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Potential of Warehouse Sharing and Electric Bicycles Deliveries in the Montreal Region

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Abstract

City logistics has become more important over the years as a greater share of the world's population lives in urban areas. This is especially true in an area of increasing use of e-commerce and greater awareness of the need to reduce transportation externalities to combat global warming. In this paper, we evaluate the potential for reducing costs and CO_2 emissions in the courier delivery industry by sharing warehouses between different delivery companies. We also consider a greater use of cargo bikes (CBs), which are more mobile and eco-friendlier. We test a cost reduction optimization model on data for the delivery of courier in the metropolitan area of Montreal, Canada. Results show a cost and GHG emissions reduction (of over 30%) when warehouses are shared between different courier companies and when CBs are used. We define a ratio between the maximum distance between a pickup or delivery site and the depot (warehouse) used and the total distance travelled. Results show that such a ratio has a significant impact on the gains brought using CBs. The maximum speed of vehicles also has a significant impact on the results.

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1 Introduction

Freight transportation is a crucial activity for the proper day-to-day functioning of urban areas. It ensures the supply of retailers, and ultimately households (Crainic et al. 2004). City logistics represents the last link in most supply chains and transportation networks (Crainic et al. 2016). It involves a multiplicity of products, such as food, regular consumer goods (Gérardin et al. 2000) or hazardous materials (Pradhananga et al. 2016), which often must be carried by specific vehicles. A few solutions have been proposed in recent years to improve city logistics and alleviate many of the negative externalities caused by it such as noise, pollution, diminished productivity and GHG emissions. Such solutions either strive to directly improve the structure of logistics networks or make a better use of the existing ones through optimization. Also, several methods are used to better understand the functioning of urban freight systems and to improve their decision-making processes (simulation, basic and advanced statistics, data gathering systems, etc.).

Freight-intensive sectors represent close to half of the American economy. This share rises to 80% in poorer countries such as Bangladesh. Each American resident generates up to 0.07 deliveries per person day (toward commercial buildings). This is on top of deliveries generated by e-commerce which reach 0.1 per person day in the USA and can rise to 0.2 in South Korea (Holguin-Veras et al. 2018). Also, e-commerce purchases generate a rising share of greenhouse gas emissions (13% in total, 23% of those resulting from burning fossil fuels, including up to 30% in OECD countries) (Taniguchi et al. 2014).

Already half of the world's population is currently living in cities and this concentration is the cause of much congestion and pollution (Taniguchi et al. 2014). Freight movement shares the same road network as private and public transportation and contributes to noise and traffic problems. There is the belief that cities are not safe and encourages people to flee downtown areas (Crainic et al. 2009). This can be encouraged by trucks stopping in the middle of the street to unload their cargo, even if there is a parking space available. This trend has provoked a reaction from many cities around the world, such as Monaco, where trucks are forbidden to drive in the central core of the town (Crainic et al. 2004).

The goal of reducing greenhouse gas emissions (GHG) is pushing decision makers to explore alternative modes of transportation, such as last mile deliveries with electric tricycles (Dablanc et al. 2014) such as cargo bikes (Brard et al. 2021). It is possible to save up to 6 tons of CO_2 for each truck being replaced by bicycle for deliveries (Taniguchi et al. 2014). Despite this interesting possibility, the literature on the conditions for the success of a greater use of electric vehicles is relatively scarce.

Another option to reduce average distances, costs and GHG emissions resulting from freight deliveries is the sharing of warehouses between different freight companies, as opposed to each company having its own dedicated warehouse, acting as a depot. This allows sending courier to warehouses which are closer to the pickup or delivery nodes. When the incompatibility between delivery nodes and warehouses is minimal, such a strategy can bring reductions in travelled distances of more than 25% (Neghabadi et al. 2021). The average distance between a given pickup or delivery site and their assigned warehouse could diminish substantially if all warehouses were available instead of only the ones owned by a specific company. Such collaboration could lead to important reductions in overall distances travelled, costs and GHG emissions. Unfortunately, carriers often do not consolidate their freight with one another (Assmann et al. 2020).

Our project aims to contribute to the reflection regarding these two promising options for improving city logistics and reducing delivery costs as well as GHG emissions. In the problem under study, we have a set of deliveries that must be satisfied. For each delivery, we have the option to make the delivery using cargo bikes or using regular trucks.

Each delivery must go through a warehouse, that may be shared by competitors or not. The objective is to minimize the sum of the delivery costs and of the loading and unloading costs at the different warehouses. The GHG emissions are computed once the optimization has been performed.

Our contributions are fourfold. First, we consider the use of cargo bikes (CBs), the sharing of warehouses between different companies, and both options at the same time. Second, we build an optimization model that represents freight operations which transit through a warehouse. Solving the problem allows us to measure the improvements brought by the sharing of warehouses between different courier delivery services, and by a more extensive use of CBs. Third, we use this model with data obtained from courier delivery in the region of Montreal, Canada. For the experiment, we consider different scenarios that represent a combination of the CBs and warehouse sharing options as well as different hypotheses regarding the actual distances travelled and the maximum distance of a node in a route involving CBs. Solving the problem on those different scenarios allows us to derive managerial insights on the use of CBs and warehouse sharing, and to measure the gains obtained both in terms of cost and GHG emissions. This represents our fourth contribution.

The rest of this paper is structured as follows. We review the scientific contributions regarding city logistics and more specifically the use of CBs and other electric vehicles as well as the sharing of infrastructure between different entities to obtain better efficiency and reduce costs in Section 2. We then introduce our experiment based on data obtained from courier deliveries in the Montreal area in 2020 and 2021 and present the mathematical model developed to represent the problem in Section 3. Section 4 details and analyses of the results obtained. A conclusion follows in Section 5.

2. Literature Review

We first look at some of the challenges of city logistics operations. We then look more specifically at the issues of warehouse sharing and CB's deliveries, and how much they are considered jointly in current research.

Because of the small entry barriers in the truck industry, truck companies are often relatively small, which makes it difficult for them to coordinate and optimize their activities. This can favour a suboptimal situation which endures because the recipients of shipments do not suffer the financial consequences of decisions made, such as traffic problems to the same extent as truck companies (Holguin-Veras et al. 2014).

To address the challenges faced by city logistics, several solutions have been proposed in the literature. One such solution, which was the most common in the literature we reviewed and which is used increasingly, is that of city distribution centres (CDC). They are consolidation centres located before the distributors and relatively close (albeit in the periphery) to the region, whether it is a downtown area, an entire city, or a specific site. Several large vehicles may not have access to a part of the urban network and such centres allow them to unload their shipments (Crainic et al. 2009). From these installations, consolidated shipments are delivered to an area (Browne et al. 2005).

A good example of the benefits of such centres can be found in the results of a simulation of the use of a CDC in Osaka, Japan. It showed a rise in the number of trucks used and, paradoxically, a reduction in the global distances travelled by them and therefore, their greenhouse gas emissions (Teo et al. 2015).

2.1 Sharing of Infrastructure

Infrastructure sharing techniques can be used to improve distribution in several industries like the food sector (Antheaume et al. 2018), or the forest industry (Sarrazin et al. 2021). It can be used in tandem with multiple other modes of transportation such as trucking (Li et al. 2018) or trains (Feng et al. 2022). It can involve the sharing of buildings (Wang et al. 2021) or a better use of parking spaces (Melo et al. 2019). Combining freight deliveries from multiple companies in the actual assignment of freight to sites could lead to reductions of travelled distances, as there would be more options available for each delivery. Potential reduction in transportation costs can be quite high (Neghabadi et al. 2021, Fernandez et al, 2018). However, such sharing of infrastructure is seldom used in practice (Assmann et al. 2020) as the sharing of resources represents a challenge in terms of their management.

2.2 Cargo Bikes Deliveries

Another technique being explored to reduce environmental and economic costs of freight deliveries is the use of electric vehicles. They can help reduce GHG emissions substantially in comparison to fuel powered vehicles (Taniguchi et al. 2014). Among these vehicles, cargo bikes (CBs) offer several advantages. They have smaller GHG emissions, they are easier to drive in dense urban areas, they cost less than conventional trucks, and can access streets in central urban areas (where conventional trucks may not go), among others. Another advantage, compared to traditional trucks, is that carbo bikes do not need to park in the outskirts of forbidden urban areas to deliver their freight manually (Lee et al. 2019). This results in service times for CBs that are only half of what they are for trucks and conventional vans (2 minutes vs. 4 minutes). Environmental gains, through lower GHG emissions with CBs, are often estimated to be higher than 90% (Büttgen et al. 2021), but the methodology on how these figures were obtained is often not presented. It is not clear if construction factors are considered in such estimates.

However, CBs have an important fixed environmental cost when they are built. Also, they have a limited autonomy, which forces them to come back regularly to the warehouse, which serves as their depot. Several projects to deploy and use such vehicles have taken place in recent years with very different results. For instance, Assmann et al. (2020) found that a greater use of electric vehicles made routes involving more conventional trucks less dense and hence more costly. They also observed a certain law of diminishing returns where these vehicles no longer brought improvements when there were more than 20 in use in an urban area (the authors used generated data). Büttgen et al. (2021) showed limited economic gains but more promising emission reductions while Niels et al. (2018) show interesting improvements for both costs and CO_2 emissions in a project covering the Munich region in Germany. The GHG emissions improvements they bring depend largely on the energy mix of a given country or region, with non-coal-producing countries like Sweden being friendlier environments for such vehicles (Fraselle, 2021). This makes the use of such vehicles particularly interesting in the province of Quebec, Canada, which mainly uses electricity produced by hydro energy (Rodriguez-Sarasti et al. (2021).

The use of such vehicles should increase because the restrictions applied on conventional vehicles will increase over time. Hence, by 2050, no vehicle using fossil fuels should circulate in the central core of European Cities (Maes et al. 2012). Considering CBs in last mile delivery is therefore an interesting and relevant avenue for research.

To use CBs, it is necessary to have warehouses adapted to their use and well located, considering that they cannot travel everywhere, notably highways. Assmann et al. (2020) have found that it is preferable to locate them to the periphery of a district (to reduce the distance travelled by a truck or other diesel vehicle) rather than locating it in the centre. Sheth et al. (2019) found that they tend to be more profitable when deliveries are made at proximity to the bike's warehouse or distribution centre, as well as lower volumes and a high density of residential units.

To the best of our knowledge, no contribution has integrated a mathematical model, a sensitivity analysis and an analysis which involved the possibility of sharing infrastructure such as a warehouse as well as a wider use of CBs. Our project aims to identify factors which should have the most influence over the profitability of both avenues. In the next section, we will present the methodology and the model developed to reach this objective.

3. Methodology and Modelling

In this section, we present the methodology and the mathematical model which we developed to optimize courier distribution in the Montreal area. The values of the parameters in the model are defined based on real data.

3.1 Methodology

To measure the conditions for the success of warehouse sharing as well as an extended use of electric CBs, we conduct an experiment involving real courier deliveries in the Montreal Census Area. To that end, we design a MIP model minimizing transportation costs as well as operational costs coming from the loading and unloading operations. The model we propose is tested on several scenarios, which represent the different possibilities regarding the CBs' autonomy, the number of warehouses using these vehicles and the possibility of sharing warehouses between different courier companies. The use of such scenarios allows us to measure the impact of six different parameters: 1- the share of the sum of distances from the clients to the warehouse actually travelled, 2- the autonomy of CBs, 3-the GHG savings obtained through the use of CBs, 4- the fleet size of CBs, 5- the number of warehouses through which CBs can transit, and 6- the possibility of sharing warehouses and opening new warehouses. The solution of the model optimizes the assignment of deliveries to different vehicle types. The use of the vehicles is constrained by different capacities, which are the vehicle load capacity, the maximum travel time, warehouse capacity, and incompatibility between some warehouses and the use of CBs. We further conduct a statistical analysis to determine which factors have a significant impact on the results.

3.2 Mathematical model

The sets, parameters and decision variables used in the MIP model are presented in Tables 1, 2 and 3, respectively.

Table 1: Sets used in the mathematical model

Set	Definition
O	Set of points of supply o
U	Set of points of demand u
W	Set of warehouses w
I	Set of origins i ($I = W \cup O$)
J	Set of destinations j ($J = U \cup W$)
Z	Set of sites z ($Z = O \cup U \cup W$)
V	Set of vehicles v
T	Set of period t
C	Set of transport companies c
K	Set of deliveries k

Table 2: Parameters used in the mathematical model

Parameter	Definition
c_{ij}^{v}	Cost ($/kg) for a delivery between origin *i* and destination *j* with a type *v* vehicle
l^{v}	Cost ($) for the loading and unloading of the courier for a tour by a type *v* vehicle.
C^{v}	Capacity (in kg) of type *v* vehicles
B	Very large number
$d_{\max}^{v}$	Maximum total distance (in km) of type *v* vehicles
d_{ij}^{v}	Distance (in km) to deliver a product from origin *i* to destination *j* with a type *v* vehicle
$v_{\max}^{v}$	Maximum speed of a type *v* vehicle
v_{ij}^{v}	Speed of a type *v* vehicle between origin *i* and destination *j*
s_{ou}^{tck}	Supply (in kg) from the point of supply *o* which must be transported by company *c* to point of demand *u* during period *t* for delivery *k*
t^{v}	Maximum amount of time, in hours, that a vehicle of type *v* can travel
tc^{v}	Maximum amount of consecutive driving hours, that a vehicle of type *v* can travel
h_{ij}^{v}	Time (in hours) to deliver from origin *i* to destination *j* with a type *v* vehicle
Q^{wc}	Capacity of yard *w* (in kg transiting through the site) for vehicles of company *c*
Q^{w}	Total capacity of yard *w* (in kg transiting through the site)
r	Ratio of the total distance travelled when considering the effect of routes
n	Number of warehouses where cargo bikes (CB's) can be used

Table 3: Variables used in the mathematical model

Variable	Definition
m_{ij}^{tvc}	Number of deliveries between origin *i* toward destination *j*, made by a type *v* vehicle working for company *c*
q_{ij}^{tvc}	Quantity (in kg) delivered from origin *i* toward destination *j*, with a type *v* vehicle working for company *c* during period *t*
$x_{ou}^{twvv'c}$	Quantity (in kg) delivered from the point of supply *o* toward the point of demand *u*, through warehouse *w* owed by company *c* with a type *v* vehicle for the first leg (*o* to warehouse) and a type *v'* vehicle for the second leg (warehouse to *u*) and during period *t*
$\delta_{ou}^{twvv'ck}$	Binary variable equal to 1 if delivery *k* from the point of supply *o* toward the point of demand *u* working for company *c* and during period *t* goes through warehouse *w* with a type *v* vehicle for the first leg (*o* to warehouse) and a type *v'* vehicle for the second leg (warehouse to *u*), 0 otherwise
θ_{ij}^{tvc}	Binary variable equal to 1 if a delivery between sites *i* and *j* during period *t*, for vehicle *v* and company *c* is performed
z^{vt}	Total number of delivery (or pickup) tours performed by type *v* vehicles during period *t*
y^{w}	Binary variable equal to one (1) if warehouse *w* allows the entrance of CBs or zero (0) if it is closed

The model we solve is as follows:

Minimize:

$$\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\sum_{v\in V}\sum_{c\in C} rc_{ij}^{v} d_{ij}^{v} q_{ij}^{tvc} + \sum_{t\in T}\sum_{v\in V} l^{v} z^{vt} \tag{1}$$

Subject to:

$$\sum_{w\in W}\sum_{v\in V}\sum_{v'\in V} \delta_{ou}^{twvv'ck} = 1 \qquad \forall o\in O, u\in U, t\in T, c\in C, k\in K \tag{2}$$

$$\sum_{k\in K} s_{ou}^{tck}\delta_{ou}^{twvv'ck} - x_{ou}^{twvv'c} = 0 \qquad \forall o\in O, u\in U, t\in T, c\in C, w\in W, v, v'\in V \tag{3}$$

$$\sum_{i\in I}\sum_{c\in C}\sum_{v\in V} q_{iw}^{tvc} - \sum_{j\in J}\sum_{c\in C}\sum_{v\in V} q_{wj}^{tvc} = 0 \qquad \forall w\in W, t\in T \tag{4}$$

$$q_{ow}^{tvc} = \sum_{u\in U}\sum_{v'\in V} x_{ou}^{twvv'c} \qquad \forall o\in O, t\in T, c\in C, w\in W, v\in V \tag{5}$$

$$q_{wu}^{tv'c} = \sum_{o\in O}\sum_{v\in V} x_{ou}^{twvv'c} \qquad \forall u\in U, t\in T, w\in W, v'\in V, c\in C \tag{6}$$

$$m_{ow}^{tvc} = \sum_{u\in U}\sum_{k\in K}\sum_{v'\in V} \delta_{ou}^{twvv'ck} \qquad \forall o\in O, t\in T, w\in W, v\in V, c\in C \tag{7}$$

$$m_{wu}^{tv'c} = \sum_{o\in O}\sum_{k\in K}\sum_{v\in V} \delta_{ou}^{twvv'ck} \qquad \forall u\in U, t\in T, w\in W, v'\in V, c\in C \tag{8}$$

$$s_{ou}^{tck}\delta_{ou}^{twvv'ck} \le C^{v}/2 \qquad \forall o\in O, u\in U, t\in T, w\in W, v, v'\in V, c\in C, k\in K \tag{9}$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{c\in C} q_{ij}^{tvc} \le z^{vt} C^{v} \qquad \forall v\in V, t\in T \tag{10}$$

$$\sum_{i\in I}\sum_{w\in W}\sum_{c\in C} rh_{iw}^{v} m_{iw}^{tvc} + \sum_{w\in W}\sum_{j\in J}\sum_{c\in C} rh_{wj}^{v} m_{wj}^{tvc} \le t^{v} z^{vt} \qquad \forall v\in V, t\in T \tag{11}$$

$$z^{vt} \le \sum_{i\in I}\sum_{c\in C}\sum_{w\in W} rd_{iw}^{v} m_{iw}^{tvc} / d_{\max}^{v} \qquad \forall v\in V, t\in T \tag{12}$$

$$z^{vt} \le \sum_{i\in I}\sum_{c\in C}\sum_{w\in W} rh_{ij}^{v} m_{iw}^{tvc} / tc^{v} \qquad \forall v\in V, t\in T \tag{13}$$

$$d_{ij}^{v}\theta_{ij}^{tvc} \le d_{\max}^{v} \qquad \forall i\in I, j\in J, t\in T, v\in V, c\in C \tag{14}$$

$$v_{ij}^{v}\theta_{ij}^{tvc} \le v_{\max}^{v} \qquad \forall i\in I, j\in J, t\in T, v\in V, c\in C \tag{15}$$

$$m_{ij}^{tvc} \le B\theta_{ij}^{tvc} \quad \forall i \in I, j \in J, t \in T, v \in V, c \in C \tag{16}$$

$$\sum_{i \in I}\sum_{v \in V}\sum_{c \in C} q_{iw}^{tvc} \le Q^{w} \quad \forall w \in W, t \in T \tag{17}$$

$$\sum_{i \in I}\sum_{v \in V} q_{iw}^{tvc} \le Q^{wc} \quad \forall w \in W, t \in T, c \in C \tag{18}$$

$$\sum_{i \in I}\sum_{v \in V | v = CB}\sum_{c \in C} q_{iw}^{tvc} \le Q^{w} y^{w} \quad \forall w \in W, t \in T \tag{19}$$

$$\sum_{w \in W} y^{w} \le n \tag{20}$$

$$m_{ij}^{tvc} \in \mathbb{N} \quad \forall i \in I, j \in J, t \in T, v \in V, c \in C \tag{21}$$

$$z^{vt} \in \mathbb{N} \quad \forall v \in V, t \in T \tag{22}$$

$$\theta_{ij}^{tvc} \in \{0;1\} \quad \forall i \in I, j \in J, t \in T, v \in V, c \in C \tag{23}$$

$$\delta_{ou}^{twvck} \in \{0;1\} \quad \forall o \in O, u \in U, t \in T, w \in W, v \in V, c \in C, k \in K \tag{24}$$

$$y^{w} \in \{0;1\} \quad \forall w \in W \tag{25}$$

$$q_{ij}^{tvc} \ge 0 \quad \forall i \in I, j \in J, t \in T, v \in V, c \in C \tag{26}$$

$$x_{ou}^{twvv'c} \ge 0 \quad \forall o \in O, u \in U, t \in T, w \in W, v, v' \in V, c \in C \tag{27}$$

The objective function aims to minimize the costs of accomplishing all the deliveries necessary to satisfy the demand for all destinations as well as the cost of loading and unloading vehicles for each route. Constraints (2) guarantee that all deliveries will be made once. Constraints (3) ensure that the total flow over the network corresponds to the sum of deliveries made. Constraints (4) guarantee flow conservation for each of the warehouses in terms of quantities delivered. Constraints (5) and (6) ensure that there is consistency between flows over the entire network and over the first and second legs (origin to warehouse and warehouse to destinations). Constraints (7) and (8) do the same for the number of deliveries. Constraints (9) guarantee that large deliveries will not be made by CBs by forbidding deliveries exceeding 50% of a vehicle's capacity. According to specialists and other researchers which we have met during our project, such large deliveries are not possible with this type of vehicle. Constraints (10) restrict the quantities that each type of vehicle can carry. Constraints (11) do the same but regarding the available time. Constraints (12) define the minimal number of tours made by each type of vehicle and for each period considering the distances travelled for each delivery. Constraints (13) do the same but in relation to the time necessary to make each delivery. Constraints (14) define a maximal distance travelled for each vehicle. It is very high for curbside trucks (1000 km) and between 50 km and 70 km for CBs. Constraints (15) define a maximal speed for each vehicle. Any OD pair where the speed exceeds the vehicle's limit cannot be travelled by the same vehicle.

Constraints (16) ensure that there is consistency between the number of deliveries and the binary variable used in (14). Constraints (17) deal with warehouses capacity and ensures that no delivery can go through a closed warehouse. Constraints (18) deal with specific warehouses capacity for each of the courier company. It ensures that for network scenarios which do not involve warehouse sharing, warehouses are used only by their owning company. Constraints (19) ensure that no CB delivery can go through a warehouse which has not been designated for the use of this vehicle. Constraints (20) make sure that the number of warehouses using CBs does not exceed the pre-established limit. Finally, constraints (21), (22) and (23) deal with integer, binary and nonnegative requirements.

3.3 Experiment – Courier Deliveries in Montreal

The data obtained from the partner comprises 67,102 deliveries over a 15-month period (between January of 2020 and April of 2021) for the Montreal Census Metropolitan Area. All deliveries transited through at least one of the 13 warehouses located on the islands of Montreal and Laval. The location of the different warehouses is illustrated in Figure 1.

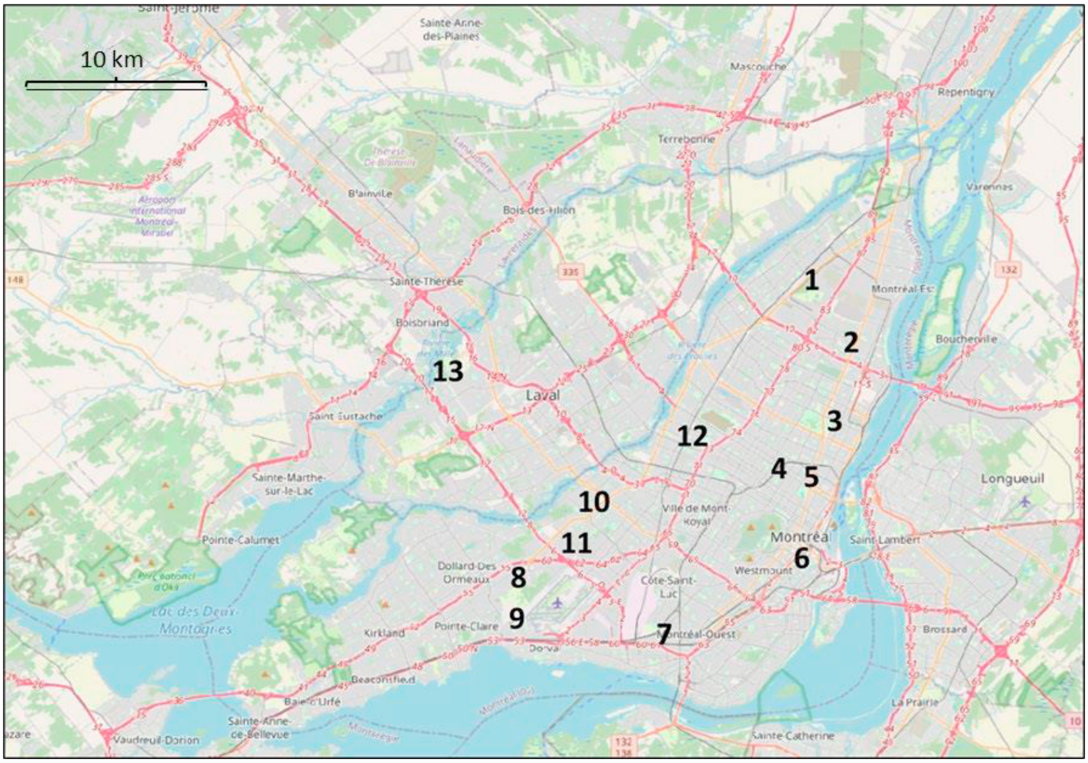

Figure 1: Location of the 13 warehouses used for deliveries in our experiment

The Montreal region includes the Island of Montreal, which is linked to its surrounding areas by a few bridges and tunnels, the Island of Laval and the surrounding suburban towns on the North Shore and South Shore of the Saint Lawrence River. Also, the Mount Royal is in the middle of the Island of Montreal and close to downtown Montreal, which creates an important obstacle for transportation in the core of the region (close to warehouse 6 in Figure 1). This makes it particularly important to measure distances according to the road network as opposed to Euclidian distances.

To have a realistic measurement of how much distance is travelled in a delivery route, we decided to solve the model once with the base case while assuming that each delivery was done separately. The base case imposes no sharing of infrastructure, and no use of CBs for the deliveries. Then, we construct delivery routes for each of the courier company, some for pickups, and some for final deliveries. Figure 2 illustrates our hypothesis.

The objective behind our hypothesis is to obtain a ratio between the distance of an actual route and the total distance of round trips between a depot and the nodes it visits. The procedure we use to set a value for the ratio is as follows. For each warehouse, we take the first deliveries in chronological order and fill a curbside truck until we cannot add another delivery without exceeding the vehicle's capacity (500 kg). This gives us a list of clients with a delivery to be made. Based on this list, we solve a travelling salesman problem (TSP) to obtain the actual delivery route. To solve the TSP, we used the Concorde TSP algorithm (Carvalho 2018). Once we obtained the solution, i.e., the actual route, we calculated the ratio between the total distance of the actual route obtained and the sum of all the distances of the nodes to the route's warehouse. In Figure 2, the sum of all round-trip distances is 20 km. With a ratio of 0.2, we would have considered a route length of 0.2 * 20 = 4 km. We calculate this ratio for each warehouse and for one instance of a pickup route, and one instance of a delivery route. It results in 26 routes used. We then calculate a weighted average for the ratios obtained by giving to each route a weight equal to its length. The result obtained was 19.59%. We rounded up this percentage to 20%. We generated other scenarios where this ratio is set between 10% and 25% (with intervals of 5%) to measure the impact which this parameter has on the results. However, although this ratio has a significant influence on the results obtained, it had a very negligible effect on the results *between* the different scenarios (always less than 0,1%). We decided to settle on using the value of 20% for the scenarios whose results are presented in this paper, which was closest to the actual value obtained when routing was used.

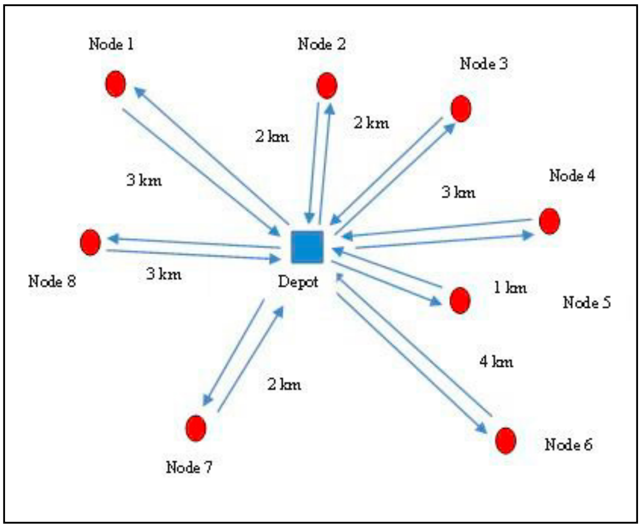

Figure 2: Graphical illustration of how routes are taken into account

We also used the results of these routes to calculate what was, on average, the ratio between the node located the furthest away from the depot and the distance travelled. This helped us exclude pickup and delivery nodes for routes involving CBs, which have a much more limited autonomy. For instance, in Figure 2, the node furthest away from the depot is located 4 km away from it while the estimated total length of the route is 20 km. This would signify that this ratio for this route would be 20%. The average percentage measured for all the route we generated was 18.26%. This ratio was multiplied by the maximum distances of each vehicle to define the parameter d^v. Any origin-destination pair which exceeded this parameter had to take a value of zero (0). We tested what would happen if this percentage was increased by 10%, while using the most representative percentage for the ratio of the actual distances travelled and the sum of all distances to the warehouse (20%).

To establish certain parameters regarding the use of CBs, we used data obtained from a report published by Brard et al. (2021) who studied the use of these vehicles in Montreal in recent years. According to this report, there was a 16% cost savings when using CBs for a delivery cost of $2.38/kg/km for CBs and $2.81 for curbside trucks. They also found the capacity of CBs to be 200 kg while curbside trucks can carry 500 kg at once. As far as speed is concerned, we used the estimates from Büttgen et al. (2020) which affirmed that the maximum speed of a CB is 25 km/h to determine on which od pairs they could travel while trucks were allowed to travel everywhere on the road network. Most OD pairs have an average maximal speed between 25 km/h and 35 km/h. We decided to test what would happen had access to origin-destination pairs over which the maximal speed varied between these values. Also, we used an estimate for the loading costs in our model found in Assmann et al. (2020). They measured a loading and unloading cost of around 4$ per deliveries with CBs and 20$ with vans.

4. Results

4.1 Scenarios and Resolution

The problem was solved using the CPLEX 12.6 version. The simplest scenario is the base case (scenario #1) where there is no warehouse sharing and no use of CBs, which greatly limits the size of the problem. The number of variables varied between 1,275,000 (for the base case) and 12,729,000. The number of constraints varied between 1,070,000 (for the base case) and 14,444,000 for scenarios involving the sharing of warehouses and the use of CBs. Solution time varied between less than 10 seconds and 5 hours to solve. Around 24 of the 26 scenarios took around 5 minutes or less to find a solution. A solution within 0.01% of the optimal solution was always found. A standard PC with a 3.6 GHz and 128.0 GB of RAM were used.

To derive interesting insights on the impacts of warehouse sharing and CB use, we define different scenarios. The different scenarios differ in the possibility of sharing warehouses, the use of CBs, the autonomy of the CBs (in km), and in the possibility for warehouses to deal with CBs. It results in a total of 26 scenarios. The list of all scenarios can be found in Table 4.

First, we wanted to measure the gains brought using CBs in their operations. We then wanted to measure the impact of expanding the autonomy of CBs to 60 and 70 kilometres, with one warehouse being used as a depot and all the warehouses. Finally, we tested the impact of sharing warehouses between different courier companies, with and without multiple hubs for CBs as well as with or without an expanded autonomy for these vehicles (again, to 60 and then 70 km). These results of each of these scenarios and for a d^v parameter equal to 28.26% (the highest value tested) as well as a maximum speed of 30 km/h for CBs are shown in Figure 2.

Table 4: List of tested scenarios

Scenario	Sharing of warehouses	Use of CBs	CB autonomy (km)	Greatest distance for a node as a % of total distance	Maximal speed (CBs)
1	No	No	Not relevant	18.26%	Not relevant
2	No	Yes	50	18.26%	25 km/h
3	No	Yes	60	18.26%	25 km/h
4	No	Yes	70	18.26%	25 km/h
5	Yes	No	Not relevant	18.26%	Not relevant
6	Yes	Yes	50	18.26%	25 km/h
7	Yes	Yes	60	18.26%	25 km/h
8	Yes	Yes	70	18.26%	25 km/h
9	No	Yes	50	28.26%	25 km/h
10	No	Yes	60	28.26%	25 km/h
11	No	Yes	70	28.26%	25 km/h
12	Yes	Yes	50	28.26%	25 km/h
13	Yes	Yes	60	28.26%	25 km/h
14	Yes	Yes	70	28.26%	25 km/h
15	No	Yes	50	18,26%	35 km/h
16	No	Yes	60	18,26%	35 km/h
17	No	Yes	70	18,26%	35 km/h
18	Yes	Yes	50	18,26%	35 km/h
19	Yes	Yes	60	18,26%	35 km/h
20	Yes	Yes	70	18,26%	35 km/h
21	No	Yes	50	28.26%	35 km/h
22	No	Yes	60	28.26%	35 km/h
23	No	Yes	70	28.26%	35 km/h
24	Yes	Yes	50	28.26%	35 km/h
25	Yes	Yes	60	28.26%	35 km/h
26	Yes	Yes	70	28.26%	35 km/h

The highest potential savings are brought by the sharing of warehouses. Sharing warehouses allows sending couriers to the warehouse which reduces total distances travelled irrespective of the courier company. Alone, they bring a saving of 30.8% of costs and almost 50% of CO_2 emissions. These gains increase slightly when there is the possibility of using CBs and even more when these vehicles autonomy is increased to 60 and 70 km. Gains brought using CBs alone are much more modest, especially when the ratio of maximal distance to total distances is lower and the maximal speed is limited to 25 km/h. However, they can reach around 15% of CO_2 emissions when both parameters are high (scenarios 21, 22 and 23). One data which illustrates how profitable is the sharing of warehouses, 82% of couriers in scenario 5 (sharing of warehouses with a ratio of 18.26% and a maximal speed of 25 km/h) transit through a different warehouse than in the base scenario (scenario 1). We also looked at the share of kg kilometres travelled by CBs for the different tested the % of kg delivered by CBs as well as the percentage of routes made by these vehicles. All results can be seen in Table 5 below.

It should be noted that, often, the extension of the CB's autonomy has a more limited effect on cost and GHG emissions reduction than an increase of CB's speed. This is because a limited speed prevents CBs from travelling on a significant part of the street grid, hence relegating them to their immediate neighbourhood. For instance, for a speed of

25 km/h and a percentage of maximal to total distance of 18,26%, we have a very slight increase in cost saving from 31.2% to 31.3% when we increase the CB autonomy from 50 km to 70 km. On the contrary, when the speed is increased from 25 km/h to 35 km/h, with the same autonomy, there is a larger increase in cost saving (for example, from 31.8% to 32.8% in cost savings with an autonomy of 50 km and a ratio of maximal distance to total distance of 28.26%). The same pattern emerges when the percentage of maximal to total distance in increased to 28,26%. Each increase of 10 km in autonomy with a speed of 25 km/h brings a cost saving of 0,4% while a speed increase of 10 km/h brings a cost saving between 1,0 and 1,5%. When the speed is at 35 km/h, the cost saving increases to 0,9% when the autonomy goes from 50 to 60 km but is only 0,1% when the autonomy reaches 70 km. GHG saving increases are always higher but follow the same pattern. For instance, when CB's autonomy is increased from 50 to 60 km (with a maximal speed of 25 km/h and a ratio of maximal distance to total distance of 18.26%), the GHG saving goes from 33.5% to 33.8%. When the speed is increased from 25 to 35 km/h with an autonomy of 50 km and a ratio of maximal to total distance of 18.26%, this GHG saving goes from 33.5% to 35.4%.

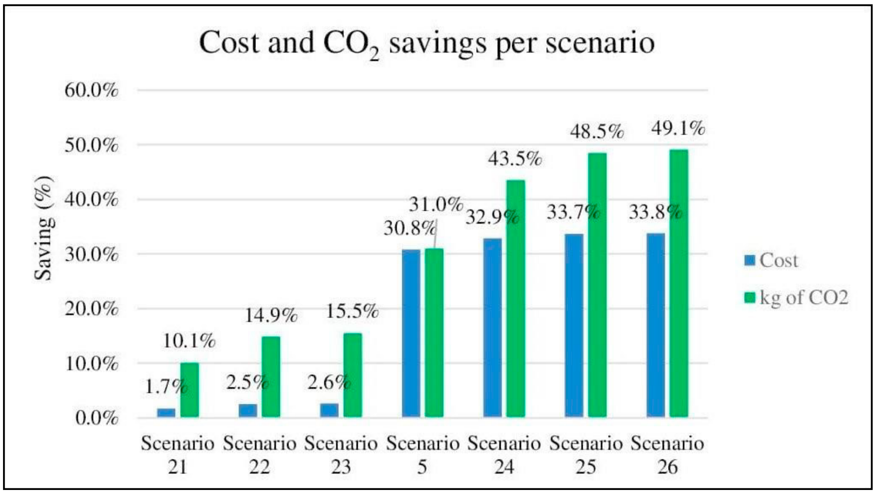

Figure 2: Cost and CO_2 savings for scenarios with expanded autonomy of CBs and/or a sharing of warehouses

Table 5: Results per scenario

Scenario	Costs Saving (%)	Kg of CO_2 Saving (%)	% of kg km with CBs	% of kg delivered with CBs	% of routes with CBs
1	0.0%	0.0%	0.0%	0.0%	0.0%
2	0.3%	1.8%	6.1%	37.7%	60.1%
3	0.3%	1.9%	8.4%	40.5%	62.9%
4	0.4%	2.5%	9.7%	41.8%	64.3%
5	30.8%	31.0%	0.0%	0.0%	0.0%
6	31.2%	33.5%	10.3%	45.8%	67.7%
7	31.2%	33.8%	14.3%	49.0%	70.5%
8	31.3%	34.3%	18.3%	51.6%	72.6%
9	0.9%	5.4%	6.2%	37.8%	60.3%
10	1.3%	7.4%	6.2%	37.8%	60.3%
11	1.4%	8.5%	10.0%	42.1%	64.5%
12	31.8%	37.2%	11.0%	46.6%	68.5%
13	32.2%	39.5%	15.1%	50.0%	71.3%
14	32.6%	41.9%	20.6%	53.6%	74.1%
15	0.6%	3.8%	11.5%	43.4%	65.9%
16	0.7%	3.8%	17.1%	47.8%	69.7%
17	0.7%	4.1%	18.7%	48.9%	70.7%
18	31.5%	35.4%	21.0%	53.1%	73.8%
19	31.5%	35.4%	29.5%	57.5%	77.1%
20	31.5%	39.2%	34.3%	59.6%	78.5%
21	1.7%	10.1%	11.2%	42.9%	59.6%
22	2.5%	14.9%	16.5%	47.0%	63.2%
23	2.6%	15.5%	17.2%	47.5%	63.6%
24	32.8%	43.5%	23.5%	55.3%	75.4%
25	33.7%	48.5%	32.9%	60.1%	78.9%
26	33.8%	49.1%	42.7%	64.1%	81.6%

4.2 Dynamic Effect Between the Use of Cargo Bikes and the Sharing of Warehouses

We decided to verify if there was any dynamic effect between the gains brought using CBs and the sharing of warehouses, i.e., if the sharing of warehouses made the use of CBs more profitable than otherwise. We measured this effect by dividing the percentage of cost (or CO_2) decrease when there was both warehouse sharing and the use of CBs at all warehouses with the sum of the cost decrease when all warehouses had CBs and there was a sharing of warehouses (separately). If the number obtained exceeded 100%, there was a certain dynamic effect; otherwise, there wasn't. It was found that there was a small dynamic effect of between 0.4% and 1.2% for costs and 1.7% and 5.9% for CO_2 emissions. Hence, CBs are more profitable when warehouses are shared than when they remain dedicated to a specific courier company. Only for scenario 8 (maximum speed of 25 km/h, ratio of 18.26% and CBs autonomy of 70 km) was this dynamic effect absent. We interpret this to mean that warehouse sharing reduces average distances, which means that more OD pairs will then be accessible to CBs than otherwise.

4.3 Perspectives

The results obtained show that more effort should be made to encourage courier companies to collaborate amongst themselves to make it possible for courier to transit by a warehouse owned by a different company from the one making the delivery. Putting forward tax and regulatory incentives could make it easier for companies to collaborate. Sharing warehouses to reduce costs also implies sharing the gains amongst the companies. Different formulas can be used such as the Shapley Value, (Shapley, 1953) or separable costs (Tijs and Driessen 1986). The responsibilities in the decision-making in such a structure should be well defined in advance.

As far as Cargo Bikes are concerned, they represent a very important potential for GHG reductions, which far outpaces their cost reduction potential. Considering the importance of reducing GHG emissions and combating global warming, governments should more thoroughly encourage the transition to these vehicles in areas where they can travel as well as research and development to widen the part of the road network where they can travel. More generally, more efforts should be made to make the road network safer for lighter vehicles such as CBs. Also, we acknowledge that for this case study, we were limited by the data that were given by our partners. We have further used papers from the literature to set the values of some parameters used in this study. Those two elements represent a limitation of our case study that could be tackled in future research. In particular, it would be interesting to test more parameters value (e.g., fuel costs, average distances, or a tax on CO_2 emissions), and to integrate more knowledge on the incentive for delivery companies to use cargo bikes and/or share warehouses. Considering the fact that our focus is on the case study with a specific partner, we did not test those elements to fit with the reality of the partner.

5. Conclusion

City logistics is an important area of potential reduction in transportation costs and GHG emissions. It could benefit greatly from the sharing of infrastructure and a wider use of mode eco-friendly vehicles such as CBs. We tested the benefits of such possibilities through an experiment with courier delivery data from the Montreal area covering more than 67,000 deliveries made between January 2020 and April 2021. A cost minimization model was developed and run with 26 scenarios. The results showed that the sharing of warehouses and a wider use of CBs would have a significant positive impact on transportation costs and even more on CO2 emissions. The maximal speed of CBs also has a significant impact on the results as it greatly influences the number of OD pairs over which these vehicles can travel. However, CBs' autonomy doesn't have a significant influence. The reason for this is that most OD pairs which could be added if CBs autonomy was extended from 50 km to 60 km or 70 km have an average speed which is too high for these vehicles. It would seem therefore that to improve these vehicles' batteries would not be useful and efforts should be deployed elsewhere.

There are certain limitations to this contribution. We relied on estimates of actual distances travelled and have not yet constructed delivery routes on a wide basis. We do not know precisely which OD pairs which CBs can access or not, which is why we included this factor in our sensitivity analysis. For instance, we know that certain streets could not be accessible to CBs because of their slope, especially if they cross the Mont-Royal, the mountain which sits in the middle of the Island of Montreal. Also, the different ratios used were the same for the entire transportation network. Building actual delivery routes will make it possible to integrate geographical differences between the different sectors within the

Montreal area.

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