A Novel Multi-Objective Two-Echelon Green Location-Routing Problem from a City Government Perspective

Rafael Aquino[1], Benjamín Barán[1], Fabio López-Pires[1,2], Fernando Sandoya[3], and Jorge Luis Chicaiza[4]
`raquinos@outlook.com`, `bbaran@pol.una.py`, `fabio.lopez@pti.org.py`, `fsandoya@espol.edu.ec`, `jorge.chicaiza@epn.edu.ec`

[1] Polytechnic School, National University of Asunción, San Lorenzo, Paraguay
[2] Itaipu Technological Park, Hernandarias, Paraguay
[3] Department of Mathematics, ESPOL Polytechnic University, Guayaquil, Ecuador
[4] Department of IT in Production and Logistics, Tech. Univ. Dortmund, Germany

Abstract. This work presents a novel two-echelon, multi-product, *Green* Location-Routing Problem formulation, from a city government perspective, for the optimization of five objective functions, two of them related to pollutant emissions minimization. Additionally, it is demonstrated that the use of city distribution centers (CDCs), compared to direct shipping, is a better strategy for a congested city as Asunción in Paraguay. Initial experimental results using an exhaustive search alternative prove a 5-21% reduction of carbon monoxide (CO) emissions, a 8-23% reduction of carbon dioxide (CO_2) emissions and a 8-17% reduction in shipping costs, given an initial investment in CDCs.

1 Introduction

The Location-Routing Problem (LRP) is an NP-Hard combinatorial optimization problem [12] considered as an extension of the well known Vehicle Routing Problem (VRP) [7]. The main difference between them is that the LRP optimizes not only routing but also depot placement [12].

The *single-echelon* LRP considers a set of potential depots and a set of customers. In a *two-echelon* (2E) LRP, the *first echelon* is composed of manufacturers and depots (also called *satellites* or *city distribution centers*, *CDCs* [2])[5], while the *second echelon* is composed of depots and customers. At first, goods are transported from manufacturers to depots, and distributed from there to the final customers. Figure 1 shows an example of a *two-echelon* LRP where α and β, located at the top, represent manufacturers from which goods are shipped to depots A and B. Customers 1 to 5 are served from depots A and B. In particular, Figure 1 shows a possible solution where two vehicles provide all needed goods to the 5 customers, using only depot A, avoiding the cost of opening depot B.

---

[5] The term *CDC* will be preferred through this document.

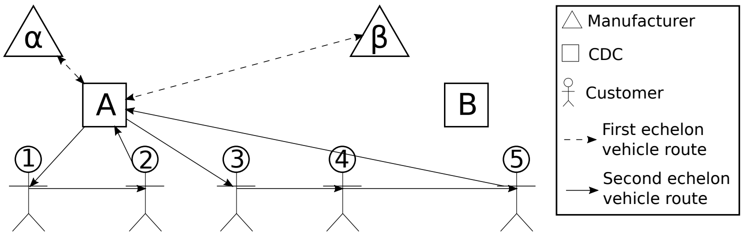

Fig. 1: An example of a two-echelon LRP. Note that the CDC B is not used.

Shipping goods directly from factories to final customers using a fleet of heavy vehicles might not be a suitable strategy for cities with traffic congestion issues, such as Asunción in Paraguay. Trucks may not be able to move through certain zones of the city because of safety or legal reasons, space restrictions or environmental concerns. Furthermore, customers generally need small quantities of products, therefore, using large vehicles may not be a cost-effective solution.

A working vehicle emits carbon monoxide (CO) and carbon dioxide (CO_2), among many others pollutants [9]; therefore, road traffic is one of the major sources of *greenhouse gas* [5]. A growing research line, known as "Green Logistics", aims to minimize harmful environmental effects of transportation [4].

Most real-life decisions cannot be accurately modeled with a single objective function [10]. A large vehicle fleet can reduce delivery time, but would increase emission of pollutants. Smaller vehicles fleets usually mean less investments and environmental impact, but these objectives are measured in different units. In this context, a Multi-Objective formulation seems the most adequate approach when modeling objectives which are contradictory or of disjoint nature.

Given that many objective functions have been studied in the literature for problems with similar characteristics, a reasonable approach for solving a Two-Echelon Green LRP would be Multi-Objective Optimization. Thus, the main contributions of this work are:

I. A novel *Green* formulation of the 2E Multi-Product LRP, from a city government perspective, considering the minimization of five objective functions, formally presented in Table 3.
II. Initial experimental results showing the benefits of using CDCs, helping city government to improve quality of life.

2 Related Works and Motivation

Most papers deal with single objective models, but there is a trend of increasing attention towards multi-objective LRPs [3]. In [10], Lopes et al. (2013) recognize that most real-life decisions cannot be accurately modeled with a single objective function. Inspired in [10], Table 1 provides a summary of different main objectives considered so far in multi-objective LRPs, grouped by identified categories.

In [1] Caballero et al. (2007) consider a five-objective LRP with uncapacitated depots and describe an application concerning the installation of waste incineration facilities in southern Spain. The objectives include social rejection to vehicle routes, rejection to facility installation and cost minimization functions.

Table 1: Summary of the main objective functions addressed in multi-objective LRP models, inspired in [10].

Category	**Objective**
Cost minimization	Number of depots Facility installation cost Transportation cost Travel distance Travel time Transportation load (weight per distance) Distance traveled by customers accessing depots Total monetary costs
Environmental aspects	Transportation risk/nuisance minimization Minimization of risk caused by proximity to facilites Minimization of risk derived from transportation and location Maximization of population satisfaction level /demand served
Equity distribution (minimization objectives)	Maximum transportation risk Maximum proximity to obnoxious facilites Maximum total risk Work time imbalance Load imbalance Unmet customer demand
Others	Other objectives regarding a specific model

In [13], Tavakkoli-Moghadam et al. (2010) present a bi-objective LRP with optional customers. The first objective aims to minimize the total system costs. The second objective maximizes the total served customer demand.

A bi-objective two-echelon, multi-period LRP with time windows for optimizing economical and environmental objectives in a perishable food supply chain network is introduced in [6]. The first objective function minimizes the total cost of a solution while the second objective minimizes the total environmental impact. To the best of authors' knowledge, this is the only Two-Echelon LRP model that can be considered as *Green*.

Govindan et al. [6] (2014) consider environmental impact of facilities and manufacturers as well as transportation: every node and every arc have an environmental impact value. The arc value is not related to the vehicle fleet, so it does not properly model the effects of vehicle fleet on the environment as vehicle emissions vary significantly depending on vehicle type, as described in [9]. As a novelty, the model proposed in the present work explicitly takes this variability into account by considering different emission levels depending on vehicle type.

None of the models reviewed in the present section ([6], [13] and [1]) consider multiple products, so they are better suited to the needs of a particular business, rather than a city government. On the contrary, the model proposed in this work considers that customers have multiple-product demands, and aims to be specially useful for city-governments when planning and running a city.

3 Proposed Multi-Objective Multi-Product Green 2E-LRP

Table 2: Parameters and decision variables used in the proposed formulation.

(a) Model parameters

Parameter		Description
First Echelon (α is used as super-script)	$t^{\alpha}_{l,i}$	Travel time between nodes $l, i \in (L \cup I)$.
	$c^{\alpha}_{l,i}$	Distance between nodes $l, i \in (L \cup I)$.
	$F^{\alpha}_{l,i}$	Fixed delivery cost from manufacturer $l \in L$ to CDC $i \in I$.
	V^{α}_{l}	Cost per delivered unit (e.g., per kg) from manufacturer $l \in L$.
	C^{α}	Vehicle pperating cost by distance unit (e.g., per km).
	Q^{α}	Maximum capacity of the vehicles.
	T^{α}	Maximum travel time of the vehicles.
	D^{α}	Maximum travel distance of the vehicles.
	E^{α}_{p}	Vehicles' emission factor of pollutant $p \in P$.
	U^{α}_{i}	Unload time required by the vehicles at CDC $i \in I$.
Second Echelon (β is used as super-script)	$t^{\beta}_{i,j,k}$	Travel time between nodes $i, j \in (I \cup J)$, of vehicle $k \in K$.
	$c^{\beta}_{i,j}$	Distance between nodes $i, j \in (I \cup J)$.
	$F^{\beta}_{i,j}$	Fixed delivery cost from CDC $i \in I$ to customer $j \in J$.
	V^{β}_{i}	Cost per delivered unit (e.g., per kg) from CDC $i \in I$.
	C^{β}_{k}	Operating cost by distance unit (e.g., per km), of vehicle $k \in K$.
	Q^{β}_{k}	Maximum capacity of vehicle $k \in K$.
	T^{β}_{k}	Maximum travel time of vehicle $k \in K$.
	D^{β}_{k}	Maximum travel distance of vehicle $k \in K$.
	$E^{\beta}_{k,p}$	Emission factor of vehicle $k \in K$, of pollutant $p \in P$.
	$U^{\beta}_{k,j}$	Unload time at customer $j \in J$, required by vehicle $k \in K$.
Other variables	O_i	Establishing cost of CDC $i \in I$.
	S_i	Maximum storage capacity of CDC $i \in I$.
	$d_{i,l}$	Demand of customer $j \in J$, of product of manufacturer $l \in L$.

(b) Decision variables that define a specific solution X

Variable		Description
First Echelon	$x^{\alpha}_{l,i,r}$	Equals 1 if node $l \in (L \cup I)$ immediately precedes node $i \in (L \cup I)$ on the route of vehicle $r \in R$, and 0 otherwise.
	$z^{\alpha}_{l,i}$	Equals 1 if CDC $i \in I$ is served from manufacturer $l \in L$, and 0 otherwise.
	$w^{\alpha}_{l,i,r}$	Fraction of the demand of CDC $i \in I$, of products from manufacturer $l \in L$, transported by vehicle $r \in R$. $\left(w^{\alpha}_{l,i,r} \in [0,1]\right)$.
Second Echelon	$x^{\beta}_{i,j,k}$	Equals 1 if node $i \in (I \cup J)$ immediately precedes node $j \in (I \cup J)$ on the route of vehicle $k \in K$, and 0 otherwise.
	y_i	Equals 1 if a CDC is established at a CDC site $i \in I$, otherwise 0.
	$z^{\beta}_{l,i}$	Equals 1 if customer $j \in J$ is served from CDC $i \in I$, otherwise 0.

Given a set of manufacturers, a set of potential CDC sites and a set of customers with known demand of several products, it must be determined: which CDCs to establish, assignment of customers to CDCs, vehicle tours for serving the customers' demand (second echelon) and vehicle tours for supplying CDCs with products from manufacturers (first echelon). The solution to the problem must be such that: demand is satisfied without exceeding vehicle capacities, maximum route length and duration, while CDC capacities are not exceeded.

With respect to the vehicles, the proposed model assumes that: *a*) there is no limit on manufacturer production capacity and *b*) every manufacturer produces a single product, and every product is unique to its manufacturer.

Assumptions about vehicles are: *a*) an homogeneous vehicle fleet is considered at the first echelon, *b*) an heterogeneous vehicle fleet is considered at the second echelon, *c*) only closed tours are considered; they must begin and end at the same facility, *d*) two pollutants are considered for this work, carbon monoxide (CO) and carbon dioxide (CO_2), although the model provides flexibility to consider more pollutants if necessary, *e*) split delivery[6] is allowed only at the first echelon and *f*) no time window are considered at any level.

The sets used in the proposed model are:

1) L, the set of manufacturers,
2) I, the set of CDCs,
3) J, the set of customers,
4) R, the set of first-echelon vehicles,
5) K, the set of second-echelon vehicles and
6) P, the set of pollutants considered.

The parameters used in the proposed model and decision variables that define a specific solution X are presented in Table 2. Due to space limitations, objective functions and problem constraints are presented without a detailed explanation in Tables 3 and 4 respectively.

4 Benefits on using 2E over single-echelon distribution

The main stakeholders of a logistic system, are: *a*) the manufacturers, *b*) the city government, *c*) the vehicle fleet operator and *d*) the customers.

On a *Two-echelon distribution scheme*, manufacturers are mostly interested in the cost of shipping goods from their facilities to the CDCs. The city government is responsible for establishing and running CDCs, therefore it is interested in the CDC establishing cost. City governments are also interested in the environmental aspects of a logistics system, namely air pollution caused by delivery vehicles. Vehicle operators are responsible for transportation. They are concerned with the usage and wear of their fleet, and they are interested in being profitable; they are looking at total delivery value minus total vehicle operational costs. Finally, the customers are focused on the delivery ocst that vehicle operators charge.

On a *single-echelon distribution scheme*, given that no CDCs are in use, large trucks will also be used to distribute customer demand. A fleet of this characteristics is generally more expensive in terms of monetary and environmental costs, therefore: *a*) the vehicle fleet would suffer greater usage wear as a result of

---

[6] Split delivery: the demand of one customer may be satisfied by more than one vehicle.

Table 3: Objective functions used in the proposed formulation.

CDC establishing cost

This cost is calculated as the sum of the establishing cost of every opened CDC.

$$F_1(X) = \sum_{i \in I} y_i \cdot O_i. \tag{1}$$

Vehicle operating costs

A vehicle's operating cost is calculated as the product between the total traveled distance and its cost factor (C^α at the first echelon, C^β_k at the second). The total operating cost is given as the sum of all vehicles' individual operational costs.

$$F_2(X) = \sum_{r \in R} \sum_{l \in (L \cup I)} \sum_{i \in (L \cup I)} c^\alpha_{l,i} \cdot x^\alpha_{l,i,r} \cdot C^\alpha + \sum_{k \in K} \sum_{i \in (I \cup J)} \sum_{j \in (I \cup J)} c^\beta_{i,j} \cdot x^\beta_{i,j,k} \cdot C^\beta_k. \tag{2}$$

The first term corresponds to the first-echelon operating cost, while the second corresponds to the second-echelon operating costs.

Carbon monoxide (CO) and carbon dioxide (CO_2) emissions

A vehicle's emissions of a given pollutant $p \in P$ are calculated as the product between the total traveled distance and an emission factor (which is usually given in grams per kilometer) E^α_p at the first echelon and $E^\beta_{p,k}$ at the second echelon. The total emissions of a given pollutant are given as the sum of all individual vehicles' emissions.

$$F_3(X) = \sum_{r \in R} \sum_{l \in (L \cup I)} \sum_{i \in (L \cup I)} c^\alpha_{l,i} \cdot x^\alpha_{l,i,r} \cdot E^\alpha_1 + \sum_{k \in K} \sum_{i \in (I \cup J)} \sum_{j \in (I \cup J)} c^\beta_{i,j} \cdot x^\beta_{i,j,k} \cdot E^\beta_{k,1}. \tag{3}$$

$$F_4(X) = \sum_{r \in R} \sum_{l \in (L \cup I)} \sum_{i \in (L \cup I)} c^\alpha_{l,i} \cdot x^\alpha_{l,i,r} \cdot E^\alpha_2 + \sum_{k \in K} \sum_{i \in (I \cup J)} \sum_{j \in (I \cup J)} c^\beta_{i,j} \cdot x^\beta_{i,j,k} \cdot E^\beta_{k,2}. \tag{4}$$

E^α_1 and $E^\beta_{k,1}$ corresponds to CO emission factors for the first and second echelon, respectively, while E^α_2 and $E^\beta_{k,2}$ to CO_2 emission factors for the first and second echelon, respectively.

Observation: Other pollutants can be added to the set P as necessary, and then the corresponding objective functions will follow the form of equations (3) and (4), in order to consider those new pollutants. The model provides enough flexibility to suit the needs of different users.

Shipping costs

The shipping costs are composed of: *a*) variable costs, which are calculated as the product between total shipped quantity of goods and an unitary delivery cost and *b*) fixed costs, which are given as fixed for each manufacturer-CDC and CDC-customer pair.

$$\begin{aligned} F_5(X) = {} & \sum_{l \in L} \sum_{i \in I} \left(\sum_{j \in J} d_{j,l} \cdot z^\beta_{i,j} \right) \cdot z^\alpha_{l,i} \cdot V^\alpha_l + \sum_{i \in I} \sum_{j \in J} \left(\sum_{l \in L} d_{j,l} \right) \cdot z^\beta_{i,j} \cdot V^\beta_i \\ & + \sum_{l \in L} \sum_{i \in I} z^\alpha_{l,i} \cdot F^\alpha_{l,i} + \sum_{i \in I} \sum_{j \in J} z^\beta_{i,j} \cdot F^\beta_{i,j}. \end{aligned} \tag{5}$$

The first two terms of Equation 5 corresponds to the first and second-echelon total variable costs, respectively, while the last two corresponds to the total fixed cost of the first and second echelons, respectively.

longer trips from manufacturers to final customers, *b*) a heavy vehicle fleet has a greater operational cost, so customers may pay a higher price for delivery and *c*) the city government will not invest in establishing CDCs thus saving money. Moreover, the environmental impact caused by the vehicle fleet emissions will

Table 4: Constraints used in the proposed formulation.

Vehicle capacity

At the first echelon, the sum of individual demands of the served customers of each CDC visited in a route must not exceed the vehicle's maximum capacity Q^α:

$$\sum_{i\in I}\sum_{l\in L} w_{l,i,r} \cdot \left(\sum_{j\in J} d_{j,l} \cdot z_{i,j}^{\beta}\right) \leq Q^\alpha, \quad \forall r \in R. \tag{6}$$

At the second echelon, every vehicle must be able to carry the total demand, of all requested products, of every visited customer:

$$\sum_{j\in J}\sum_{i\in(I\cup J)}\sum_{m\in L} d_{j,m} \cdot x_{i,j,k}^{\beta} \leq Q_k^{\beta}, \quad \forall k \in K. \tag{7}$$

Route length

At the first echelon, the length of every vehicle route $r \in R$ must not exceed the vehicle's limit D^α

$$\sum_{l\in(L\cup I)}\sum_{i\in(L\cup I)} c_{l,i}^{\alpha} \cdot x_{l,i,r}^{\alpha} \leq D^\alpha, \quad \forall r \in R. \tag{8}$$

At the second echelon, the length of every vehicle route $k \in K$ must not exceed the vehicle's limit D_k^α

$$\sum_{i\in(I\cup J)}\sum_{j\in(I\cup J)} c_{i,j}^{\beta} \cdot x_{i,j,k}^{\beta} \leq D_k^{\beta}, \quad \forall k \in K. \tag{9}$$

Route Duration

A route's total duration, at each echelon, is given as the sum of the time spent unloading goods at every node, and the time spent traveling node to node. The route's total duration must not exceed the vehicle's limit T^α at the first echelon

$$\sum_{i\in I}\sum_{l\in(L\cup I)} U_i^{\alpha} \cdot x_{l,i,r}^{\alpha} + \sum_{l\in(L\cup I)}\sum_{i\in(L\cup I)} t_{l,i}^{\alpha} \cdot x_{l,i,r}^{\alpha} \leq T^\alpha, \quad \forall r \in R, \tag{10}$$

and it must not exceed the vehicle's limit T_k^α, for every vehicle $k \in K$, at the second echelon

$$\sum_{j\in J}\sum_{i\in(I\cup J)} U_{k,j}^{\beta} \cdot x_{i,j,k}^{\beta} + \sum_{i\in(I\cup J)}\sum_{j\in(I\cup J)} t_{i,j,k}^{\beta} \cdot x_{i,j,k}^{\beta} \leq T_k^{\beta}, \quad \forall k \in K. \tag{11}$$

CDC Capacity

The total demand of all customers served from a CDC $i \in I$, must not exceed the CDC's maximum storage capacity S_i

$$\sum_{j\in J}\sum_{m\in L} z_{i,j}^{\beta} \cdot d_{j,m} \leq S_i, \quad \forall i \in I. \tag{12}$$

increase and the city traffic may suffer from heavy vehicles entering and parking in highly congested areas as downtown.

Two problem instances will be used for comparison. Instance 1 will consider the following: *a*) a single-echelon distribution scheme, with no CDCs and *b*) only heavy vehicles. On the other hand, Instance 2 will consider the two-echelon model above presented.

The two considered instances are built around the Gran Asunción area in Paraguay. Two big farms are chosen as manufacturers, two existing city supply centers as CDCs and five supermarkets as customers. Figure 1, presented in Section 1, shows an example using the given entities. $L = \{\alpha, \beta\}$ is the set of manufacturers, $I = \{A, B\}$ the set of CDCs and $J = \{1, 2, 3, 4, 5\}$ is the set of customers. As CO and CO_2 emissions are optimized, $P = \{\mathrm{CO}, \mathrm{CO_2}\}$ is the set of pollutants.

Due to space restrictions, data for the considered instances may be found online at `http://www.ug.edu.ec/mdp/fss/`.

Remarks on the test dataset are:

a) maximum allowed travel time per vehicle is set to 12 hours,
b) emission factor for the vehicles are taken from [8],
c) travel times are calculated using a reference speed of 25 km/h (value within normal urban speed range [8]),
d) it is assumed that all vehicles travel at the same speed and
e) shipping costs and unload times are directly proportional to the vehicle fleet operating costs and type (light or heavy).

An exhaustive search, that tests every possible solution to the problem, is performed for each considered instance in order to find an optimal, non-dominated solution set.

4.1 Experimental Results and Analysis

Table 5: Sets of optimal non-dominated solutions for the two instances. *Sol.* stands for *Solution*.

(a) Single-echelon instance solutions set S.

Sol. $s \in S$	**Objective functions**			
	$F_2(s)$	$F_3(s)$	$F_4(s)$	$F_5(s)$
s_1	225.07	171926.10	31.73	163.50
s_2	269.70	206016.54	38.02	148.20

(b) Two-echelon instance solutions set S^*.

Sol. $s^* \in S^*$	**Objective functions**				**Dominance over the set** S
	$F_2(s^*)$	$F_3(s^*)$	$F_4(s^*)$	$F_5(s^*)$	
s_1^*	167.78	123213.54	23.44	151.80	Dominates s_1. Not comparable to s_2.
s_2^*	212.95	157763.66	29.81	135.90	All solutions of S.
s_3^*	214.34	157187.36	29.86	135.90	All solutions of S.
s_4^*	172.72	121778.36	23.67	151.80	Dominates s_1. Not comparable to s_2.
s_5^*	220.57	155902.08	30.19	135.90	All solutions of S.
s_6^*	221.85	155268.48	30.23	135.90	All solutions of S.
s_7^*	177.08	119628.64	23.78	151.80	Dominates s_1. Not comparable to s_2.
s_8^*	222.65	154359.84	30.19	135.90	All solutions of S.
s_9^*	221.91	155223.12	30.23	135.90	All solutions of S.

The optimal, non-dominated solution sets for single and two-echelon instances are presented in Table 5. Given that a single-echelon solution will always have zero CDC establishing cost, the corresponding objective function ($F_1(X)$) is not included in the comparison. The set $S = \{s_1, s_2\}$ is formed from the single-echelon instance solutions, and the set $S^* = \{s_1^*, \cdots, s_9^*\}$ from the two-echelon

Table 6: An example of a objective function comparison of single-echelon solutions S with respect to the two-echelon solution $s_2^* \in S^*$. *Sol.* stands for *Solution*, *Op.* for *Operating* and *Shp.* for *Shipping*.

Sol.	**Objective functions**				**Op. cost saving (%)**	**Shp. cost saving (%)**	**Comment**
	$F_2(s^*)$	$F_3(s^*)$	$F_4(s^*)$	$F_5(s^*)$			
s_1	225.07	171926.10	31.73	163.50	6	17	Clearly, s_2^* is better in every considered objective.
s_2	269.70	206016.54	38.02	148.20	22	8	
s_2^*	212.95	157763.66	29.81	135.90	-	-	

instance solutions. Considering the Pareto dominance criteria [11], 6 of 9 solutions of S^* (roughly 67%) dominate the entire set of single-echelon solutions S. The rest of S^* are non-comparable to the solutions of S. It is worth emphasizing that no solution of S is optimal (non-dominated) in the Pareto sense, when considering objective functions $F_2(X)$ to $F_5(X)$.

The decision maker can choose one of the dominant solutions from the set S^*, such as s_2^*; in that case, a comparison of objective function values of solutions from set S with respect to s_2^* is presented in Table 6. According to the presented results, it can be seen that:

a) a *two-echelon* distribution scheme combined with a light-vehicle fleet for final-customer distribution produces less pollutant emissions, from 5 to 21% less carbon monoxide (CO) and from 8 to 23% less carbon dioxide (CO_2),

b) by using CDCs (*two-echelon* distribution), shipping costs are reduced by 8 to 17% and vehicle operating costs by 8 to 23%, according to data presented in Table 6 and

c) the CDCs establishing costs are a city government investment that will be amortized over time.

Finally, it is worth mentioning that in addition to the advantages of pollution reduction there exists possibilities of centralized traffic improvements, as well as a 8-17% saving in shipping costs that can be used to afford CDC costs while the other part is distributed among the stakeholders.

5 Conclusions and Future Work

This work presented a novel *Green* two-echelon, multi-product LRP model formulation, from the city government perspective, with five objective functions, two of them related to the minimization of pollutant emissions. This model provides enough flexibility to include additional objective functions that minimizes several other pollutant emissions. After comparing the single-echelon and two-echelon's best solutions, it was demonstrated that the use of CDCs is a better strategy than direct-shipping, considering economical and environmental aspects, with the potential of improving traffic (not quantitized in this work).

Once the CDCs are established in a city (the problem studied in the present article), new studies will be needed, based on the results of their operation, to establish new ones.

Emission factor is a simple yet valuable approach for modeling vehicle emissions. Vehicle emissions variations depend on many different factors such as speed, driving style, engine temperature and others. A model capable of taking these factors into account will be more accurate but more complex, and therefore, left for future work.

Another echelon can be added between CDCs and customers: loading/unloading bays, which are small street areas specially reserved for cargo vehicle parking.

Finally, given that an exhaustive search is not scalable for larger, real-world problems, it is worth mentioning that a Multi-objective Evolutionary Algorithm (MOEA) is under research to solve the proposed 2E-LRP from a city government perspective.

References

1. Caballero, R., Gonzalez, M., Guerrero, F.M., Molina, J., Paralera, C.: Solving a multiobjective location routing problem with a metaheuristic based on tabu search. application to a real case in andalusia. European Jrnl. of Op. Res. 177(3) (2007)
2. Cattaruzza, D., Absi, N., Feillet, D., González-Feliu, J.: Vehicle routing problems for city logistics. EURO Journal on Transportation and Logistics 6(1) (2017)
3. Drexl, M., Schneider, M.: A survey of variants and extensions of the location-routing problem. European Jrnl. of Op. Res. 241(2) (2015)
4. Eglese, R., Bektas, T., et al.: Green vehicle routing. Vehicle Routing: Problems, Methods, and Applications 18 (2014)
5. Esteves-Booth, A., Muneer, T., Kubie, J., Kirby, H.: A review of vehicular emission models and driving cycles. Jrnl. of Mech. Engineering Sci. 216(8) (2002)
6. Govindan, K., Jafarian, A., Khodaverdi, R., Devika, K.: Two-echelon multiple-vehicle location-routing problem with time windows for optimization of sustainable supply chain network of perishable food. Internat. Jrnl. of Prod. Econ. 152 (2014)
7. Hassanzadeh, A., Mohseninezhad, L., Tirdad, A., Dadgostari, F., Zolfagharinia, H.: Location-routing problem. In: Facility Location: Concepts, Models, Algorithms and Case Studies, chap. 17, pp. 359–417. Physica-Verlag Heidelberg, first edn. (2009)
8. Heijne, V., Ligterink, N., Stelwagen, U.: 2016 emission factors for diesel euro-6 passenger cars, light comm. vehicles and euro-vi trucks. Tech. rep., TNO (2016)
9. Hickman, J., Hassel, D., Joumard, R., Samaras, Z., Sorenson, S.: Meet methodology for calculating transport emissions and energy consumption. Tech. rep., EC (1999)
10. Lopes, R., Ferreira, C., Santos, B., Barreto, S.: A taxonomical analysis, current methods and objectives on location-routing problems. Int. Trn. Op. Res. 20 (2013)
11. von Lücken, C., Barán, B., Brizuela, C.: A survey on multi-objective evolutionary algorithms for many-objective problems. Comput. Opt. and Apps. 58(3) (2014)
12. Marinakis, Y.: Location-routing problem. In: Encyclopedia of Optimization, pp. 1919–1925. Springer, second edn. (2009)
13. Tavakkoli-Moghaddam, R., Makui, A., Mazloomi, Z.: A new integrated mathematical model for a biobjective multidepot location-routing problem solved by a multiobjective scatter search algorithm. Jrnl. of Manuf. Systs. 29 (2010)