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Abstract. We examine an innovative system for organizing deliveries in a collaborative fashion for an *n*-tier hyperconnected city logistics system. We focus on the tactical planning of services within the first tier of the system, i.e., from external zones generally located on the outskirts of the city (logistics platforms, urban/city distribution/consolidation centers, etc.) to satellites from which goods are distributed to final customers, and introduce a new optimization model for that purpose. The key distinctive feature of this model is that we consider a coalition of carriers and logistic operators who share their resources (fleets of vehicles and warehousing capacity) and information flows to provide more effective services, thus lowering costs and environmental impact. Preliminary computational results confirm the attractiveness of the envisioned system.

Keywords. Collaborative logistics, City Logistics, physical internet.

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1 Introduction

Transport and logistics have become increasingly important in the development, organization, and operation of our society. Recently, the intensity of logistic activities has grown strongly in terms of volume since most of our activities require the movement of people and goods, which must be efficient and at minimum cost. These requirements can only be achieved with efficient infrastructure, services, and logistics and transport activities. More specifically, the transportation of goods is an important factor for most economic and social activities in urban life (OECD, 2003). In fact, the transport of goods in cities constitutes from 15% to 20% of all vehicle trips. This complexity is amplified by the increase of population and urbanization. In 2014, 54% of the worlds population was living in urban areas. The United Nations (2004) are expecting a further increase of 66% by 2050 and of 85% by 2100 (OECD, 2003). In this context, the demand that distribution networks must deal with is larger than ever before and will be getting even larger in the future. Consequently, the freight transportation industry has become the major source of various kinds of nuisances for city dwellers, such as noise, congestion, pollution, etc.

To address these problems, new paradigms for organizing and planning urban freight transportation have emerged; we are specifically interested in *City Logistics* (CL) and *Physical Internet* (PI). The main objective of City Logistics is to reduce the negative impacts of freight movements in urban areas in terms of congestion, mobility, and environmental impacts, without penalizing the different social and economic activities (Taniguchi and Thompson, 2002; Taniguchi, 2014; Bektaş et al., 2017). It thus aims to improve the efficiency of goods movements while controlling the presence of freight vehicles in urban areas and reducing empty vehicle flows, (Benjelloun and Crainic, 2008; Dablanc, 2007).

Physical Internet (PI) is a new concept for freight transportation and logistics aiming to improve the economic, environmental and social efficiency and sustainability of the way in which physical objects are moved, stored, realized, supplied, and used around the world (Montreuil et al., 2012, 2013). Using concepts similar to those of the digital Internet and mimicking the way that data packets transit in digital networks, the PI idea is to route goods that are encapsulated in modular containers (called π-*containers*) through a global, interconnected and open network (Montreuil, 2011; Sarraj et al., 2014a). The PI concept is increasingly present in research, recent applications demonstrating real gains in interurban freight transportation, supply chains, and logistics (Ballot et al., 2014; Sarraj et al., 2014b).

Several concepts, such as cooperation, consolidation, the way of implementing the activities of transport and storage of goods, are key concepts for both City Logistics and Physical Internet. These transport systems are complementary, since City Logistics provides the final segments of interconnected logistics and Physical Internet transportation networks. Despite the importance of these concepts, Crainic and Montreuil (2016) have claimed that no study has explored the links and synergies between these advanced systems of freight transport and logistics. Moreover, to the best of our knowledge, no planning, modeling or optimization methods have been developed for this type of hyperconnected networks. We aim to fill these gaps by introducing the idea of hyperconnected (in the sense of PI) urban logistic systems, which we call *Hyperconnected City Logistics* (HCL). Our overall objective is to explore and discuss the key concepts, potential benefits, and challenges in term of research and development of Hyperconnected City Logistics.

In this paper, we initiate the development of models and optimization methods required to plan effective HCL networks. More precisely, we introduce a new integer programming formulation to examine tactical decisions related to the design and management of a hyperconnected service network implementing City Logistics principles. We then illustrate the potential of this model by performing a computational case study to evaluate the gains that could be obtained in an HCL system when there is cooperation between several logistical actors, e.g., when resources such as transport fleet and satellite capacity are shared. In this computational study, two transportation modes, trucking and urban tramway, are considered.

The paper is organized as follows. In the following nomenclature (Table 1) we define the notation that will be used in the remainder of the paper. In Section 2, we formally define the problem that we tackle and discuss some of its relationships with the existing literature. The mathematical model is introduced in Section 3. Then, we present our case study in Section 4. Section 5 concludes the paper and discusses future research paths.

2 Problem definition

The problem that we address here is the tactical design of a Hyperconnected City Logistics network. Following ideas common in City Logistics, we assume a two-level distribution network in which goods are first moved from large logistical platforms located outside of the urban area proper (we refer to these as *external zones*) by *urban vehicles* of significant capacity to much smaller platforms, called *satellites*, located within the city core; from satellites, goods are delivered to the final customers using much smaller vehicles with a low environmental footprint called *city freighters*. While many authors have addressed City Logistics problems as two-level routing problems (see, e.g., Hemmelmayr et al. (2012)), we follow here Crainic et al. (2009) and consider a general framework for two-tier city logistics systems (2T-CL) that models the first level as a service network design problem. Furthermore, to deal with a wide range of alternatives, we allow for the existence of several modes, e.g., trucking and tramway, at this first level. We also assume that goods are moved in π-containers and that we therefore can restrict ourselves to a

P:	length of planning horizon (in periods)
N:	set of carriers that are members of the coalition
M:	set of transportation modes
ε:	set of external zones
ε^m:	set of external zones for mode $m \in M$
Z:	set of satellites
Z^m:	set of satellites for mode $m \in M$
u_{zp}:	volume of merchandise that satellite $z \in Z$ can handle in period p
u_{zp}^m:	number of urban vehicles of mode $m \in M$ that satellite $z \in Z$ can accommodate in period p
u_{zp}^t:	number of urban vehicles of type $t \in T$ that satellite $z \in Z$ can accommodate in period p
T:	set of all urban vehicle types
T^m:	set of urban vehicle types for mode $m \in M$
u_t:	capacity of urban vehicle type $t \in T$
D:	set of demands
v_d:	volume of demand $d \in D$
Z_d:	subset of satellites in Z through which demand $d \in D$ can be routed
S_{dz}:	cost of distributing demand $d \in D$ from satellite $z \in Z$
a_d^o:	lower bound of the time window for picking up demand $d \in D$ at its origin
b_d^o:	upper bound of the time window for picking up demand $d \in D$ at its origin
a_d^d:	lower bound of the time window for delivering demand $d \in D$ to its destination
b_d^d:	upper bound of the time window for delivering demand $d \in D$ to its destination
R:	set of services of urban vehicles
R^n:	set of services of urban vehicles performed by carrier $n \in N$
R_{tep}:	set of services of urban vehicles of type $t \in T$ from external zone $e \in \varepsilon$ during period p
R_{tp}^z:	set of services of urban vehicles of type $t \in T$ arriving in satellite $z \in Z$ during period p
R_{mp}^z:	set of services of urban vehicles of mode $m \in M$ arriving in satellite $z \in Z$ during period p
e_r:	external zone $e \in \varepsilon$ of service $r \in R$
m_r:	mode $m \in M$ of service $r \in R$
t_r:	urban vehicle type $t \in T$ of service $r \in R$
u_{t_r}:	capacity of an urban vehicle of type $t \in T$ for service $r \in R$
F_{der}:	cost of assigning demand $d \in D$ to external zone $e \in \varepsilon$ for service $r \in R$
σ^r:	ordered sequence of satellites in Z visited by service $r \in R$
w_{zr}:	waiting time of service $r \in R$ at satellite $z \in Z$
τ_o^r:	departure time of service $r \in R$ from an external zone
τ_i^r:	departure time of service $r \in R$ from satellite $i \in Z$
h_r^n :	service time of service $r \in R$ when performed by carrier n
h_t:	service time of a urban vehicle of type t at a satellite (in number of periods)
f_{rm}^n:	operating cost of service $r \in R$ performed by carrier $n \in N$ with mode $m \in M$
mC_N:	total cost incurred by the complete coalition N
α_n:	weight of carrier $n \in N$ in the coalition
α_n^-:	lower bound on the share of the total cost or service time incurred by carrier $n \in N$
α_n^+:	upper bound on the share of the total cost or service time incurred by carrier $n \in N$
y_{rm}^n:	$0,1$ decision variable: yes/no service $r \in R$ using mode $m \in M$ is assigned to carrier $n \in N$
x_{rdz}:	$0,1$ decision variable: yes/no demand $d \in D$ is assigned to service $r \in R$ and satellite $z \in Z$

Table 1: Nomenclature

single product for planning purposes.

The main goal of our problem is to plan a schedule of first-tier services repeatedly operated over a fairly time horizon (e.g., 6 months). However, it must be emphasized that in the model we only consider a short planning horizon consisting of a typical day or even less. It is assumed that the schedule obtained from the optimization model is for a typical day. Crainic et al. (2009) suggest to decompose the problem, so as Fontaine et al. (2017), we focus on the first layer and approximate the routing costs of the second layer. Because of demand uncertainty and a very high complexity level in the second layer, customers will have a predefined subset of possible satellites, but we do not consider the actual routing in the tactical planning process. Thus, we propose a service network design problem for the first layer of this HCL network. In the following, we review the main elements of this problem.

2.1 The tactical planning problem

At the core of the problem is the set D of demands to be serviced by the coalition of shippers. It is assumed that in the HCL environment, various carriers will create a pool of shared demands, which could, in theory, be satisfied by any one of them. These demands must travel from external zones to satellites to customers at times specified by various time windows: for demand $d \in D$, we have an availability time window $[a_d^o, b_d^o]$ at the origin and a delivery time window $[a_d^d, b_d^d]$ at the destination (customer). In practice, it is not tractable to deal directly with these time windows. Availability time windows, as we shall see, can be handled by restricting the set of services that may handle a given demand. As for the time windows at customer locations, we assume that they can be transferred to the satellites by an approximation of the delivery times obtained in the optimal solution of the second-tier routing problem. As mentioned by Fontaine et al. (2017), in practice, one would solve the actual second-tier routing problem on the-day-before when the true demands are realized. As part of the approximation exercise, one would derive for each demand d a subset of satellites Z_d through which this demand could be routed.

Another core element of the model is the transportation supply. This is partly described by the availability of various fleets of heterogeneous vehicles of different modes, e.g., the number n_{et} of urban vehicles of type $t \in T$ in external zone $e \in \varepsilon$ provided by the members of the coalition. The other critical part of the description of the transportation supply is given by the *transportation services* themselves. Here, we assume that it is possible to enumerate a (non-exhaustive) list of potential services that carriers are interested in operating. The optimization process will thus select which services should be operated to transport given demands. In our planning environment, we assume that each service $r \in R$ is characterized by the carrier performing it, its mode $m_r \in M$, the type $t_r \in T$ of urban vehicle type that it operates, its capacity u_{t_r}, the external zone

$e_r \in \varepsilon$ from which it operates, the ordered sequence σ^r of satellites in Z that it visits, its departure time τ_o^r from external zone e_r, its departure time τ_i^r from satellite $i \in Z$, and its waiting time w_{zr} at satellite $z \in Z$. All of these information allow us to compute the cost F_{der} of assigning demand $d \in D$ to external zone $e \in \varepsilon$ for each possible service $r \in R$ capable of handling it. It is important to notice that a large part of the detailed information about services does not appear per se in the optimization model: it is simply pre-processed to derive model parameters.

2.2 Ressource management

In City Logistics, many capacity restrictions need to be considered. Crainic et al. (2009) already define several restrictions such as the capacity of vehicles or satellites. In many traditional CL systems, in order to ensure the efficient transfer of goods into satellites, urban vehicles and city-freighters are not allowed to wait in satellites in general. However, this is not very realistic, since in reality there can be a waiting time before the transfer operations. Therefore in this problem consider satellites with storage. In these satellites we allow a short-term storage before loading freights in city-freighters. As a result, the constraints of moving goods from urban vehicles to city-freighters will be more flexible and realistic. Note, however, that each satellite is defined by a limited space, which can be used for the transfer of goods. This space limits the size of the tramway cars or the number of urban vehicles at a given moment. In addition, there may also be a time limit during which unloading or loading must be performed. This is particularly the case if passenger services are combined with freight transport. Definitely a passenger tramway car should not wait in a cross-docking station because of unloading or loading activities. Because of that, we define various capacity limits for each satellite z at each period p: volume u_{zp} of merchandise that the satellite can handle in period p, maximum numberu_{zp}^m of urban vehicles of mode $m \in M$ that the satellite can accommodate in period p, and maximum numberu_{zp}^t of urban vehicles of of type $t \in T$ that the satellite can accommodate in period p.

2.3 Controlling the collaboration

A distinctive element about our model is the presence of several carriers operating in collaborative fashion. To ensure a sustainable collaboration, it is very important to regulate the activities of the coalition in order to prevent any of its member from a loss of revenue, or an over-usage of its resources. We make the assumption that each participant n has a share or weight α_n, which is a target for its level of activities or the costs it incurs. We therefore define lower and upper bounds α_n^- and α_n^+ based on α_n to regulate the activities of participant n.

3 Mathematical model

In order to present the integer programming model that corresponds to the problem described in the previous section, we introduce two families of decision variables:

$$y^n_{rm} = \begin{cases} 1 & \text{if service } r \in R \text{, using mode } m \in M \text{, is assigned to carrier } n \in N \text{ ,} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

$$x_{rdz} = \begin{cases} 1 & \text{if demand } d \in D \text{ assigned to service } r \in R \text{ and satellite } z \in Z, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

We consider three versions of the IP model. The first corresponds to the basic version of the model without any constraints on the activities of members of the coalition (Case 0). The second version (Case 1) introduces constraints on the share of the costs incurred by each member of the coalition. The final version (Case 2) adds other constraints on the activities of the coalition members. We first present the basic model

3.1 Basic model (Case 0)

$$\text{Min} \quad C_N \quad = \quad \min \sum_{n \in N} \sum_{m \in M} \sum_{r \in R^n} f^n_{rm} y^n_{rm} + \sum_{d \in D} \sum_{r \in R} \sum_{z \in Z} (S_{dz} + F_{der}) \, x_{rdz} \tag{3}$$

$$\text{subject to} \qquad \sum_{n \in N} y^n_{rm} \quad \leq 1, \qquad r \in R, \quad m \in M \tag{4}$$

$$\sum_{r \in R} \sum_{z \in Z} x_{rdz} \quad = 1, \qquad d \in D \tag{5}$$

$$\sum_{z \in Z} \sum_{d \in D} v_d x_{rdz} \quad \leq u_{t_r} y^n_{rm}, \qquad r \in R, \quad m \in M, \quad n \in N \tag{6}$$

$$\sum_{n \in N} \sum_{m \in M} \sum_{r \in R_{tep}} y^n_{rm} \quad \leq n_{et}, \qquad t \in T, \quad e \in \varepsilon, \quad p \in P \tag{7}$$

$$\sum_{n\in N}\sum_{m\in M}\sum_{p'=p-h_t+1}^{p}\sum_{r\in R^z_{tp'}} y^n_{rm} \leq u^t_{zp}, \qquad t\in T, \quad z\in Z, \quad p\in P \tag{8}$$

$$\sum_{n\in N}\sum_{t\in T^m}\sum_{p'=p-h_t+1}^{p}\sum_{r\in R^z_{mp'}} y^n_{rm} \leq u^m_{zp}, \qquad m\in M, \quad z\in Z, \quad p\in P \tag{9}$$

$$\sum_{d\in D}\sum_{r\in R} v_d x_{rdz} \leq u_{zp}, \qquad z\in Z, \quad p\in P \tag{10}$$

$$y^n_{rm} \in \{0,1\}, \qquad r\in R, \quad m\in M, \quad n\in N \tag{11}$$

$$x_{rdz} \in \{0,1\}, \qquad r\in R, \quad d\in D, \quad z\in Z \tag{12}$$

The objective function (3) minimizes the costs of selecting and operating services, plus the costs of assigning demands to given external zones and satellites. These assignment costs include the operational costs for a terminal, as well as transportation costs between external zones and satellites.

Constraints (4) ensure that each possible service is performed by at most one carrier. Constraints (5) prevent split deliveries by assigning each demand to a single service and satellite. The capacity constraints of urban vehicles are enforced by (6). Constraints (7) limit the maximum number of available vehicles of each type in each period, in each external zone. Constraints (8) and (9) limit the number of urban vehicles handled by each satellite in each period, respectively by vehicle type and by mode. Constraints (10) are capacity constraints on the volume of merchandise handled in each satellite in each period. Finally, (11) and (12) are non-negativity constraints for the decision variables.

3.2 Models with additional constraints (Cases 1 and 2)

For **Case 1**, we wish to add constraints on the share of the total costs borne by each carrier in the coalition. More precisely, we add constraints (13), which, depending on the weight of a given carrier n in the coalition, impose lower and upper bounds, respectively α_n^- and α_n^+, on the fraction of the total costs that it incurs.

$$\alpha_n^- \sum_{n' \in N} \sum_{m \in M} \sum_{r \in R^{n'}} f_r^{n'} y_{rm}^{n'} \leq \sum_{r \in R^n} \sum_{m \in M} f_r^n y_{rm}^n \leq \alpha_n^+ \sum_{n' \in N} \sum_{m \in M} \sum_{r \in R^{n'}} f_r^{n'} y_{rm}^{n'}, \quad n \in N \tag{13}$$

For **Case 2**, we keep the formulation of **Case 1**, but we add constraints (14) to limit the use of the fleet of each carrier in the coalition, in terms of the maximum service time. Once again, we impose upper and lower bounds on the fraction of service time performed based on the weight of the carrier in the coalition.

$$\alpha_n^- \sum_{n' \in N} \sum_{m \in M} \sum_{r \in R^{n'}} h_r^{n'} y_{rm}^{n'} \leq \sum_{r \in R^n} \sum_{m \in M} h_r^n y_{rm}^n \leq \alpha_n^+ \sum_{n' \in N} \sum_{m \in M} \sum_{r \in R^{n'}} h_r^{n'} y_{rm}^{n'}, \quad n \in N \tag{14}$$

4 Computational study

We performed a series of computational experiments to validate and assess the performance of the proposed model. We also wished to assess the impact of allowing collaboration with some constraints in the context of an HCL network. Among other things we wanted to see how the model reacted in terms of performance measures, transportation costs, and fleet and facility utilization.

4.1 Experimental framework

The different instances considered were solved using a commercial solver. We implemented the model in C++ with CPLEX Concert Technology 12.8.0.0 and CPLEX 12.8.0.0 was the solver. Computational experiments were run on a group of 27 machines each with two Intel (R) Xeon (R) X5675 3,07 GHz processors and 96 Gb of RAM. Each machine has 12 cores and each experiment used a single thread.

As mentioned in the previous section, three cases were examined: **Case 0** corresponds to the basic network design formulation, while **Case 1** and **Case 2** introduce various constraints on the activities of carriers in the coalition to account for the fact that the overall revenues, costs, and resource usage should be shared fairly.

The test instances were based on four networks derived from a typical city setting proposed by Crainic and Sgalambro (2014) and Fontaine et al. (2017). However, the data were generated randomly. Each network possesses two distribution centers (external zones). The four networks contain respectively 4, 6, 8 and 8 satellites. The two 8-satellite networks differ by their configuration. Distances between points were computed as Euclidean distances and travel speeds vary according to vehicles. The planning horizon was made of 36 periods of 5 minutes each, for a total of 3 hours. Each satellite can receive a truck or a tramway in each period and handle 5000 units of product. To study the impact of collaboration, we considered several combinations of coalitions. Two of these consider individual carriers operating respectively a truck and a tramway. The third one corresponds to a coalition made up of the two previous carriers with a share of 60% for the company owning the truck and a share of 40% for the tramway company. Finally, a coalition of three carriers operating a truck, a tramway, and a different truck with shares of 40-35-25% was examined.

For each of the four network, four scenarios with respectively 70, 80, 90, and 100 services and 2, 3, 3, and 3 carriers were solved for four different demand scenarios: 150, 160, 170, and 180 demands, and for the three cases for a total of 192 instances.

4.2 Computational results

All instances were run with a time limit of one day, i.e., 86,400 seconds of CPU time. Within this time limit, most instances could be solved. For the few instances that could not be solved, the optimality gap ranged from 0.0099 % to 0.002 %, which is insignificant in the context.

Our experiments showed that, for similar instances, running times were increasing sharply with the number of demands. For instance, if one considers Scenario 1 with two carriers and 70 services, when the number of demands goes from 150 to 180, the average running time increases from 48 to 170 seconds for **Case 0**, from 914 to 2,566 seconds for **Case 1**, and from 1,292 to 9,694 seconds for **Case 2**. When looking at scenarios with more carriers and services (i.e., Scenarios 2 to 4), the average running time increases from 309 to 645 seconds for **Case 0**, from 8,669 to 14,235 seconds for **Case 1**, and from 9,289 to 82,467 seconds for **Case 2**. One may be surprised to see the sensitivity of running times with respect to the number of demands, but this effect is quite clear across all scenarios and cases.

Less surprising is the impact of increasing the number of carriers from two to three (along with the number of services): for instance, **Case 0** with 180 instances requires 170 seconds on average for two carriers and 645 with three carriers. This effect is even more pronounced for more complex instances: for **Case 2** with 180 demands, one witnesses a nine-fold increase in running time from 9,694 to 82,467 seconds.

As could be expected, including the additional constraints of **Case 1** and **Case 2** has a very significant impact on running times; for example, the average running time for instances with three carriers and 180 demands goes from 645 s for **Case 0**, to 14,235 s for **Case 1**, and to 82,467 s for **Case 2**. This shows that constraining the activities of carriers to meet some collaboration targets has a major impact on the difficulty of the problem at hand.

As for the cost of the optimal solutions, the total cost incurred by the coalition increases somewhat with the number of demands, but not very substantially. In fact, for most cases and scenarios, the cost increase is not even proportional to the increase in the number of demands. For example, for Scenario 2 with 80 services, one observes an increase in the total coalition cost from 10,612 to 12,119 (a 14.2 %-increase) as one goes from 150 to 180 demands (a 20 %-increase). One can imagine that this corresponds to some economies of scale.

As could be expected, when other parameters are fixed, costs go down when the number of available services increases from 70 to 100: for example, the total coalition cost, on average, for **Case 0** and 180 demands decreases from 12,171 for 70 services to 11,311 for 100 services. This is normal since, when there are more services, there are more options to route demands from their origin to their destination.

As for the impact of the addition of constraints in **Case 1** and **Case 2**, it is significant, especially when capacity constraints are tight, since it restricts the use of more efficient modes, such as the tramway. The most pronounced impact is observed for Scenario 1 (70 services) with 180 demands: the average coalition cost is 12,171 for **Case 0**, 13,938 for **Case 1**, and 14,030 for **Case 2**. It is interesting to note that while there is always a progression from **Case 0** to **Case 1**, and to **Case 2**, the magnitude of the jumps can differ a lot: in the previous example, there was a significant increase from **Case 0** to **Case 1** and a pretty small one from **Case 1** to **Case 2**. This can be contrasted with the situation of Scenario 3 (90 services) with 170 demands: here one goes from 11,086 for **Case 0**, to 11,097 for **Case 1**, and to 12,586 for **Case 2**.

An extensive discussion of the results of this computational study can be found in Jemai (2018).

5 Conclusion and further research

In this paper, we have examined important elements of Hyperconnected City Logistics, a system based on collaboration and sharing of resources among carriers operating in the same urban environment. This system links and combines ideas and principles of two major paradigms in freight transportation: City Logistics and Physical Internet.

This combination lead to significant improvements in the efficiency and environmental footprint of urban freight transportation networks.

While some papers have examined issues related to Hyperconnected City Logistics (Crainic and Montreuil, 2016), this is, as far as we know, the first paper to actually propose an optimization model for the tactical planning of the first tier of a two-tier HCL system, based on a service network design formulation. Our computational results show that this model can be solved by a commercial solver for instances of modest size. They also allow for an assessment of the benefits of collaboration among carriers and of the impact of constraints aimed at enforcing a fair apportionment of costs, resources, and activities among the various participants.

Two paths for future research come naturally to mind. The first one concerns the development of advanced solution methods, perhaps based on Benders decomposition or metaheuristics, to tackle larger, more realistic, instances of the problem at hand. A second one is related to the explicit introduction of uncertainty in the model by resorting to stochastic programming or robust optimization models.

At a more general level, one might wish to explore different protocols or rules to organize collaboration among stakeholders in the context of Hyperconnected City Logistics.

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References

Ballot, E., Montreuil, B., Meller, R., 2014. The Physical Internet: The Network of Logistics Networks. Retrieved from https://www.ladocumentationfrancaise.fr/catalogue/9782110098658/index.shtml.

T. Bektaş, T. G. Crainic, and T. Van Woensel. 2017. From managing urban freight to smart city logistics networks. In K. Gakis and P. Pardalos, editors, *Networks Design and Optimization for Smart Cities*, 143–188. World Scientific Publishing.

Benjelloun, A., Crainic, T. G., 2008. Trends, challenges and perspectives in City Logistics. In Transportation and land use interaction, proceedings TRANSLU´08 (pp. 269-284). Bucharest, Romania: Editura Politecnica Press.

Crainic, T. G., Ricciardi, N., Storchi, G., 2009. Models for evaluating and planning city logistics transportation systems. Transportation Science 43.4, 432–54.

Crainic, T. G., Montreuil, B., 2016. Physical internet enabled hyperconnected city logistics. Transportation Research Procedia 12, 383–398.

Crainic, T. G., Sgalambro, A., 2014. Service network design models for two-tier city logistics. Optimization Letters 8.4, pp. 1375–1387.

Dablanc, L., 2007. Goods transport in large European cities: Difficult to organize, difficult to modernize. Transportation Research Part A: Policy and Practice 41.3, 280–285.

Fontaine, P. Crainic, T. G., Jabali, O., Rei, W., 2017. Multi-modal scheduled service network design with resource management for two-tier city logistics. Publication CIRRELT-2017-27. Centre interuniversitaire de recherche sur les réseaux d´entreprise, la logistique et le transport, Université de Montréal, Montreal, QC, Canada.

Hemmelmayr, V.C., Cordeau J.-F., Crainic, T. G., 2012. An adaptive large neighborhood for two-echelon vehicle routing problems arising in city logistics. Computers & Operations Research 39.12, 3215–3228.

Jemai, L., 2018. Planification de réseaux hypersonnectés et mutualisés de transport urbain de marchandises. Publication CIRRELT-2018-38. Centre interuniversitaire de recherche sur les réseaux d´entreprise, la logistique et le transport, Université de Montréal, Montreal, QC, Canada.

Montreuil, B., 2011. Toward a Physical Internet: meeting the global logistics sustainability grand challenge. Logistics Research 3.2-3, 71–87.

Montreuil, B., Ballot, E., Fontane, F., 2012. An Open Logistics Interconnection model for the Physical Internet. IFAC Proceedings Volumes 45.6, 327–332.

Montreuil, B., Meller, R.D., Ballot, E., 2013. Physical Internet foundations. In T. Borangiu, A. Thomas, D. Trentesaux (Eds.), Service orientation in holonic and multi agent manufacturing and robotics (pp. 151-166). Berlin, Heidelberg, Germany: Springer. https://doi.org/10.1007/978-3-642-35852-4

Sarraj, R., Ballot, E., Pan, S., Montreuil, B., 2014a. Analogies between Internet network and logistics service networks: challenges involved in the interconnection. Journal of Intelligent Manufacturing 25.6, 1207-1219.

Sarraj, R., Ballot, E., Pan, S., Hakimi, D., Montreuil, B., 2014b. Interconnected logistic networks and protocols: simulation-based efficiency assessment. International Journal of Production Research 52.11, 3185–3208.

OECD, 2003. Delivering the Goods: 21st Century Challenges to Urban Goods Transport. Paris, France: OECD Publications. Retrieved from https://www.itf-oecd.org/delivering-goods-21st-century-challenges-urban-goods-transport

Taniguchi, E. (2014). Concepts of City Logistics for Sustainable and Liveable Cities. Procedia - Social and Behavioral Sciences 151, 310–317.

Taniguchi, E., Thompson, R., 2002. Modeling City Logistics. Transportation Research Record 1790, 45–51.

United Nations (2004). World Urbanization Prospects: The 2003 Revision. United Nations, New York: United Nations Publications.