direct delivery network, the increase in overall costs due to the implementation and operation of UCCs cannot be fully compensated by the benefits they bring (CO₂ reduction, reduction in the number of trucks). This result is in line with the various studies in this field, which mention the need for subsidies to allow for a financial balance of delivery systems with UCCs. This is corroborated by scenarios S5 and S6 with a balanced capacity of UCCs and an hybrid delivery system (HD-EQU); in these scenarios the number of open UCCs is reduced compared to the potential of exploitable UCCs: 3 out of 6 in low speed (LS) and 5 out of 6 in high speed (HS). This conclusion is also similar to what has been observed in real

operation in the case of UCCs for the distribution in the multi-tenant building Tokyo Sky Tree Town operated by one of freight carriers in charge of the joint delivery system in Tokyo⁴. Indeed these operating and profitable UCCs receive about 60% of the delivery flow while 40% of the flow is provided by direct deliveries.

- With regard to the Bordeaux conurbation, our methodology provides a significant contribution to urban planning. Indeed, the good performance of the network with a balanced total capacity of UCCs (EQU) shows the need to increase the capacity and number of UCCs currently in service for parcel distribution in the city center. Indeed, the current use of UCCs in Bordeaux is, below the capacity of the INF network, which itself has demonstrated its limitations in this experimental study. The implementation of a medium-term distribution plan therefore requires moving towards the EQU capacity level; on the other hand, the network with high capacities (SUP) did not provide a significant advantage over the EQU capacity level in the current context of delivery demands. In addition, the current location of two UCCs (U and LH) in the north of Bordeaux does not seem to be an optimal decision in terms of transport costs. In fact, the northern most UCC (LH) is not used since UCC Urby (U) is able to absorb the flow of parcels from the north of Bordeaux. The methodology therefore already provides an important aid to urban planners concerning the current evolution of the Bordeaux distribution network compared to the existing situation (DD). Notice that it easily allows for the integration of the future evolution of the Bordeaux conurbation, which is undergoing strong demographic and economic growth. This will enable the analysis and evaluation of the adequacy of new locations or new capacities of UCCs to respond to an increase in the transport of parcel flows.

6. Conclusions

Although a key point of our study is that it is largely based on real data related with the distribution situation in city of Bordeaux, our methodology is fairly generic as it is based on a two-tier multi-commodity network flow model, optimizing the costs travelled by the trucks and the operating costs of UCCs while deciding whether or not to open UCCs. This model makes it possible to represent the main entities of an urban logistics network as well as the flows between them. Therefore our methodology can be easily instantiated in other city centers in order to plan and/or evaluate a parcels distribution system. Recorded demands history and geographical location of entities can be easily collected using the big data and mapping applications available today. In this article, we evaluate the performance of an urban parcels distribution network in the city of Bordeaux. This city has been growing rapidly in recent years and this has led to problems of traffic congestion in the city center. To date, new transport organizations are emerging such as the use of UCCs in the north of the city, which is still at an experimental stage. The main findings of our experimental study includes that the mandatory use of UCCs (ND) and thus the prohibition of direct deliveries, leads to an increase in the transport cost which makes this assumption difficult to implement without financial compensation from the city authorities in form of subsidies, which have been proved inefficient in the related literature. Our study highlights that the scenario with hybrid delivery (HD) combined with balanced capacity for UCC (EQU) and high speed (HS) provides the best total cost reduction (15.3%) compared to direct delivery. Although optimizing the total distance and the emission is not the main goal, they are significantly reduced (34.7% for distance and 26.9 % for CO₂). It also highlights that under the same experimental conditions (EQU and HD) the reduction of the average speed on L2 (LS) leads to a decrease of the gains (cost, distance, CO₂). Lastly, the network with a balanced total capacity of UCCs (EQU) is sufficient for the existing demand and therefore the network with high capacity UCCs is not justified

⁴ Taniguchi, E., , Joint delivery systems to multi-tenant buildings using urban consolidation centres, 3rdVREF Conference on Urban freight, Gothenburg, 18thOctober 2018

It should be recalled that one of the first studies focusing on the implementation of UCCs in Bordeaux concluded that UCCs were not cost-effective in the medium term with one UCC in the north (CUBa, 2012; CUBb, 2012). Our experiments using updated cost values and exploiting an extended network of potential UCCs show that UCCs are useful and that the redundancy of UCCs in the northern sector is not necessary since one of the two UCCs (LH: Logistic Hotel) is not used in the best performing scenario.

The foreseeable changes in urban policy in the city of Bordeaux tend to reinforce the limitations and restrictions on access to the city center. The using of flow-limiting constraints on the network arcs is therefore a future work in the Bordeaux case study.

Future studies will focus on coupling our distribution network with the public transport distribution network (bus and tram) in order to assess the potential of mix-mode or multi-modal deliveries (truck and tram/bus). To this end, it would be useful to develop a simulation model, notably based on multi-agents, which would allow for the testing of more scenarios and more hypotheses while relying on the real data collected in this study.

Appendix A

Table 5. Trucks cost

	Distance cost <i>TruckKMCost</i> (€/km)	Daily cost <i>TruckDailyCost</i> (€/day)	Hourly Cost <i>TruckHourlyCost</i> (€/hour)
LCV (diesel)	0.11	69.79	22.79
HGV (diesel)	0.43	175.53	18.74

Table 6. UCCs costs and capacities

		UCC (<i>u</i>)							
Networks	Parameters	U	LH	T	M	TS	MS	CAP-UCCs	DEM
EQU	<i>UCCOpenCostu</i> (€)	316.2	948.6	33.55	79.65	92.79	146.79		
	<i>UCCHandleCost</i> (€)	0.01	0.02	0.01	0.01	0.01	0.01		
	<i>CapUCCu</i> (parcels)	1,667	5,000	667	2,500	1250	1250	12334	12321
		UCC (<i>u</i>)							
Networks	Parameters	U	LH	T	M	TS	MS	CAP-UCCs	DEM
EQU	<i>UCCOpenCostu</i> (€)	316.2	948.6	53.68	159.30	154.65	244.65		
	<i>UCCHandleCost</i> (€)	0.01	0.02	0.01	0.01	0.01	0.01		
	<i>CapUCCu</i> (parcels)	1,667	5,000	667	2,500	1250	1250	12334	12321
SUP	<i>UCCOpenCostu</i> (€)	316.2	948.6	53.68	212.4	412.4	652.4		
	<i>UCCHandleCost</i> (€)	0.01	0.02	0.01	0.02	0.02	0.02		
	<i>CapUCCu</i> (parcels)	1,667	5,000	667	3,334	3,334	3,334	17336	12321
INF	<i>UCCOpenCostu</i> (€)	316.2	948.6	53.68	0.0	0.0	0.0		
	<i>UCCHandleCost</i> (€)	0.01	0.02	0.01	0.0	0.0	0.0		
	<i>CapUCCu</i> (parcels)	1,667	5,000	667	0.0	0.0	0.0	7334	12321

Table 7 Trucks capacities and speeds**Table 7.a** (HGV)

Levels	Truck Capacity <i>TruckCap (parcel *)</i>	Mean speed <i>TruckSpeed (km/hour)</i>
L1	60	50

Table 7.b (LCV)

Levels	Truck Capacity <i>TruckCap (parcel*)</i>	Mean speed <i>TruckSpeed (km/hour)</i>	
		High Speed	Low Speed
L2	15	35	15
DD	15	44	36

* parcel weight : 4 kg

Table 8. Driving parameter

Driving Time (DTM)	6 (hours)
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Table 9. CO2 Emissions factors (GES, 2018)

Type of trucks	EF (g CO2 e / ton.km)
LCV (diesel)	682
HGV (diesel)	235

Appendix B

Table 10. Demands (source, destination, number of parcels) and geographical positions of warehouses

WAREHOUSES - source nodes (i)		PROXIMITY LOGISTICS SPACES – destination nodes						Total		
		Fondaudege		Meriadeck		Capucins				
		N° dem (k)	Parcels Qty. (supply _{k,i})	N° dem (k)	Parcels Qty. (supply _{k,i})	N° dem (k)	Parcels Qty. (supply _{k,i})			
	Coordinates (Long., Lat.)									
	W1	-0.692669	44.826441	1	370	2	459	3	643	1 472
	W2	-0.541592	44.887157	4	370	5	459	6	643	1 472
	W3	-0.512718	44.881938	7	370	8	459	9	643	1 472
	W4	-0.551958	44.827704	10	313	11	389	12	545	1 247
	W5	-0.604854	44.896303	13	269	14	334	15	469	1 072
	W6	-0.606874	44.895942	16	244	17	303	18	425	972
	W7	-0.650301	44.774602	19	240	20	298	21	417	955
	W8	-0.481566	44.838436	22	228	23	283	24	396	907
	W9	-0.695928	44.829718	25	215	26	267	27	374	856
	W10	-0.543624	44.885517	28	133	29	165	30	232	530
	W11	-0.689022	44.841587	31	80	32	99	33	139	318
	W12	-0.546920	44.890475	34	77	35	96	36	134	307
	W13	-0.547636	44.852245	37	43	38	53	39	75	171
	W14	-0.528467	44.899606	40	28	41	35	42	49	112
	W15	-0.685099	44.835512	43	24	44	29	45	41	94
	W16	-0.606530	44.898322	46	23	47	29	48	40	92
	W17	-0.610103	44.893109	49	11	50	14	51	19	44
	W18	-0.723005	44.764335	52	11	53	13	54	19	43
	W19	-0.688818	44.842620	55	10	56	12	57	17	39
	W20	-0.508219	44.868872	58	8	59	10	60	14	32
	W21	-0.693319	44.827177	61	8	62	9	63	13	30
	W22	-0.687060	44.752279	64	4	65	5	66	7	16
	W23	-0.748553	44.807937	67	3	68	4	69	6	13
	W24	-0.525398	44.902320	70	3	71	4	72	5	12
	W25	-0.537725	44.830809	73	3	74	3	75	4	10
	W26	-0.528750	44.890011	76	3	77	3	78	4	10
	W27	-0.537290	44.789348	79	2	80	3	81	4	9
	W28	-0.695377	44.828946	82	1	83	2	84	2	5
	W29	-0.500507	44.846607	85	1	86	1	87	1	3
	W30	-0.584157	44.872946	88	1	89	1	90	1	3
	W31	-0.542701	44.810660	91	1	92	1	93	1	3
	TOTAL				3 097		3 842		5 382	

Table 11. Geographical positions of UCCs and PLSs

Urban Consolidation Centers	Coordinates (Long., Lat.)	Proximity Logistics Spaces	Coordinates (Long., Lat.)
Urby (U)	-0,558192 44,872247	Fondaudege	-0,583011 44,872247
Logistic Hotel (LH)	-0,556964 44,880268	Meriadeck	-0,583648 44,880268
Triporteurs (T)	-0,549290 44,856070	Capucins	-0,570008 44,856070
MIN (MIN)	-0,543850 44,820630		
Talence-station (TS)	-0,601060 44,816420		
Mérignac-station (MS)	-0,627720 44,842770		

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