24th EURO Working Group on Transportation Meeting, EWGT 2021, 8-10 September 2021, Aveiro, Portugal

Comparing home and parcel lockers' delivery systems: a math-heuristic approach

Pasquale Carotenuto [a]*, Riccardo Ceccato[b], Massimiliano Gastaldi [b,d], Stefano Giordani [c], Riccardo Rossi [b], Alessio Salvatore [a,c]

[a] *Istituto per le Applicazioni del Calcolo "M. Picone" – Consiglio Nazionale delle Ricerche, via dei Taurini 19, Roma – 00185, Italy*
[b] *University of Padova – Department of Civil, Environmental and Architectural Engineering, via F. Marzolo 9, Padova – 33131, Italy*
[c] *University of Rome "Tor Vergata" – Dipartimento di Ingegneria dell'Impresa, via del Politecnico 1, Roma – 00133, Italy*
[d] *University of Padova – Department of General Psychology, Via Venezia, 8, Padova – 33131, Italy*

Abstract

E-commerce is a continuously growing sector worldwide, with important repercussions on the delivery system in urban areas and especially in the Business to Consumer (B2C) sector. The delivery of a package to a consumer's address involves not only high costs for couriers (greater number of kilometres travelled), but also increased congestion and greater environmental pollution (greater volume of pollutants released into the air). To rationalize deliveries in urban areas the use of collection points, equipped with lockers, to store the goods that users have ordered has been considered in literature. This work compares two alternative delivery options: deliveries to the consumer's home versus to Lockers. To make this comparison we used a cluster first route second math-heuristic approach. In the clustering phase, we experimented a new clustering function, while the routing phase consists in solving an instance of the Traveling Salesman Problem for each generated cluster. Finally, we applied the math-heuristic to a real case (the Italian municipality of Dolo near Venice) and compared the two delivery alternatives. We evaluate the performance considering two different fleets of vehicles, with small and medium capacity. In addition, since additional trips might be performed by consumers to pick up parcels at Lockers, a sensitivity analysis was carried out to analyse the sustainability of the proposed city logistics scheme.
Peer-review under responsibility of the scientific committee of the 24th EURO Working Group on Transportation Meeting.
Keywords: City logistics, Freight Urban distribution, Vehicle routing, Math-heuristics

1. Introduction

E-commerce is a continuously growing sector worldwide, with important repercussions on the delivery system in urban areas and especially in the Business to Consumer (B2C) sector. Furthermore, the restrictions on the mobility of people, as an action to combat the COVID-19 pandemic, have further enhanced this trend and consolidated this habit among consumers. The delivery of a package to a consumer's address involves not only high costs for couriers (greater number of kilometres travelled), but also increased congestion and greater environmental pollution (greater volume of pollutants released into the air) (Ambrosino et *al.* 1999, Ranieri et *al.* 2021). This type of problem falls within the so-called City Logistics problems and has been the subject of extensive study in recent years (Crainic, 2008; Wang et *al.* 2014, Taniguchi, 2015; Taniguchi et *al.*, 2016, Taniguchi et *al.*, 2020, Nathanail et *al.*, 2021). A lot of attention has been paid to the study of delivery systems, capable of reducing the negative impacts of urban distribution (Kiba-Janiak et *al.*, 2021). Several studies in the literature, consider parcel locker as last mile delivery system to rationalize deliveries in urban areas, i.e., the use of collection points equipped with lockers to store the objects that users have ordered (Allen et *al.* 2007, Carotenuto et *al.*, 2018, Buldeo Rai et *al.* 2019, van Duin et *al.* 2020, Schnieder and West. 2020, Enthoven

* Corresponding author. Tel.: +39-064-993-7326; fax: +39-064-404-306.
E-mail address: carotenuto@iac.cnr.it

Peer-review under responsibility of the scientific committee of the 24th EURO Working Group on Transportation Meeting.

et *al*. 2020). Furthermore, and more importantly, parcel lockers can be done without time restrictions (typically lockers are accessible 24 hours a day, 7 days a week) with lockers being located in strategic positions, where consumers are not obliged to make long detours from the usual routes. Many previous authors compared home delivery and parcel lockers solutions, highlighting the positive impacts of the latter, in terms of reduced travelled distances and polluting emissions. However, results highly depend on assumptions in evaluation procedures (Schnieder et *al.* 2021) and site-specific conditions, like the locations of lockers (Prandtstetter et *al.* 2021); moreover, several studies do not take the movement of customers into account (Iwan et *al.* 2015, Jiang et *al.* 2019) or do not consider congestion effects on road networks (Jiang et *al.* 2019, Schnieder et *al.* 2021).

The present work describes a delivery model based on small-town collection centres that can be located in sites frequently visited by users for other reasons. It improves the methodology and the results reported in a previous work (Carotenuto et *al.*, 2018), by considering that additional trips might be carried out by customers to pick up parcels at Lockers, thereby increasing traffic and emission, and potentially mitigating the advantages of the proposed delivery system (Liu et *al.*, 2019, Mommens et *al.*, 2021). The analysis was carried out considering that companies often are not the owner of the vehicles, but they manage the fleet of external courier company; we then evaluated the possibility to use different fleets of vehicles, with small or medium size. The first ones are more suitable to perform the home delivery, since many stops must be performed without having access to dedicated parking zones (like in many urban areas); in this case it is easier to park small size vehicles. The second ones, instead, can be more efficient considering the Locker delivery. Close to the lockers, indeed, there are parking areas dedicated to freight delivering; therefore, the use of medium-size vehicles can be more efficient in this case. To compare the approach of delivery to the consumer's home versus delivery to lockers, we used a "cluster first route second" mathematical heuristic approach that could guarantee a fair compromise between the quality of the solution and the computational time. For the clustering phase we propose a new model, while the routing phase consists in solving an instance of the Traveling Salesman Problem (TSP) for each generated cluster. The proposed approach allows us to evaluate a saving indicator (km travelled) between the two delivery systems (direct delivery to the end user and delivery to city collection centres or lockers) and a pollution indicator derived directly from the latter. In particular, many scenarios were generated, each of them considering different number of customers' individual trips towards Lockers, in order to define the sustainability degree of the adopted city logistics scheme. The entire procedure was applied to a real case in the town of Dolo (Italy).

2. Methodology

2.1. The Multi-Depot Capacitated Vehicle Routing Problem

Planning both home delivery and parcel locker can be modelled by a Multi-Depot Capacitated Vehicle Routing Problem (MDCVRP). Our approach is to deal with the MDCVRP heuristically, by subdividing it into two phases, applying a math-heuristic approach to have a good-quality solution in a short time amount. The result of the first phase is a partition of the set of demand requests into clusters to be served by a single vehicle starting from a specific depot, while the second phase seeks to define the optimal route to serve each subset. Therefore, in the second phase, for each generated cluster it is only necessary to solve a TSP instance over the delivery points related to the identified cluster and the depot used to serve it. To obtain the final solution we solve the TSP's considering the Dantzig et *al.* (1954) model with the subtour elimination constraints proposed by Desrochers and Laporte (1990). The model adopted for the first clustering phase is described below.

Let $V_C = \{v_1, \ldots, v_n\}$ be the set of customers (clients or lockers) and $V_D = \{v_{n+1}, \ldots, v_{n+m}\}$ the set of depots. We consider the (complete) directed graph $G = (V, A)$, where $V = V_C \cup V_D$ is the set of nodes, and $A = V \times V$ is the set of arcs. We denote with c_{ij} the distance cost (length or travel time) to go from node i to node j, with d_i the demand of customer i, and with Q the (loading) capacity of each vehicle. We assume that K_O vehicles are available at depot $o \in V_D$. For clustering purpose, we consider a set V_{VC} of virtual centers and, for the sake of simplicity, we assume $V_{VC} = V$, introducing set V' containing set V_{VC} and a certain number of copies of each virtual centre.

We introduce two sets of binary variables: h_{jo}, which is equal to 1 if a cluster of customers centred in virtual centre $j \in V'$ and served from depot $o \in V_D$ is generated, and 0 otherwise; w_{ijo}, which is equal to 1 if customer $i \in V_C$ is assigned to the cluster represented by the couple virtual centre $j \in V'$ and depot $o \in V_D$, and 0 otherwise. Then the clustering problem is formulated as follows:

$$min\ z = \sum_{o \in V_D} \sum_{j \in V'} (c_{oj} + c_{jo}) h_{jo} + \sum_{i \in V_C} \sum_{o \in V_D} \sum_{j \in V'} \frac{1}{2} [(c_{ij} + c_{ji}) + (c_{io} + c_{oi}) - (c_{jo} + c_{oj})] \quad (1)$$

$$\sum_{j \in V'} \sum_{o \in V_D} w_{ijo} = 1 \qquad \forall\, i \in V_C \quad (2)$$

$$\sum_{o \in V_D} h_{jo} \leq 1 \qquad \forall\, j \in V' \quad (3)$$

$$\sum_{j \in V'} h_{jo} \leq K_o \qquad \forall\, o \in V_D \quad (4)$$

$$\sum_{i \in V_C} \sum_{o \in V_D} d_i\, w_{ijo} \leq Q \sum_{o \in V_D} h_{jo} \qquad \forall\, j \in V' \quad (5)$$

$$w_{ijo} \leq h_{jo} \qquad \forall\, i \in V_c, j \in V', o \in V_D \quad (6)$$

$$w_{ijo} \in \{0,1\} \qquad \forall\, i \in V_c, j \in V', \quad o \in V_D \quad (7)$$

$$h_{jo} \in \{0,1\} \qquad \forall\, j \in V', o \in V_D \quad (8)$$

Constraints (2) ensure that each customer is assigned exactly to one generated cluster. Constraints (3) and (4) respectively guarantee that each virtual centre can be assigned to one depot at most and that, for each depot, the number of used vehicles cannot exceed the number of available vehicles. Constraints (5) ensure that the total demand of customers assigned to the same cluster cannot exceed vehicle capacity Q. Lastly, constraints (6) imply that a customer can be assigned only to a generated cluster.

To evaluate the effectiveness of the clustering phase, we consider the objective function (1) that generalizes the one proposed in Carotenuto et *al*. (2018). The objective function consists of two terms: with the first we evaluate the total round-trip distance cost to go from depots to virtual centres, over the generated clusters; while the second term is used to estimate the additional total distance cost to serve customers. In more detail, the additional cost to serve a customer is evaluated assuming to visit it diverting as less as possible from the main route depot-virtual centre-depot. To assess the additional cost, we considered the mean distance costs between three couple of nodes: customer-virtual centre, customer-depot, and depot-virtual centre; we sum the first two amounts and then subtract the last one.

Respect to the previous work, we evaluated more precisely the impact of the trips between customers and the virtual centre, formerly evaluated considering the distance round-trip. Moreover, we also consider the maximum number of vehicles allowable for the daily delivery.

2.2. The transportation assignment problem

In order to obtain realistic costs among nodes, a transportation assignment problem has to be solved. In particular, the aim is to estimate vehicle flows and travel conditions (e.g. times) for each component of a transportation network (road link connecting two nodes), which result from Origin-Destination demand trips, path choice behaviours, and the mutual interactions between transportation supply and demand (Cascetta, 2009). To reach this target, an assignment model based on Deterministic User Equilibrium is adopted. According to this approach, the problem is solved by finding the equilibrium of the system, i.e., a configuration in which demand, path and link flows are consistent with the costs that they generate in the network (Cascetta, 2009). Moreover, the method assumes that, to reach their destinations, users choose paths having the minimum averaged costs. In addition, the network is considered as congested, where link costs depend on traffic flows following the Bureau of Public Roads (BPR) delay functions, which are calibrated for each road segment.

In this way, travel time and distance are obtained for each link of the network. These results are used for two purposes: estimating the cost for each pair of nodes as input for the MDCVRP, and calculating vehicle polluting emissions to evaluate the sustainability of the analysed system.

2.3. Scenario building

In order to reach the aim of the paper, several scenarios are generated. The first one is considered as reference scenario, in which there are direct shipments from the depots to the end-user zones. The alternative scenarios concern the adoption of Lockers; however, in these cases, since users might decide to perform dedicated trips to reach the pick-up points, both shipments from depots to Lockers and additional customers' trips are considered. Specifically, to test the effects of these potential new trips, different scenarios are tested with different dedicated trip production rates.

To generate these scenarios, we considered different rates of dedicated individual trips towards lockers, ranging from 0% to 30% of the total delivery demand by 10% steps. For each scenario, polluting emissions both from delivery vehicles and dedicated trips towards lockers were estimated. Specifically, following the procedure proposed by the European Environment Agency (EMEP/EEA, 2019). results from the traffic simulation, and the characteristics of the adopted delivery vehicles and circulating users' vehicles fleet were included as input. To increase the realism of the application and the reliability of results, travel habits of users were considered. In particular, the number of additional trips on motorized means towards lockers was estimated by analysing the actual modal split related to different travel distances reported by residents in the study area.

For each scenario, traffic assignment is applied, the MDCVRP is solved, and polluting emissions are estimated, thus evaluating the sustainability of the system in many realistic conditions.

3. Case study

The previously described methodology was applied to a real case in the town of Dolo (north-eastern Italy) with about 15000 inhabitants in 24 square kilometres. Fig. 1 displays the location of the 65 considered user zones, the 2 depots and the 19 lockers.

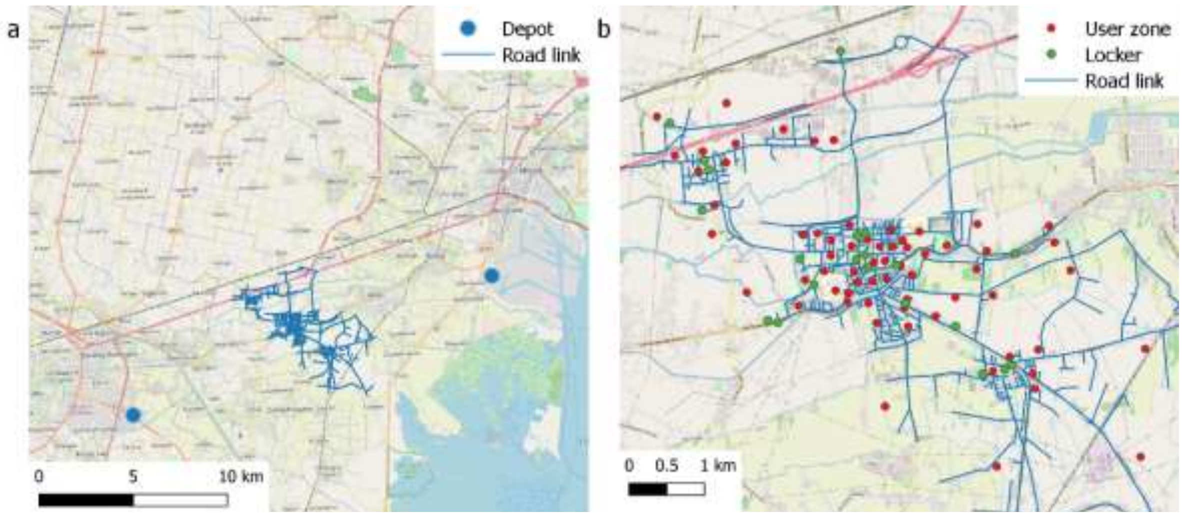

Fig. 1. (a) Location of depots; (b) Location of user zones and lockers.

For each user zone, the average number of deliveries on a weekday was estimated by considering characteristics of the population and data about online purchases in the area. The location of lockers was defined by identifying potential attractor points which are likely to be often reached by individuals (e.g., a train station, a supermarket, a hospital). In order to define the number of deliveries associated to each locker, we assumed as user behavioural model, that a customer chooses the locker closest to him (house, work, etc.) and that lockers have sufficient capacity. We compare the use of two different types of real vehicles. The first ones with a small capacity of 83 loading units, used preferably for the home delivery; the second ones with a medium capacity of 200 loading units, to serve the Lockers. In both cases, one customer or one locker is served by a single vehicle from a single depot.

The transportation network consists of 2435 one-way links and 1143 nodes. Traffic simulation was performed by assigning a previously estimated Origin-Destination matrix containing about 15750 trips on motorized vehicles carried out during the 2-hour morning peak period, thus evaluating the worst conditions of the system.

4. Results and discussion

In this paragraph we will analyse the solutions obtained with our method on a real case study comparing the results with the ones obtained using a similar approach previously proposed in the literature. We test both models developing the mathematical formulations of both phases using AMPL with the commercial solver Gurobi.

First, home delivery solutions are compared with a lockers delivery solution without including additional individuals' dedicated trips. In particular, Tables 1 and 2 compare the results obtained after the clustering and routing phases with the proposed math-heuristic (MH2) and the one presented in the literature (MH1) (Carotenuto et *al*. 2018) provided by the two fleets considering the home and lockers delivery, respectively. We then evaluate the percentage gap between the solution found with the two models in terms of distance and pollution (%gap = 100*(MH1-MH2)/MH1). The rows correspond to the number of vehicles used to fulfil the total demand, the distance travelled by the fleet (in kilometres) and the CO2 emissions (in kilogram).

Table 1 – Home delivery solutions

	Fleet of small vehicles (Q = 83)			Fleet of medium vehicles (Q = 200)		
	MH1	MH2	%gap	MH1	MH2	%gap
N. of vehicles	6	6		4	3	
Distance (km)	185.75	183.74	1.083	140.19	118.78	15.267
CO2 (kg)	36.283	35.889	1.086	30.614	25.753	15.878

Table 2 – Locker delivery solutions

	Fleet of small vehicles (Q = 83)			Fleet of medium vehicles (Q = 200)		
	MH1	MH2	%gap	MH1	MH2	%gap
N. of vehicles	7	7		3	3	
Distance (km)	166.21	165.90	0.185	79.03	78.53	0.634
CO2 (kg)	32.466	32.406	0.185	17.619	17.360	1.470

The tables highlight the improvement obtained with the new heuristic method in both scenarios and regardless of the fleet of vehicles used to perform the delivery. These improvements are present both in terms of kilometres travelled and in terms of reducing pollutions. As regards the fleet of small vehicles we provide slight improvements ranged between 0.185% and 1.086%. With the new clustering model solutions are improved possibly also with respect to the number of used vehicles. This happens, for example, for the home delivery case with medium-size vehicles, where the used vehicles are reduced from 4 to 3. Moreover, for this case we also experimented a large improvement (more than 15%) in terms of both travelled distance and CO2 emissions. Regarding the impact of the two delivery scenarios, we may note that with the fleet of small vehicles, the CO2 emissions decreased more than 9% with both models. Instead, a most striking reduction is obtained with the fleet of medium vehicles; in this case we obtained a reduction of over 32%; passing from 30.614kg to 17.619kg with the model MH1 and from 25.753kg to 17.360kg with MH2.

Finally, to complete the analysis we also considered polluting emissions generated by the dedicated trips made by the customers for going to lockers (Table 3). As mentioned above, to evaluate the impact of these movements, we assume that each customer chooses the closest locker.

Table 3 – CO2 emissions due to dedicated trips

% of dedicated trips	CO2 (kg)
30%	11.12
20%	7.41
10%	3.71

Figure 2 shows the impact of the dedicated trips with different fleets of vehicles (with small and medium capacity) and the two models (MH1 and MH2). The blue columns correspond to the pollution due to the customer home deliveries, and the red ones to locker deliveries, the remaining columns refer to the scenarios with the dedicated trips carried out by the customers when going to the lockers to pick up their parcels. Then, the last three columns represent the total emissions evaluated by summing the CO2 due to the depots-lockers delivery and the customers-lockers trips.

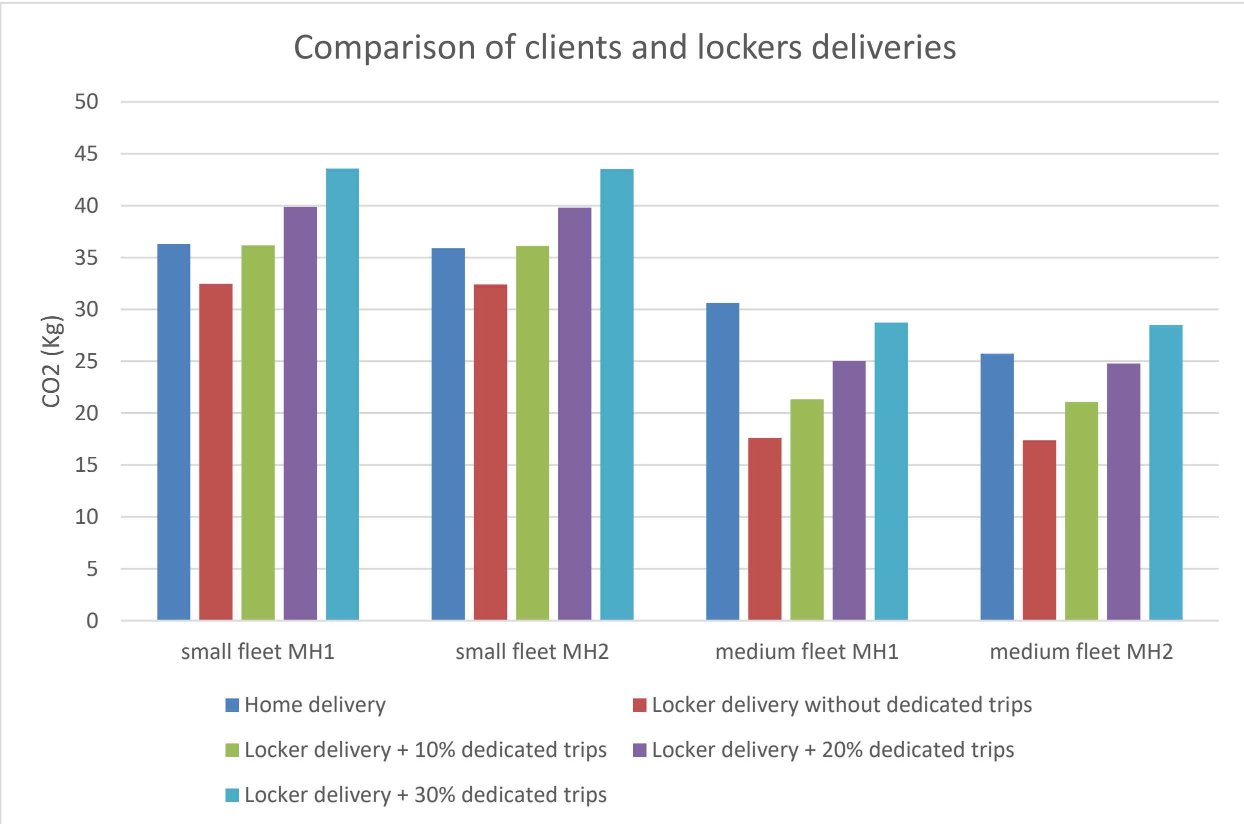

Figure 2 – Analysis of sustainability of the proposed city logistics scheme.

When the fleet of small vehicles is used, the benefits in term of pollution reduction occur only if at most 10% of customers carries out dedicated trips (green columns). With the medium fleet, instead, even with dedicated trips between 20% and 30% we obtain benefit using lockers. Finally, the new model with the medium fleet gives the best performance.

Overall, results in Figure 2 highlight the potential environmental benefits of lockers against home delivery, however these advantages might be mitigated by fleet composition and the number of dedicated customers' trips. Therefore, the optimization of vehicle type and the choice of lockers' location are found to be fundamental factors affecting the sustainability of the city logistics system.

5. Conclusions

This work analyses the delivery problem related to the e-commerce field. Two different strategies of delivery are proposed: the home delivery and the delivery to city collection centres or lockers. To carry out deliveries we considered two homogeneous fleets of vehicle, with small and medium capacity. A clustering first route second strategy is defined to solve the problem, introducing a new clustering model. After the first phase a TSP instance is solved, for each generated cluster, to define the sequence of visit.

For both strategies, we compared the results obtained using the new proposed model with those produced with a model previously presented in the literature. The results corroborate the introduction of the new model, in fact, under all scenarios considered, the solutions provided by the new model outperform those obtained with the competing model, regardless of the fleet. Finally, the sensitivity analysis shows that the use of lockers can reduce the pollution even considering the dedicated trips, between 20% and 30%, of customers to the lockers.

By analysing the results, a possible future research may concern the use of split delivery models to reduce the CO2 emissions and further optimize the usage of the fleet. Moreover, additional pollutants may be considered (such as CO, NOx and PM109, which may be added in the objective function of the Multi-Depot Capacitated Vehicle Routing Problem.

References

Ambrosino G., Sassoli P., Bielli M., Carotenuto P., Romanazzo M. (1999), "A modeling framework for impact assessment of urban transport systems", *Transp. Res. D*, 4(4): 73-79.

Buldeo Rai, H., Verlinde, S., Macharis, C. (2019). City logistics in an omnichannel environment. the case of brussels. *Case Studies on Transport Policy*, 7(2): 310-317

Carotenuto P., Gastaldi M., Giordani S., Rossi R., Rabachin A., Salvatore A. (2018), " Comparison of various urban distribution systems supporting e-commerce. Point-to-point vs collection-point-based deliveries", *Transportation Research Procedia*, 30: 188-196.

Cascetta, E., 2009. "Transportation systems analysis: models and applications", Second Edi. ed. Springer Science & Business Media, New York.

Crainic T. G. (2008), *City Logistics*, CIRRELT Report 2005-25, 1-46.

Dantzig G, Fulkerson D, Johnson S (1954) Solutions of a large-scale traveling-salesman problem. *Oper Res* 2(4): 393–410

Desrochers M, Laporte G (1990) Improvements and extensions to the Miller–Tucker–Zemlin subtour elimination constraints. *Oper Res Lett* 10(1): 27–36

EMEP/EEA, 2019. Air pollutant emission inventory guidebook 2019.

Enthoven, D. L. J. U., Jargalsaikhan, B., Roodbergen, K. J., uit het Broek, M. A. J., Schrotenboer, A. H. (2020). The two-echelon vehicle routing problem with covering options: City logistics with cargo bikes and parcel lockers. *Computers and Operations Research*, 118

Iwan S., Kijewska K., Lemke J. (2015) "Analysis of Parcel Lockers' Efficiency as the Last Mile Delivery Solution - The Results of the Research in Poland", *Transp. Res. Procedia*, 12: 644-655.

Jiang L., Chang H., Zhao S., Dong J., Lu W. (2019) "A Travelling Salesman Problem with Carbon Emission Reduction in the Last Mile Delivery", *IEEE Access*, 7: 61620-61627.

Kiba-Janiak, M., Marcinkowski, J., Jagoda, A., Skowrońska, A. (2021). Sustainable last mile delivery on e-commerce market in cities from the perspective of various stakeholders. literature review. *Sustainable Cities and Society*, 71

Liu C., Wang Q., Susilo Y. O. (2019) "Assessing the impacts of collection-delivery points to individual's activity-travel patterns: A greener last mile alternative?", *Transp. Res. Part E Logist. Transp. Rev*, 121: 84-99.

Mommens, K., Buldeo Rai, H., van Lier, T., Macharis, C. (2021). Delivery to homes or collection points? A sustainability analysis for urban, urbanised and rural areas in belgium. *Journal of Transport Geography*, 94

Nathanail, E., Karakikes, I., Mitropoulos, L., Adamos, G. (2021). A sustainability cross-case assessment of city logistics solutions. *Case Studies on Transport Policy*, 9(1):219-240.

Prandtstetter, M., Seragiotto, C., Braith, J., Eitler, S., Ennser, B., Hauger, G., Steinbauer, M. (2021). On the impact of open parcel lockers on traffic. *Sustainability* (*Switzerland*), 13(2): 1-19

Ranieri, L., Digiesi, S., Silvestri, B., Roccotelli, M. (2018). A review of last mile logistics innovations in an externalities cost reduction vision. *Sustainability* (*Switzerland*), 10(3)

Schnieder M., West A. A. (2020) "Comparison of Time-Area Requirements of Parcel Lockers vs. Home Delivery: A Cyber-Physical System of Last Mile Delivery,"*2020 Forum on Integrated and Sustainable Transportation Systems (FISTS)*, pp. 298-303

Schnieder, M., Hinde, C., West, A. (2021). Sensitivity analysis of emission models of parcel lockers vs. Home delivery based on hbefa. *International Journal of Environmental Research and Public Health*, 18(12)

Taniguchi E. (editor), (2015). *City Logistics: Modelling, planning and evaluation*, Routledge – Francis and Tylor Group.

Taniguchi E., Thompson R.G., Yamada T. (2016). "New opportunities and challenges for city logistics". In Proceedings of the 9th International Conference on City Logistics, Tenerife, Canary Islands (Spain), 17-19 June 2015. *Transportation Research Procedia*, 12: 5–13.

Taniguchi, E., Thompson, R. G., Qureshi, A. G. (2020). Modelling city logistics using recent innovative technologies. *Transportation Research Procedia*, 46: 3-12.

Wang, X., Zhan, L., Ruan, J., J. Zhang (2014). How to Choose “Last Mile” Delivery Modes for E-Fulfillment. *Mathematical Problems in Engineering*, Vol. 2014, Article ID 417129, 11 pages.

van Duin J.H.R., Wiegmans B.W., van Arem B., van Amstel Y. (2020). From home delivery to parcel lockers: a case study in Amsterdam, *Transportation Research Procedia*, 46: 37-44.